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PART II.—PAPERS CHIEFLY OF A THEORETIC NATURE

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PHYSIOGRAPHY OF THE CHATTANOOGA DISTRICT, IN TENNESSEE GEORGIA, AND ALABAMA

BY

CHARLES WILLARD HAYES

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PHYSIOGRAPHY OF THE CHATTANOOGA DISTRICT, IN TENNESSEE, GEORGIA, AND ALABAMA.

By C. W. Hayes.

INTRODUCTION.

The process of development which has resulted in the present form of the land is always a complicated one and many factors enter into the final product. The factors and the manner in which they are combined vary widely in different regions, and it is often impossible to determine the weight which should be given to each. In order to understand the process of geographic development in the more obscure regions it is desirable to study it where the conditions are comparatively simple, and it is essential that in the region selected for study certain conditions should be uniform over a considerable area within which other conditions should vary as widely as possible. Differences in resulting forms can then be ascribed to their true causes and the correct value can be given to the several factors.

The aim of the following paper is to set forth the results of a study of a region in which several distinct types of land surface are characteristically developed under such conditions that the part taken by the several factors can be fairly well determined; to trace the process of drainage development and the origin of the present land forms upon rocks of diverse erodibility and diverse structure; and, finally, by a concurrent examination of drainage and surface, to read the recent geologic history of the region.

DEFINITION OF THE CHATTANOOGA DISTRICT.

The region selected for study is situated in southeastern Tennessee, northeastern Alabama, and northwestern Georgia. Its location is shown on the accompanying index map, Pl. I. The district chiefly considered, and represented on the large-scale maps forming Pls. II and III, is bounded by the meridians 84° 30′ and 86° and the parallels 34° and 36°, and comprises three square degrees of the earth's surface, or nearly 12,000 square miles. This area embraces twelve quadrangles, as follows: McMinnville, Pikeville, Kingston, Sewanee, Chattanooga, and Cleveland, chiefly in Tennessee; Stevenson and Fort

Payne in Alabama; and Ringgold, Dalton, Rome, and Cartersville in Georgia. The city of Chattanooga is located almost exactly in the center of this rectangular area, and being the best-known geographic feature, either natural or artificial, within its limits, the area is called the Chattanooga district.

NATURE OF THE PROBLEMS TO BE CONSIDERED.

This district displays, within comparatively narrow limits, several well-marked types of geologic structure and topographic configuration. In the eastern portion is a region in which the strata are intensely folded and faulted and in a part of which metamorphism has affected the rocks, in some degree obliterating original differences and rendering the rocks more or less homogeneous. The forms assumed by maturely adjusted streams upon such complicated structures are well illustrated in this part of the district, and also, other conditions being the same, the widely different topographic forms produced by rocks of diverse and uniform erodibility.

In the western portion of the district the strata are practically horizontal, but the beds generally vary widely in hardness. The resulting topographic and drainage forms are strongly contrasted with those which characterize the eastern division.

In the central portion of the district are several isolated arches with associated thrust faults, simple types of the structures so extensively developed in the eastern division. The adjustment of the streams in this central division is in various stages of incompleteness, and the complicated process by which consequent is transformed into subsequent drainage, with the formation of anticlinal valleys and synclinal ridges, is admirably illustrated.

Finally, the preservation of surfaces reduced to base-level peneplains at several distinct epochs suffices for determining the present altitude of former base-levels, and hence the deformations which the region has suffered in recent geologic time. Eliminating those drainage modifications which can be attributed directly to the influence of structure and rock character, very considerable adjustments remain which must be regarded as the direct results of these deformations.

The physiography or systematic geography of this district will be considered under two main heads: First, geomorphology, the description, classification, and correlation of the land forms; second, geomorphogeny, the active processes by which these forms have been developed. The two can not be completely separated, for the description of land forms will necessarily contain some implication of the processes by which they were produced, and, on the other hand, the discussion of the processes involves constant reference to the product.

A. Hoen & Co. Lith. Baltimore.

It should be clearly understood at the outset that the student who is thoroughly conversant with principles and methods of the modern geographic school will find in the present paper much that is elementary and entirely familiar. It is written, however, more particularly for those who do not possess this familiarity with the most recent methods, so that a restatement of many elementary principles is essential to a clear understanding of the problems discussed. On the other hand, while the principles of modern geography have been stated elsewhere, the science is of so recent and rapid growth that the final statement of even the most fundamental principles has perhaps not yet been reached, and each restatement from a slightly different point of view may therefore have some value. Furthermore, the mass of observations on which the generalizations of the science rest is as yet comparatively small, and it is chiefly as a contribution to this groundwork of facts that the present paper seeks justification for its existence.

GEOMORPHOLOGY.

GENERAL RELATIONS.

SUBDIVISIONS OF THE SOUTHERN APPALACHIAN PROVINCE.

The district defined in the foregoing paragraphs forms but a small part of the Appalachian province, and to enable the reader to grasp fully the significance of its topographic details it is necessary to outline briefly the main features of the larger division. As defined by the writer,[1] the Southern Appalachian province embraces the region bounded on the east, south, and west by the Cretaceous and later sediments of the Coastal and Gulf plains and the Mississippi embayment. On the north the boundary is less definite, but may conveniently be regarded as coinciding with the Ohio, Kanawha, and James rivers. The region thus outlined admits of a natural division into five subprovinces or physiographic districts. These correspond with Powell's[2] physiographic regions, except that two of the latter are again subdivided. These five divisions of the Southern Appalachian province are narrow belts of country having approximately parallel sides and extending in a northeast-southwest direction parallel with the Atlantic coast-line. They are shown in outline on the accompanying index map (Pl. I). Named in order from southeast to northwest, they are (1) the Piedmont Plain, (2) the Appalachian Mountains, (3) the Appalachian Valley, (4) the Cumberland Plateau, (5) the interior lowlands. These divisions may be very briefly characterized as follows:

The Piedmont Plain.—The Piedmont Plain is the belt of elevated country along the eastern base of the Appalachian Mountains. The

[1] The Southern Appalachians, C. W. Hayes: Nat. Geog. Mon. No. 10, 1895.

[2] Physiographic regions of the United States, J. W. Powell: Nat. Geog. Mon. No. 3, May, 1895.

altitude of its western edge is about 1,000 feet, and it slopes gradually eastward to about 600 feet at the eastern edge, where it merges with the Coastal Plain. Its surface is intersected by many rather deep and narrow valleys, whose streams have cut through the deep mantle of soil and decayed rock into the harder rock beneath. The Piedmont Plain swings westward around the southern end of the Appalachian Mountains, and there comes in contact with the Appalachian Valley.

The Appalachian Mountains.—In Virginia the Appalachian Mountains form a single range, but southward this becomes complex and expands into a broad mountain belt, having a width of 70 miles in western North Carolina. In its expanded portion the mountain belt has a continuous chain along its eastern side, the Blue Ridge, and another along its western side, the Unaka chain, while the region between the two is occupied by irregular mountain groups and high valleys. Of the two bounding chains the Unaka is the higher, but its crest does not form a continuous watershed. The rivers head upon the lower Blue Ridge to the east and flow westward across the mountainous belt and through gaps in the higher and more rugged Unakas.

The Appalachian Valley, or valley belt.—The Appalachian Valley is a lowland belt lying between the Appalachian Mountains and the Cumberland Plateau. It is occupied by various river systems, in the northern part flowing eastward to the Atlantic through breaks in the Blue Ridge, in the central part westward by the New and Tennessee rivers to the Ohio, and in the southern part southward directly to the Gulf. The great valley is thus seen to be independent of any single river and to be a natural physiographic unit, depending for its characteristics chiefly upon the character and structure of the underlying rocks. In southern Tennessee the surface of the valley is throughout lower than that of the adjacent plateau, being interrupted by only one crest of considerable height—White Oak Mountain. Toward the northeast and, to a somewhat less extent, toward the southwest, in Georgia and Alabama, the valley belt contains many long, narrow ridges, whose even crests reach nearly or quite to the level of the adjacent highlands.

The Cumberland Plateau, or plateau belt.—The Cumberland Plateau generally presents a bold and regular escarpment toward the valley upon the east. Its western escarpment in Alabama and Tennessee is equally bold, but extremely irregular, forming a sinuous line between this division and the interior lowlands. In Kentucky the western margin is less distinct, the plateau merging with the lowlands through a belt of foothills. The surface of the plateau rises gradually toward the northeast from about 600 feet above sea level in central Alabama to 2,000 feet in the latitude of Chattanooga. In Tennessee, Georgia, and Alabama the plateau is separated into a number of more or less isolated plateaus varying greatly in extent. The valleys effecting this isolation are of two kinds: First, those whose position depends directly upon structure, as the valley on the Sequatchie anticline; and, second, those formed by streams cutting transversely across the plateaus, as in the case of the Tennessee River. In northern Alabama the plateau is still further dissected, its remnants forming a series of small isolated table-mountains, or mesas.

The interior lowlands and Highland Rim.—The last division westward consists of the interior lowlands, forming a less elevated plateau which bears the same relation to the Cumberland Plateau that the Atlantic Piedmont does to the Appalachian Mountains. It is made up of the central basin of Tennessee and the surrounding Highland Rim, the latter extending into northern Alabama and across central and western Kentucky.

FORMS OF RELIEF.

Having thus briefly characterized the five physiographic subdivisions of the Southern Appalachian province, the features of the region under consideration may now be described in somewhat greater detail. As shown on the index map, the Chattanooga district includes portions of all these subdivisions, embracing the southern extremity of the Appalachian Mountains, a small portion of the Piedmont Plain, and sections entirely across the Appalachian Valley, the Cumberland Plateau, and the Highland Rim, the latter being a subdivision of the interior lowlands.

THE WESTERN TYPE.

The Cumberland escarpment.—Perhaps the most striking topographic feature of the region is the eastern escarpment of the Cumberland Plateau. This passes diagonally across the district from northeast to southwest, separating it into two nearly equal portions. In the northern half of the district—that is, as far south as Chattanooga—the escarpment, forming here the edge of Walden Plateau, has a slight but regular curvature, concave to the east. Southward from Chattanooga it forms the edge of Lookout Mountain, which lies to the east of Walden. It makes a deep reentrant angle in passing around the head of McLamore Cove, and its general outline is slightly concave westward. In the northern division the escarpment varies between 800 and 1,000 feet in height, while southward from Chattanooga it decreases from 1,250 feet at Lookout Point to about 400 feet at the southern edge of the district.

The plateaus.—In the half of the district to the northwest of this dividing line the relief is distinctly of the plateau type. The greater part of the highland surface reaches a common altitude and is comparatively level, while the slopes to the lowlands are generally steep and often precipitous. The streams which head upon the highlands plunge into narrow canyons, whose sides are even steeper than the outer escarpments of the plateau. In the northern portion of the district there are large areas in which the streams have not yet trenched the plateau surface to any extent, while in other portions, particularly west of Tennessee River in Alabama, the plateau is so deeply dissected that only remnants of the highland remain as flat-topped mesas, more or less completely isolated, but each retaining the characteristics of the original plateau from which it has been carved.

The Highland Rim.—West of the plateau, and separated from it by the sinuous escarpment which, as stated above, forms the western border of the plateau belt, is a broad plain, its gently undulating surface having an altitude of about 1,000 feet. This is the Highland Rim, a part of the interior lowlands, which stretch westward to the Ohio River and beyond. It is separated from the central basin of Tennessee by an escarpment somewhat similar to that which separates it from the Cumberland Plateau, but lower and less regular. In the extreme northwestern corner of the district this plain is seen to be deeply dissected, and the stream valleys in reality form a part of the lower plain to the west. This deeply dissected belt generally characterizes the outer margin of the Highland Rim, forming a sort of fringe along its contact with the interior basin.

In this northwest corner are found, in close proximity, the main features which dominate and give character to the topography of the entire northwestern half of the district. Short Mountain is an isolated mesa with level summit and steep sides. In form and altitude it represents the Cumberland Plateau. To the south and east of this mesa extends the level Highland Rim, while to the northwest the narrow strips of lowland along the larger streams represent the lower plain of the central basin.

It thus appears that the Highland Rim is a terrace, separated by steep escarpments from the more extensive plains on either side, the one 800 feet higher and the other 400 feet lower.

THE CENTRAL TYPE.

The relief in the southeastern half of the district is of a type totally different from that northwest of the Cumberland escarpment. As shown on the index map (Pl. I), this division includes portions of the three eastern divisions of the Southern Appalachian province. Each of these is characterized by its own type of surface, and all are distinctly different from the plateau type which prevails to the west.

The great valley belt enters the district near its northeast corner, with a breadth of 33 miles, which increases to something over 45 miles toward the southern edge. It is about equally divided between the Tennessee and Coosa drainage basins, the Tennessee, which occupies the northern portion, turning westward and leaving the valley belt at Chattanooga. While in general a lowland belt, when examined in detail its surface presents considerable diversity.

The valley lowlands.—No extensive areas of level country are found in this district except in its southern portion along the Coosa River. From the vicinity of Rome, extending southwestward, the Coosa lowlands, or "flatwoods," as they are locally called, form a belt 10 or 12 miles in width but little above the narrow flood plain of the river. This lowland is developed entirely upon soft or soluble rocks, and where the Coosa flows upon more resistant formations it is confined to a comparatively narrow valley. The same is true of the Tennessee and all other streams, both large and small; the extent of the bordering lowland is dependent directly upon the nature of the underlying rocks.

Starting, then, with the level of the larger streams, as the Tennessee and Coosa, between 600 and 700 feet above tide, there is generally, though not always, a strip of flood plain, and a short distance above this a strip of level lowland which is never reached by the present floods. The extent of the flood plain depends upon the size of the stream and the character of the underlying rocks, while the higher plain depends chiefly upon the latter factor.

The valley ridges.—Above these level lowlands are many hills and ridges occupying the greater portion of the valley belt. The ridges are parallel among themselves and with the borders of the belt, while the hills generally have a linear arrangement and often pass into distinct ridges. This parallelism depends directly upon the structure of the valley belt, a dependence which will be more fully explained later.

These valley ridges fall into two classes: First, those which attain altitudes of 900 to 1,100 feet, and second, those from 1,500 to 1,700 feet. The first class is by far the larger, particularly north of the Georgia-Tennessee line. To the second class belong White Oak Mountain and its southward continuation, Taylors Ridge, with a group of parallel ridges to the east of the latter, called collectively the Chattooga Mountains. Upon either side of this group is a broad belt occupied by the lower ridges and lowland valleys. The high ridges terminate west of Rome, and thence southward nearly to the limits of the district the valley belt is occupied by the Coosa Flatwoods and the low hills extending eastward to the edge of the Piedmont Plain. On the extreme southern edge of the district are two short ridges which exceed the Chattooga Mountains in height, but do not have the regular even crests which characterize the latter.

THE EASTERN TYPE.

The Appalachian Mountains.—Only a small part of the Appalachian Mountains comes within the Chattanooga district. The Blue Ridge is far to the eastward, as are also most of the interior mountain groups and intermontane valleys. The southern extremity of the Unaka Range, the western member of the system, forms an abrupt border to a portion of the valley belt, extending southward to the Coosawattee River. Between this southern point of the range and the eastern edge of the district is Mountaintown Valley, a broad basin whose once level surface is now deeply trenched by narrow stream channels. This basin, as well as the country adjoining it on the south for a distance of 15 miles beyond the Coosawattee, has all the characteristics of the intermontane valleys farther north, except that its altitude is not so great. The southern extremity of an interior mountain group is seen in Pine Log Mountain, which terminates just north of the Etowah River.

The Piedmont Plain.—From the base of Pine Log Mountain a nearly level plain stretches toward the east and south, interrupted only by an occasional isolated knob, as Kenesaw and Lost mountains, rising above its even surface and by numerous narrow stream channels sunk below it. This is the western portion of the Piedmont Plain. Its margin, where it comes in contact with the valley belt, forms a somewhat abrupt escarpment from 300 to 400 feet in height, in places deeply dissected by the backward cutting of northwestward-flowing streams. The small portion of this plain included within the Chattanooga district is wholly in the Etowah Basin, and being near a large stream, at low level, its surface is much more deeply dissected than a short distance to the east in the Tallapoosa Basin.

STRATIGRAPHY.

In the region under discussion there is so intimate a relation between the composition and structure of the strata on the one hand and the forms of surface relief on the other, that these factors must be at least briefly considered before a complete understanding of the geographic development of the region can be reached. Considered with reference to their effect upon the topography, the rocks of the district may be separated into two primary groups: 1, unaltered sedimentary formations belonging to the Paleozoic system and occupying the three western physiographic divisions of the district; 2, the metamorphic and igneous rocks of undetermined age which underlie the two eastern physiographic divisions.

GROUP 1. UNALTERED SEDIMENTARY FORMATIONS.

Characteristics of the subgroups.—The Paleozoic strata are subdivided on the geologic maps of the region into 23 formations, and for convenience of description these may be placed in 5 subgroups, as follows: (1) The 6 lowest formations of the Cambrian form the Chilhowee series in East Tennessee, corresponding to the Weisner series in Alabama.

This subgroup is composed of alternating beds of conglomerate, quartzite, and siliceous shale, all materials nearly insoluble, and therefore well adapted for resisting erosion; hence the outcrops of these rocks are marked by high ridges, as seen in Beans Mountain, an outlier of the Unakas, and in Indian and Weisner mountains south of the Coosa River. (2) The 10 formations next above, including the remainder of the Cambrian and the greater part of the Silurian, consist of limestones alternating with more or less calcareous shales. They occupy a very large proportion of the Appalachian Valley, and in general they are easily eroded, to a large extent by solution. Some beds of sandy shale and sandstone, constituting the Rome formation, offer more than ordinary resistance and produce the higher ridges in the areas occupied by this subgroup. One of the limestone formations also, the Knox dolomite, contains a large proportion of insoluble material, chiefly chert. This forms a heavy residual mantle on the surface of its outcrops, and thereby to some extent protects them from erosion, giving rise to moderately high hills and irregular ridges. (3) At the top of the Silurian and in the lower part of the Carboniferous, which are here separated by only a few feet of Devonian shale, are sandstone and chert beds of unusual resistance. These together form White Oak and Chattooga mountains, while the chert beds have been chiefly instrumental in preserving the Highland Rim. (4) The next subgroup contains but a single formation, the Bangor or lower Carboniferous limestone. Although its thickness is something less than a thousand feet, this has been one of the chief factors in determining the characteristic topographic forms in the Cumberland Plateau division, chiefly by reason of its sharp contrast in solubility with the strata above and below. (5) Finally, the two upper formations, constituting the last subgroup, are Coal Measure conglomerates, sandstones, and sandy shales. The conglomerate near the base is particularly well adapted for resisting erosion. These rocks cap the Cumberland Plateau, and by reason of the complete absence of easily soluble constituents, have preserved for a very long time large areas of the plateau surface.

Characteristics of the group as a whole.—It should be further noted that, considering group 1 as a whole, most of the Paleozoic formations, so far as they can be observed, show a tendency to grow thicker and less calcareous toward the southeast, although the change varies widely in degree. Thus some which are pure limestones in middle Tennessee are made up largely of sandstone and shale at the eastern side of the Appalachian Valley. This fact, of course, has an important influence in modifying their topographic value, so that in a few cases, strata of the same age produce entirely different topographic forms on opposite sides of the district. The change in character from east to west also indicates clearly the source from which the materials composing the strata were derived and the distribution of land and sea during their deposition, thus throwing considerable light upon the early geographic development of the region.

GROUP 2. METAMORPHIC AND IGNEOUS ROCKS.

Subgroup A, feldspathic rocks.—The second group, embracing the metamorphic and igneous rocks, may be separated into two subgroups on the basis of relative erodibility. The first includes those formations which contain a considerable proportion of feldspar, and hence nearly all the igneous rocks together with the feldspathic sandstones and conglomerates. In these the feldspar is an element of weakness. When subjected to long-continued action of atmospheric agencies, it is converted into kaolin, and the rock of which it is a constituent readily breaks down. This decay of the feldspathic rocks often proceeds to a considerable depth, and it is not uncommon to find in this region granite or diorite weathered to an incoherent sand for a distance of 50, 70, or even 100 feet from the surface. The Piedmont Plain is composed chiefly of such easily weathered crystalline rocks, largely igneous, while Mountaintown and Talking Rock valleys owe their existence to the presence of a large area of highly feldspathic sediments.

Subgroup B, nonfeldspathic rocks.—The second subgroup includes nonfeldspathic rocks, chiefly slates, graywackes, and conglomerates. Differences originally existing in these sedimentary formations have been to a large extent obliterated by the process of metamorphism which they have undergone. Clay shales have been converted into slates or argillites, which offer nearly as much resistance to erosion as do the most siliceous rocks. Hence, these metamorphic rocks, although varying widely in composition, are to a considerable extent homogeneous. In the valley belt, by first attacking the weaker formations, the agents of erosion generally leave long, narrow ridges in relief, but here they cut channels across the various beds almost as readily as parallel with them. From this results the irregular topography seen in the southern end of the Unakas. The characteristic forms, entirely absent elsewhere in the district, are high and rather sharp peaks from which radiate many fingering spurs separated by narrow, V-shaped stream channels.

RELATION OF ERODIBILITY TO FORMS OF RELIEF.

These relations between the composition or erodibility of the rocks underlying the district and the forms of relief to which they give rise are expressed graphically by the curve on the accompanying diagram (fig. 1). The relative thickness of the several subgroups is indicated by the vertical distances, while relative erodibility is indicated by the length of the horizontal lines. The relations expressed by the curve will be considered at greater length in a subsequent part of this paper.

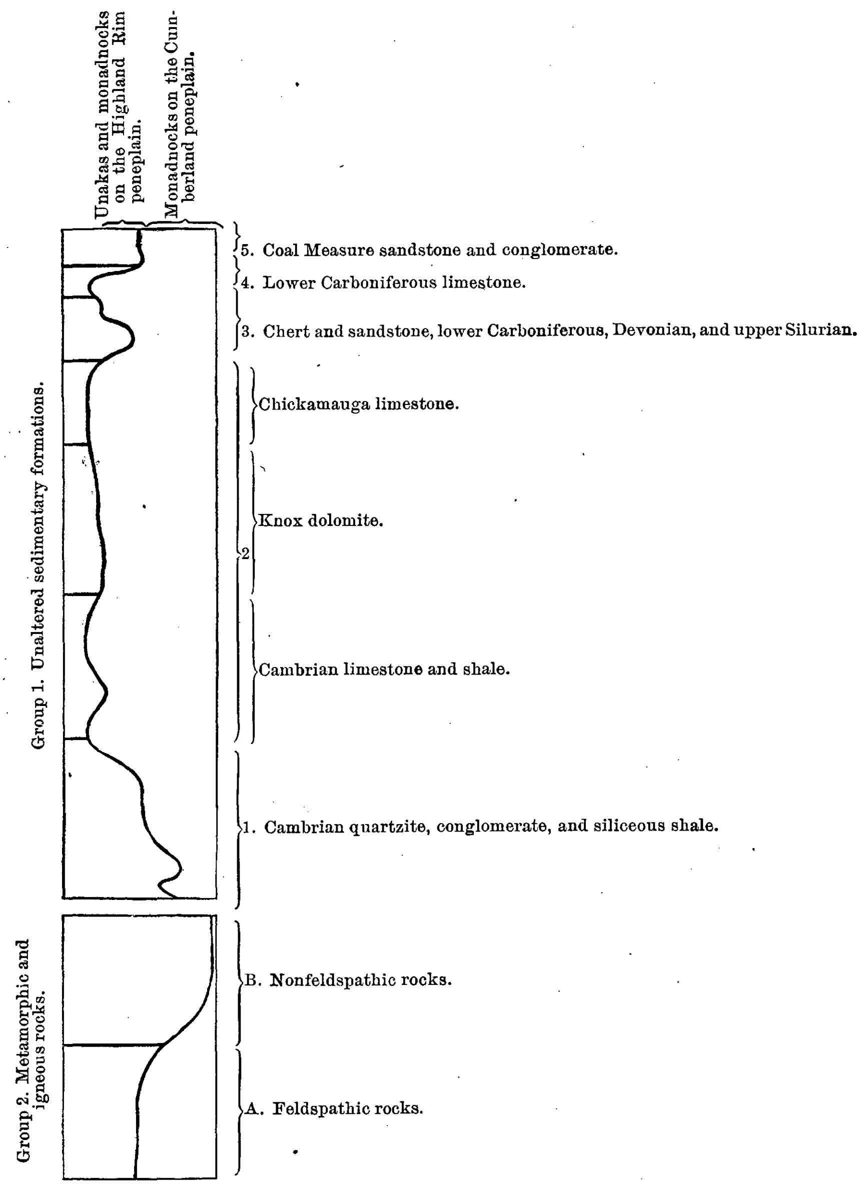


FIG. 1.—Curve illustrating the relation of topographic relief to lithologic composition.

STRUCTURE.

Another factor in the geographic development of this region, second in importance only to the lithologic character of the beds, is its geologic structure. Since the rocks of the three western physiographic divisions are wholly of sedimentary origin, they must originally have been laid down in nearly horizontal layers; but, in a part of this region, they are now inclined at all possible angles. Omitting those portions of the Appalachian Mountains and the Piedmont Plain included within the Chattanooga district, the remainder of the area under consideration is divided by the Sequatchie anticline into two somewhat unequal parts, in which widely different types of structure prevail.

Isolated folds.—The Sequatchie anticline has a direction about 30° east of north. It flattens out toward the northern edge of the district, but extends beyond its limits toward the southwest for more than 100 miles. It has the typical unsymmetrical form characteristic of Appalachian folds—that is, the beds dip much more steeply on one side of the axis than on the other and, as is nearly always the case, the gentler dips are upon the eastern side of the axis. Also from a point near the upper end of Sequatchie Valley southwestward the strata are broken along the steep side of the arch and a thrust fault is developed, its plane dipping southeastward at an angle of 30° or 40° from the horizontal. Northward from the Tennessee line a broad, shallow syncline—the Walden Plateau—intervenes between the Sequatchie anticline and the Cumberland escarpment. This syncline continues southward into Alabama, but its eastern edge does not there coincide with the limits of the valley belt, being separated from it by the Wills and Lookout anticlines and the long, narrow syncline of Lookout Mountain. These two anticlines are very similar to the Sequatchie, but are not nearly so long.

Valley-belt structure.—Eastward from the Cumberland escarpment, entirely across the valley belt, the structure is extremely complicated. The lateral compression to which the region has been subjected probably first produced a series of parallel folds similar to the Sequatchie anticline. As the compression continued beyond the strength of the beds, they were in many cases fractured along the steep sides of the folds, and wherever this took place the anticline was thrust over upon the adjacent syncline. Thus the strata, particularly throughout the valley belt in Tennessee, are in the form of narrow, closely compressed folds, intersected by a large number of fault planes. They are thus cut into many long, narrow blocks which overlap each other, all dipping steeply to the southeast. These blocks of strata are made up of beds which differ in their capacity for resisting degradation, as shown by the curve on the preceding page (fig. 1). Hence, the resistant beds form long, narrow ridges or lines of hills, and the soft beds form narrow, parallel valleys between them. In the southern third of the valley belt which lies within the district a modification of this type of structure is found. Instead of many parallel fault planes dipping rather steeply to the east, there are a few having a very low inclination, on which the strata have been thrust long distances, in some cases several miles, and which have themselves been subsequently folded. The result is that, while the strata have perhaps suffered as much compression as farther north, they have in general lower dips and there is not the regular and manifold repetition of hard and soft beds. Hence the linear arrangement of hills and ridges is less prevalent or wholly wanting.

Areas of horizontal rocks.—The region west of the Sequatchie anticline has the simplest possible structure. The strata retain almost exactly their original horizontal position. If this region has been subjected to the same compression as that to the east, the force has been transmitted to other areas and has not produced marked folds here. On the extreme edge of this area, in the escarpment facing upon Sequatchie Valley, the strata dip steeply westward; but within a short distance, only a few rods, the dips become so light that the beds appear to be perfectly horizontal. This condition continues westward to the edge of the district and far beyond. It is found, however, that while the beds appear horizontal, there is a quite uniform dip toward the southeast of from 25 to 30 feet per mile. This gentle southeastward dip is interrupted in the northern portion of the district by a low anticline whose axis is about parallel with that of the Sequatchie anticline. The fold flattens out rapidly toward both the northeast and the southwest. It is thus seen that all the highlands having a distinct plateau or mesa habit are confined to areas underlain by beds which are practically horizontal.

Relation of erodibility to structure and relief.—It is only where there are marked contrasts in the erodibility of adjacent beds that their geologic structure has an important influence on the consequent topographic forms. Where the rocks are to a large extent homogeneous, as in the two eastern physiographic divisions of the district, it matters little whether the beds are horizontal or steeply inclined, the resulting topography will be essentially the same and the particular forms developed will depend upon other factors.

DEFINITION OF PHYSIOGRAPHIC TERMS.

Considerable diversity prevails in the use by various writers of certain physiographic terms, and it may be well to state in advance the exact manner in which they will be used in this paper.

The term *base-level*, synonymous with *base-level of erosion*, is restricted to Powell's original use, namely the plane below which erosion can not proceed, the general base-level being sea level. There may be an indefinite number of *local* base-levels in any region, each determined by the outlet of the stream whose drainage basin is considered; but only one *general* base-level, and it is the latter that is always referred to unless the contrary is distinctly stated. It should be clearly understood, then, that a base-level is not a topographic form, but a mathematical *plane*, which may or may not, and generally does not, coincide with a land surface.

A *base-leveled surface* is any land surface, however small, which has been brought approximately to a base-level, either general or local, by the processes of gradation. When such a surface has considerable extent it becomes a *base-level plain.* Since no region of great extent is known to have been reduced to a perfect plain, a modification of the term is required for application to the product of the gradation process over a broad area. Hence the term *base-level peneplain* or simply *peneplain* is applied to a surface of which a greater or less proportion has been reduced to the condition of a base-level plain, but which contains also some unreduced residual areas. The terms base-level plain and peneplain have reference only to degree of perfection attained by the gradation processes, and not to the degree of preservation from subsequent dissection. In other words, they apply to the surfaces restored to their original condition. Hence a base-level plain may be an actual topographic feature, a land surface, or it may be only in part a present land surface and in part a surface restored by inference from existing remnants.

Unreduced areas rising distinctly above the general level of a peneplain are included under the general term *residuals.* These are of two classes, *unakas* [1] and *monadnocks*, the classification depending on their form and extent. A *monadnock* is a more or less completely isolated residual, rising above a portion of a peneplain which is well advanced toward complete reduction to a base-level plain. A *unaka* is a large residual mass in relief above a less advanced peneplain. It may or may not display on its surface the remnants of an older peneplain than the one above which it rises. Since these two classes of residuals differ chiefly in extent, it will be readily understood that no sharp line can be drawn between them. From one point of view a given residual may be regarded as a unaka and from another as a group of monadnocks. Further, the classification implies no invariable relation to any particular plain or age, but only to degree of development. It follows from the nature of the processes involved that most often monadnocks alone will be associated with the oldest peneplain in any region, and that the remnants of this plain will be preserved upon unakas and monadnocks rising above the next peneplain below.

The processes which tend to produce a base-level plain are embraced under the term *gradation.* This includes *aggradation* and *degradation*, and the latter includes *corrasion*, through the agency of flowing water (also ice), and *erosion*, through the agency of the complicated forces which tend to the lowering of the general land surface.

The term *gradation period* is employed for the entire time during which the base-level remains in one position; that is, the interval between two elevations of the earth's surface of sufficient magnitude to produce a marked change in the position of sea level. Each gradation period is divided into a *degrading epoch* and a *base-leveling epoch.* In the former the mechanical agents of corrasion are active, while in the latter, during which an actual plain is being formed, the chemical agents of erosion are chiefly effective.

[1] The term *unaka*, used here for the first time in a generic sense, is derived from the Unaka Mountains of East Tennessee and North Carolina, which may be regarded as the type of the land forms to which the name is applied.

The above is not intended as a comprehensive analysis of topographic forms or agencies, but simply to define the meaning which will be attached to a few terms in the present paper.

CLASSIFICATION OF RELIEF WITH REFERENCE TO PENEPLAINS.

Having examined the topography of the disirict in some detail and discussed the two factors which have largely determined its forms of relief, we may now consider the origin of these forms in a somewhat broader way. From even a cursory examination of the region or of a contour map by which its relief is represented (Pls. II and III), it is evident that the dominating features in its topography are three base-level plains or peneplains, separated by vertical intervals which vary considerably in different parts of the district. The three peneplains may for convenience be designated from the regions in which each is most perfectly displayed; viz: (1) the Cumberland, (2) the Highland Rim, and (3) the Coosa.

THE CUMBERLAND PENEPLAIN.

Relation to slightly undulating strata.—To the casual observer the level surface of the Cumberland and adjoining plateaus appears to be due wholly to the presence of horizontal beds of resistant sandstone. A more careful examination, however, discloses the fact that the plateau surface does not always, or even generally, coincide with a particularly resistant bed. It is true the small isolated mesas are usually capped by a hard stratum, but when the broader plateau areas are considered the surface is found to be composed of soft shale as well as of harder sandstone. Again, the strata are not so nearly horizontal as the general plateau surface, which to a considerable extent truncates hard and soft beds alike. Hence it is evident that this surface is the result of degradation—that it is an imperfectly preserved base-level plain.

Development in the central portion of the district.—Since the gradation which produced the plain was sufficiently long continued to reduce the plateau sandstones nearly to base-level, its effects should be found elsewhere in the district. The less resistant rocks of the valley belt were doubtless even more perfectly reduced than those of the plateau, but they have not been able to withstand the subsequent erosion to which the whole region has been subjected, and no remnants of the Cumberland Plain are found within this belt.

Development in the eastern portion of the district.—In the mountain and piedmont belts to the east, the plain was apparently developed only upon the highly feldspathic rocks and the least altered slates, while the nonfeldspathic conglomerates and indurated slates, then, as now, formed considerable elevations above base-level. The best-preserved remnants of the plain in this eastern portion of the district are found to the east and south of Beans Mountain, forming a platform from which rises the southern end of the Unaka Range; they also occur south of this range in Mountaintown and Talking Rock basins. Still farther south in the piedmont the plain was more perfectly developed, but conditions which favored complete reduction also favored subsequent dissection, so that only small remnants are left. A short distance beyond the limits of the district, however, the conditions for the preservation of the plain, although of a different kind, have been almost as favorable as in the Cumberland Plateau, and large areas of its surface remain practically intact.

Variations in altitude.—If the plain which can thus be reconstructed from the remnants found in various parts of the region was at one time near the base-level of erosion, it must then have been approximately horizontal. At present, however, it shows considerable variation in altitude, and it is inferred that the oscillations, of which the net result has been elevation to its present position, were accompanied by considerable warping.

In the plateau division the altitude of the reconstructed plain at the southern edge of the district is about 1,200 feet above sea level. From this it increases gradually to a maximum of 2,000 feet along a line crossing the plateau from Sewanee N. 60° E. This increase in altitude gives the plain a grade of about 10 feet to the mile.

To the north of this axis of maximum elevation, and west of the Sequatchie anticline, its altitude decreases slightly, to 1,800 feet at the edge of the district, while east of the anticline the descent is more rapid, reaching 1,600 feet near the Emory River. On the eastern side of the valley there is a similar increase in altitude from 1,200 feet, at the southern edge of the district, to about 1,700 feet near the Hiwassee River. The plain also shows a descent of about 200 feet from a meridian through the center of the district to its eastern edge. It is thus seen that if the plain has been properly reconstructed the warping has produced an irregular dome-shaped elevation, whose apex is a little north and west of the center of the district.

Hypothesis of diverse base-levels.—An alternative hypothesis should, however, be considered, viz: That instead of a single warped base-level plain, the remnants above described belong to two or more distinct peneplains formed during successive periods of gradation at successively lower levels. When two base-leveled areas are formed in the same region at different elevations, this is the natural conclusion, and their correlation, with the inference of warping, is an hypothesis on which rests the burden of proof.

CORRELATION OF PENEPLAINS.

The evidence on which the conclusion rests in this and most other cases may be very briefly considered. Correlations are easy in proportion to the extent and continuity of the peneplains under consideration. Hence the difficulties are greatest with very old or very young plains—in the case of the former, because subsequent degradation has generally left only isolated remnants, and in the case of the latter, because gradation has reduced only limited areas to base-level; in both the element of continuity is lacking.

By continuous tracing.—A base-level plain is sometimes so perfectly preserved that it can be traced continuously for long distances, within which it shows notable change in altitude. This is the most satisfactory method of correlating different areas, but its application is somewhat exceptional. A case in which it can be applied is on the Sand Mountain Plateau, the continuation of Walden Plateau, southwestward from the Tennessee gorge. For a distance of 75 miles within the district this plateau has a smooth surface, unbroken either by depressions or by eminences. Its uniformity is not due to the controlling position of any resistant stratum, for a variety of beds, both hard and soft, come to the surface. It was unquestionably the product of a single period of base-leveling, and was originally nearly horizontal, though, as stated above, it now varies in altitude from 1,200 to 1,800 feet.

By degree of dissection.—Two peneplains formed in the same region on similar rocks, but during successive gradation periods, will necessarily show distinctly different degrees of preservation, since the older peneplain will have been subjected to degradation during the entire period in which the younger one was formed, in addition to the degradation of subsequent periods which both have suffered in common; or, stated in general terms, where other conditions are approximately the same, the dissection of elevated peneplains is roughly proportional to the time during which they have been subjected to stream corrasion. Applying this formula of correlation or differentiation to the case in hand, it will be noted in the first place that there is no particular degree of dissection associated with any particular altitude. In general the portions of the plain having the greatest altitude are most deeply dissected, but this is due chiefly to the fact that the efficiency of corrasion increases rapidly with increased declivity, and hence is greatest where the interval between present and former base-levels is greatest. It is manifest that the largest areas of the plain at 2,000 feet could not have been preserved in their present condition during a gradation period long enough for the production of the very perfect plain on similar rocks 800 feet lower.

Comparing the different areas east of the valley belt which have been correlated as parts of the same base-level plain, it is found that, when allowance is made for differences in local conditions, all show approximately the same degree of dissection, although the altitudes vary from 1,100 to 1,700 feet.

The two principles above stated, *continuity* and *relative dissection*, but chiefly the first, are sufficient for the correlation of the various base-leveled areas in the plateau region as a single deformed peneplain. They are also both applicable, but chiefly the second, to the correlation of the base-leveled areas east of the valley as a single peneplain. For the correlation of these two plains, however, other evidence must be sought, since they are nowhere continuous, being separated by a broad belt of lowland, and since both the character and the structure of the strata are so different that no strict comparison can be made as to relative dissection.

By coincidence of projected plains.—Wherever the deformation of a base-level plain has been determined with certainty, it is found to be in broad, gentle undulations, the elevations generally taking the form of elongated domes. Very abrupt changes in slope are rare, and hence a gradient determined upon a remnant of a base-level plain may be continued for a considerable distance beyond its margin with a fair degree of certainty. In this way base-leveled areas rather widely separated both horizontally and vertically may be correlated as a single deformed plain. Apply this principle to the present case. The base-level plain in the eastern part of the district rises gradually toward the northwest, while the eastern portion of the plain in the plateau region descends with about the same gradient toward the southeast. If the two gradients be continued across the intervening valley, they will exactly coincide, and hence it is inferred that the base-leveled areas on opposite sides of the valley are portions of a single deformed plain originally continuous.

By determination of recent drainage changes.—A fourth means of determining deformations of a peneplain, and hence of correlating base-leveled surfaces which are found at varying altitudes, should be mentioned here, although it is not applicable to the present case. It is a consideration of the drainage. At the conclusion of a gradation period the streams of a region are delicately adjusted, and if the elevation which inaugurates a new gradation period is accompanied by warping, this will result in stream readjustments the evidence of which persists for some time. Hence recent stream adjustments may generally be taken as indicating deformation, and a study of the adjustments may indicate the character of the deformation and thus lead to a correlation of base-leveled surfaces having distinctly different altitudes. The application of this pinciple is confined chiefly to recent peneplains, since the evidence of stream adjustments does not persist for a very long time.

RELATION OF RIDGE CRESTS TO PENEPLAINS.

Assuming that the above conclusions are correct—that the various base-leveled areas described are parts of a single deformed plain—it is a simple matter to determine approximately the altitude which the plain, if restored, would have in any part of the valley belt. The high valley ridges—White Oak and Chattooga mountains—do not at any point reach the altitude of this restored plain. The highest of the ridges are about 100 feet and the general crests 200 or 300 feet below it. Do these high points, or even crests, mark another base-level plain lower than the one thus far considered? An affirmative conclusion has been reached[1] from a consideration of similar facts elsewhere in the Appalachian province, and the question is pertinent here. Also a very large measure of confidence has been based by various writers—particularly by Davis—upon the determination of base-level plains from the altitude of even-crested ridges.

The ridges in question owe their relief to the presence of an exceptionally resistant stratum of sandstone between less resistant limestones and shales. They owe their narrow, linear form to the steep inclination of the resistant stratum which carries it below base-level within narrow horizontal limits. The ridges are in the main monoclinal, though some portions are synclinal and anticlinal. The crest of each ridge is remarkably uniform in height, except that the synclinal points are usually somewhat higher than the monoclinal portions. There is, however, some difference in height between adjacent parallel ridges, and this difference appears to be closely correlated with slight differences in the character of the resistant stratum or its dip.

Considering the final stages in the process of gradation by which this base-level plain was produced, it seems probable that the outcrops of this resistant stratum were marked by slight elevations above the adjoining perfect plain. The final reduction, except where erosion was supplemented by corrasion, could be accomplished only by solution, and the character of the rocks must have caused the reduction of these areas to lag slightly behind that of the soluble limestones or of the softer Coal Measure sandstones and shales farther west. When active degradation was again inaugurated by uplift of the whole region, the limestones were first removed, leaving the horizontal sandstones in relief as broad plateaus and the steeply inclined sandstones as narrow ridges. Erosion attacked the plateaus actively on their margins, but was practically powerless to reduce their summits. Hence, while the area of the plateaus became constantly smaller, those portions which were left preserved the old base-leveled surface practically intact. The case was very different, however, with the inclined sandstones of the ridges. Although in themselves more resistant than those forming the plateaus and less perfectly reduced in the former gradation period, they could not for any considerable time retain their former crests under the new conditions. As their relief became more pronounced by the lowering of soft beds on either side, erosion became active, and they must have undergone a gradual reduction toward the new base-level. Moreover, the process of degradation is very uniform on such a ridge crest, where corrasion is practically absent and only the forces of erosion are in play. Hence if the ridge crest was originally level it might remain so indefinitely or until it had been reduced far below the former surface of the base-level plain. The rate of lowering of the crest would be modified by differences in structure or character of the

[1] Some stages of Appalachian erosion, Arthur Keith: Bull. Geol. Soc. Am., Vol. VII, 1896, p. 519.

resistant stratum, producing precisely such differences in altitude as are observed in the ridges under consideration. Hence the conclusion is reached that, while the even crest of a ridge indicates the probability of former reduction nearly to base-level, it does not serve to determine the altitude of a base-leveled surface. It may coincide with such a restored surface, but the coincidence will be purely accidental.

Even-crested ridges may sometimes be employed indirectly in restoring a base-level plain. Thus the crest of White Oak Mountain is ascertained, by the means described above, to be about 300 feet below the restored surface. Similar ridges in the region south of the district are composed of beds having about the same resistance and the same structure. Hence it is probable that the rate of reduction may be not far different in the two cases, and that the former base-level, if restored, would be about the same distance above them. It will be readily seen that the problem contains so many unknown factors that the conclusion reached is to be regarded with considerable suspicion.

RESIDUALS ON THE CUMBERLAND PLAIN.

In the foregoing account of the Cumberland peneplain it has been treated as a perfectly reduced surface. While it is probable that at the conclusion of its gradation period the land surface was generally reduced nearly to base-level, some residual areas still remained in relief, and these form the present monadnocks, represented by the darkest tint on the accompanying maps (Pls. II and III).

Monadnocks in the eastern portion of the district.—The monadnocks are most conspicuous in the eastern portion of the district and beyond its limits in the Appalachian Mountain belt. The Unaka Mountains are composed of a group of monadnocks, in some cases approaching unakas in character, while the higher portions of the outliers on the north, and the interior mountain groups on the south, form typical isolated monadnocks. The latter rise with surprising abruptness from the even surface of the peneplain.

Monadnocks in the plateau division.—In the plateau division the monadnocks are less conspicuous, particularly in the southern portion of the district, where the surface must have been reduced to a very perfect plain. They are of two kinds. The first includes those which occur along the western edge of Walden Plateau, together with the Crab Orchard Mountains and a few high points toward the northern end of Lookout Mountain. These are composed of more or less steeply inclined strata, generally an unusually resistant bed of massive conglomerate. The second class includes the isolated knobs or mesas, which rise from 100 to 300 feet above the general level of the plateau. They are composed of horizontal strata, and although sometimes capped by a bed of conglomerate, are more often made up entirely of comparatively soft sandstones and shales. The significance of this last class of monadnocks will be pointed out on a subsequent page.

THE HIGHLAND RIM PENEPLAIN.

Development and preservation on the Highland Rim.—In the foregoing description of the topography of the district a broad area of level country was noted lying west of the Cumberland Plateau. Its surface is scarcely trenched by stream channels, except near its western margin, which borders on the lowlands of middle Tennessee. This Highland Rim is the best-preserved portion of the next peneplain below the one already described, and is regarded as the type locality from which the whole is named. As in the former case, the preservation of a base-leveled surface is due largely to the presence of the resistant beds along its outer margin; but while these beds have been efficient in its preservation, they did not control gradation during its formation, since they have a gentle dip eastward and the plain is found truncating beds of widely different degrees of resistance in its different portions.

Development and preservation in the valley belt.—In the valley belt the peneplain was generally developed, although its surface was probably not so near a perfect plain as on the Highland Rim, since the rocks encountered are much more variable in composition and the different varieties occur in long, narrow strips. The degradation of the several varieties goes on at different rates, so that while some areas were perfectly reduced others lagged slightly behind and formed low monadnocks to the end of the base-leveling epoch. The conditions which were unfavorable for uniform reduction were also unfavorable for the preservation of the plain, so that no considerable areas are preserved in the valley belt. Nevertheless, to an observer looking across the belt from any altitude above 1,000 feet on either side the existence of a peneplain is at once manifest. The great majority of hills and ridges reach nearly to a common altitude, above which a few, as White Oak and Chattooga mountains, stand up conspicuously. The peneplain, so far as it is preserved at all, throughout the valley belt is upon rocks of intermediate resistance, chiefly siliceous limestones and sandy shales. Considerable areas of such rocks occur southeast of the Coosa Valley, and in these the peneplain is fairly well shown. In the narrow anticlinal valleys some areas are preserved upon limestones, but this is due to favorable location and the presence near by of massive residuals.

Altitude and deformation.—Elsewhere in the Appalachian province a peneplain, probably corresponding in age to the one under consideration, shows decided deformation, but within the limits of this district the Highland Rim plain retains a very uniform altitude. Upon the Highland Rim it is approximately 1,000 feet above sea level, while in the valley belt its altitude is about 1,150 feet at the northeastern corner of the district and 950 feet at the southern edge. This difference in altitude of 200 feet is doubtless two or three times as great as the difference which prevailed in the same region during the base-leveling epoch, and hence the district has suffered a slight southward tilting since the formation of the peneplain and probably also a slight differential elevation along a meridian passing a little west of Chattanooga.

RESIDUALS ON THE HIGHLAND RIM PENEPLAIN.

The residuals which rise above the Highland Rim peneplain are represented on the maps (Pls. II and III) by the gray-tinted areas. They are very much more extensive than the Cumberland Plain residuals, since they embrace all of the latter and in addition all areas on which the older peneplain is preserved. They include monadnocks and unakas, both typically developed.

Monadnocks on the Highland Rim.—On the Highland Rim itself Short Mountain is one of the best examples of the first class of residuals. It is perfectly isolated and rises with steep slopes abruptly from the level plain. Its summit probably reaches approximately to the altitude which the higher plain would have if restored over this region. It is difficult to give a reason for the preservation of this monadnock during the gradation period which was sufficient for the production of so perfect a plain as the one surrounding it. Its location at a distance from main drainage lines may have been the most important factor. The capping of horizontal conglomerate doubtless enabled it to retain its original altitude while its area decreased by lateral waste.

The level surface of the plain is interrupted by many monadnocks along the eastern margin of the Highland Rim. These are portions of the adjacent plateau which have been detached by the active corrasion of streams originally flowing upon the plateau surface. Many have lost their sandstone cap and have the form of rounded hills, which are being rapidly reduced to the level of the plain, chiefly by chemical erosion.

Plateau unakas.—The broad plateau areas on which the surface of the Cumberland peneplain is so well preserved form unakas when considered with reference to the Highland Rim peneplain. They are separated into several more or less distinct unakas by the base-leveled anticlinal valleys.

Monadnocks in the valley belt.—In the valley belt the two classes of elevations already described constitute two types of monadnocks. The first class includes the low hills or ridges upon rocks of medium resistance, which rise one or two hundred feet above the general level of the peneplain. These represent the lag of certain areas, due to location or rock character, slightly behind the general surface in the process of reduction. The second class includes the ridges which rise prominently above this peneplain nearly to the level of the one above. They represent areas of distinctly more resistant beds, which have been unable to retain the older peneplain only by reason of their unfavorable structure. While these valley ridges have the essential characteristics of monadnocks, they show distinct differences from the original type, depending directly upon their structure.

Unakas east of the valley belt.—East of the valley belt the residuals above the Highland Rim peneplain are even more extensive than in the plateau belt. The preserved areas of the Cumberland Plain form a high platform, above which rise the isolated and grouped monadnocks already described. Taken together and considered with reference to the lower base-level, they form the typical unaka.

THE COOSA PENEPLAIN.

Lowland valleys.—In describing the topography of the district a series of lowland valleys was noted only a short distance above the present channels and flood plains of the streams. These valleys constitute the third and lowest peneplain which can be distinguished in this region. Their extent is indicated by the yellow tint on the maps (Pls. II and III) bordering most of the larger streams. The Coosa peneplain is confined to areas of easily erodible rocks, though not all areas of such rocks have been reduced to this level, but only such as were rather favorably located with reference to drainage lines. The Coosa "flatwoods" constitute the largest area of the peneplain. This region is underlain by calcareous shales and limestones, which are planed off to a level surface, on which are frequently formed deposits of gravel and silt. These unconsolidated deposits appear to have been connected with the final stages of the base-leveling epoch, or possibly with the oscillations and changes in grade which closed the epoch. Their presence indicates its recency.

Relation to the Tennessee-Coosa divide.—The Coosa peneplain is not developed across the Tennessee-Coosa divide at any point, a fact which proves that the present arrangement of the main drainage lines in the two basins was established prior to this last gradation period.

Altitude and deformation.—The altitude of the Coosa peneplain is something over 700 feet at the southern edge of the district and about 100 feet higher at the northern edge. This slope is but little more than the normal grade of a base-leveling stream, so that the region has probably suffered only a slight deformation since the close of the last gradation period. When examined in minute detail considerable variation is discovered in the altitude of various portions of this peneplain. Also base-leveled surfaces are found at all altitudes up to and even above the next higher peneplain. These are not to be taken as indicating distinct base-leveling epochs, but simply as representing the influence of local conditions. They depend upon the existence of *local* base-levels and are to a large extent independent of the *general* base-level. They illustrate the extreme complexity of the gradation process when followed into its details and the manner in which every possible phase of the process may generally be found in a single region of moderate extent.

GEOMORPHOGENY.

ORIGIN OF THE PENEPLAINS.

Theory of subaerial denudation.—In the foregoing account of the three peneplains which are distinguished in this region, as well as in all previous discussion of these or other peneplains in the Appalachian province, it has been tacitly assumed or explicitly stated that they are the product of subaerial gradation. That the forces involved in this process are competent to produce such peneplains is a proposition from which there is little if any dissent, at least among American geologists. There is, however, another process considered by some even more competent to produce the effects observed, namely, the process of marine denudation. The opposing views have been stated by Davis,[1] with a discussion of the criteria for the discrimination of plains formed by the two processes. Some of the tests suggested and others applicable in this region may be briefly considered.

Theory of marine denudation.—If the plains are the product of wave action there should be unmistakable signs of the instrument by which they were produced. In the first place, there should be, resting upon the cut surface, stratified deposits composed of the material worn from the retreating land by the advancing waves, but in proportion as the age of the peneplain is great the probability of these unconsolidated materials remaining is small, so that this test is less applicable to the higher and older plains than to the lower ones. Nothing resembling a marine deposit occurs on either of the plains, even where the conditions are such as to favor its preservation. It is true that some deposits of silt and gravel are found at certain points on the Highland Rim and Coosa plains, but these are clearly alluvial and not marine. They are generally associated with the larger streams, and the coarse material is always of foreign and not local origin, as it would be if it were the product of beach action.

In some cases where no deposits are now to be found on an erosion surface their former existence is demonstrated by the present stream courses, which show a discordance with the structure. Having their channels determined while flowing upon the uniform surface of horizontal beds, they are superposed, by subsequent erosion, upon the underlying hard and soft beds in a manner distinctly different from that which they would have assumed by the process of adjustment. Such cases of superposition, which are abundant in some regions, are rare in this, and most of the cases which do occur may be explained in other ways. A striking case, which might be taken for inheritance from an overlying terrane, is the course of the Tennessee after it leaves the valley at Chattanooga and turns westward across the Walden Plateau. The anomalous course of this river has been fully discussed

[1] Plains of marine and subaerial denudation, W. M. Davis: Bull. Geol. Soc. Am., Vol. VII, 1896, pp. 377-398.

by Hayes and Campbell,[1] whose conclusion there seems no reason to question. A comparison of the Tennessee gorge through Walden Plateau with other parts of its valley shows that the river must have found its outlet to the west after the Appalachian Valley had been excavated nearly to its present depth; that is, at or near the close of the Highland Rim gradation period, and hence it can not at this point be superposed from beds which might have rested upon the Cumberland Plain. There seems to be no evidence, then, that any stratified deposits have ever been spread over the erosion surface in this region, and, if this is the case, there is strong probability that the plain was not formed by marine denudation.

Further evidence may be obtained from an examination of the margins of the plains. A wave-cut escarpment has certain well-marked characteristics which should permit easy discrimination. One feature is its linear character. Waves are most effective agents of erosion upon projecting headlands, where their force is least checked by an expanse of shallow water and where the products of erosion are most rapidly removed. Hence the tendency is for the waves to cut regular escarpments, having long sweeps and gentle curves. Only where the rocks present the greatest diversity in hardness will the sea cliff present curves of small radius. Further, the qualities which make rocks capable of resisting erosion by waves are quite different from those which enable them to withstand subaerial degradation. In other words, erodibility of a rock depends on one set of qualities when waves are the active agent and on another set when subaerial agents act. In the latter case the most important feature is the presence or absence of a soluble constituent. In case of marine erosion, on the other hand, solubility is of minor importance, and a pure limestone, if free from joints and fractures, may resist wave action longer than a sandstone.

When the two peneplains, but more particularly the two lower ones, where they are in contact with an unreduced residual, are examined with these two points in view, they are found to exhibit none of the characteristics which should belong to plains of marine denudation. As already noted, the escarpment of the Cumberland Plateau facing upon the Highland Rim is extremely irregular. Salient spurs project far out from the plateau, where they would have been exposed to the full violence of the waves had the plain been carved by such agents, and these spurs are not composed of exceptionally hard rock, but, as will be shown later, owe their preservation to their position with reference to the streams. Even if it be conceded as possible that the Highland Rim plain may have been formed by waves in middle Tennessee, the same origin can not possibly be ascribed to the corresponding plain in the Sequatchie and Appalachian valleys. The relation between rock solubility and lowland is here so marked that there can be no possible doubt of the lowland having been produced by subaerial degradation.

[1] Geomorphology of the Southern Appalachians, C. W. Hayes and M. R. Campbell: Nat. Geog. Mag., Vol. VI, 1894, pp. 63-126.

Conclusion.—In the presence of so much evidence it seems safe to conclude that wave action had no part in the formation of these peneplains, but that they are the product of subaerial erosion, the process of degradation by which all land surfaces are being brought slowly but surely toward sea level—the base-level of erosion.

DRAINAGE OF THE DISTRICT.

The description of drainage might properly be included in the first part of this paper under the Geomorphology of the district, but since the streams have been in large measure the active agents in producing the present and past land forms their consideration was deferred and included in this second part, the Geomorphogeny, which deals with the origin of the land forms.

RIVER SYSTEMS.

The streams of this region belong to three distinct river systems, the Cumberland, Tennessee, and Coosa. The first two are parts of the larger Mississippi system, while the Coosa helps form the Alabama River, and thence flows to the Gulf. The areas within the drainage of these several rivers are indicated on the accompanying maps (Pls. IV and V), on which broad brown lines follow the main divides and the narrow broken lines follow secondary divides, outlining some of the more important subordinate basins. The northwestern portion of the district is in the basin of Cumberland River, for the most part drained by Caney Fork and its tributaries, but including also the head of Stony River. Southwest of Caney Fork is Elk River, a tributary of the Tennessee, which joins the latter west of the plateau. A broad belt extending diagonally across the district embraces the area lying within the Tennessee drainage. This has been subdivided into its more important basins. Of these the Sequatchie Basin is wholly within the limits of the district, which embraces also portions of the Emory, Hiwassee, and Chickamauga basins, together with a larger number of smaller ones whose trunk streams do not attain any considerable volume before joining the Tennessee River.

Finally, the southeastern third of the district embraces a considerable portion of the Upper Coosa Basin. The Conasauga-Oostanaula-Coosa forms the trunk stream which receives two large tributaries, the Coosawattee and Etowah, from the east, and two somewhat smaller, the Armuchee and Chattooga, from the west, besides a large number of less important tributaries.

TYPES OF STREAM BASINS.

Even a cursory inspection of the map reveals wide differences between the streams in different portions of the district. The most striking differences are in the forms of the valleys and the manner in which tributaries join the trunk streams. Compare, for example, the valleys of the Collins, Sequatchie, Little, and Hiwassee rivers, which may be taken as representing four distinct types of drainage development.

Type I, Collins River.—This stream drains a broad, oval area. At each bifurcation of the stream the branches are approximately equal in size—that is, there is no main trunk which dominates the basin. The axis of the basin, followed approximately by the Nashville, Chattanooga and St. Louis Railroad, is occupied by a comparatively small stream. The plan of the drainage is practically the same in the western part of the basin, where the streams are in shallow depressions, on the Highland Rim, and in the eastern part, where they occupy irregular canyon-like valleys cut deeply within the Cumberland Plateau, or shallow depressions upon its surface. Everywhere the drainage area is covered by a series of branching streams, with no regularity in their arrangement and no prevalent direction of flow.

Type II, Sequatchie River.—The striking features of the Sequatchie Basin are its great length compared with its breadth and the dominant character of its axial stream. It is 70 miles in length, while its greatest breadth is only 18 miles and its average breadth less than 10 miles. No portion of the Sequatchie River departs so much as 2 miles from a straight line joining its source and mouth. It has two important tributaries, the Little Sequatchie and Brushy creeks, both joining it from the west in the lower half of its course. There are no tributaries of any size from the east, the limits of the basin being upon the extreme western edge of the Walden Plateau. Finally, the basin has a definite relation to the structure of the region, its axis coinciding with the axis of an anticline.

Type III, Little River.—The basin of Little River is also long and narrow, though the ratio of length to breadth is not so great as in the last case. There is a well-marked trunk stream parallel to the axis of the basin, but some distance to the east of it. The tributaries, which are all from the west, join the trunk nearly at right angles. Finally, the axis of the basin also coincides with a structural axis, which in this case is the axis of a syncline.

Type IV, Hiwassee River.—The Hiwassee Basin, or so much of it as is included in the district, combines in some measure the characteristics of Types I and II. It has considerable breadth in proportion to its length and a dominant axial stream, which receives many tributaries of about equal size from both sides. These tributaries join the main trunk in a definite manner, approximately at right angles. Each tributary itself occupies a long, narrow basin structurally similar to the Sequatchie Basin. The trunk stream, as in Types II and III, has a definite relation to the structural axes, but instead of being parallel with them is at right angles to their trend.

CLASSIFICATION OF STREAMS.

The remaining secondary basins of the region more or less closely conform to these four principal types, although a number of them are themselves composite, containing two or more distinct types in their subordinate basins. In a general way they may be grouped in four classes on this basis. In the first class belong most of the basins west of the Sequatchie anticline, including tributaries of the Sequatchie and Tennessee rivers. The second class includes the basins occupying anticlines, such as Wills and Lookout valleys, McLamore and Grassy coves, and the basins of many subordinate streams in the valley belt. The third class includes the basins of streams upon Walden and Lookout plateaus, the basin immediately west of Crab Orchard Mountains, and the subordinate basins occupied by tributaries of the Armuchee. The fourth class includes basins of the large eastern tributaries of the Coosa system and a number of smaller basins tributary to the Tennessee north of Chattanooga.

RELATIONS OF DRAINAGE TO GEOMORPHOGENY.

Considering the drainage in its broader relations, the most striking feature is the anomalous course of the Tennessee River. From the Tennessee line southward the broad lowland of the valley belt offers an easy and direct route to the Gulf; but the river, instead of following this direct route, turns westward at Chattanooga, entering a narrow gorge through the Walden Plateau. After reaching the Sequatchie Valley it turns southward for a few miles, and then again westward through the Cumberland Plateau, after which it turns northward to join the Ohio, flowing, to reach sea level, more than twice the distance that would be required if it remained in the valley belt. This peculiar course of the Tennessee, and many of the minor peculiarities of drainage noted in the above classification, are intimately connected with the recent geological history of the region, which, if perfectly known, would fully explain the origin of its topographic features and the process of adjustment by which the drainage has reached its present form. Many phases of this history have been fully discussed by Mr. Campbell and the writer in a paper[1] to which reference has already been made, and only so much of the matter contained in that paper will be repeated here as is necessary for a clear understanding of the subject. One important conclusion, namely, as to the age of the several peneplains above described, will be accepted as sufficiently proved for present purposes and will not be further discussed here. This conclusion makes the Cumberland base-leveling epoch late Cretaceous, the Highland Rim epoch probably Eocene, and the Coosa epoch Neocene.

[1] Geomorphology of the Southern Appalachians, C. W. Hayes and M. R. Campbell: Nat. Geog. Mag., Vol. VI, 1894, pp. 63-126.

SUBDIVISIONS OF GEOMORPHOGENY.

Any subdivision of the physiographic development—the geomorphogeny—of this region must be in some measure arbitrary, since the processes have been continuous in their operation. Nevertheless, the forces which have brought about the final result, although continuous, have not acted with equal intensity at all times. There have been periods of stability and comparative inactivity, alternating with profound revolutions. These revolutions or partial breaks in the continuous process have been of varying degrees of magnitude. Thus, the Appalachian revolution, which occurred at the close of the Carboniferous, entirely changed the conditions throughout the whole of the Appalachian province. It separates the history of the western portion of the province, at least, into two volumes; in the earlier volume the history is recorded chiefly in the sediments laid down upon the sea bottom, and in the later (1) in the forms inscribed by erosion upon a land surface and (2) in the adjustments of drainage. The earlier volume is subdivided into chapters by the changing conditions on the sea bottom and adjacent lands which gave rise to the differences in the successive rock formations composing the stratigraphic column. The later volume is also subdivided into chapters by oscillations of the land which changed the rate and character of gradation and the form of stream adjustment.

From the manner in which these changes in conditions are recorded only the latest can be determined in detail, since the record of each event in some measure obliterated those previously inscribed.

CYCLES OF GRADATION AND STREAM ADJUSTMENT.

At least three cycles of gradation and stream adjustment can be distinguished in the history of this region. The first is very long and complex, covering the whole of the period from the Appalachian revolution to the end of Cretaceous time. If the record had not been obliterated, this period would doubtless be subdivided into several cycles, each as distinct and important as those which followed. All previous records, however, were removed in the production of the Cumberland peneplain, which is itself the unmistakable record of a very long gradation period. The second cycle is likewise recorded in the formation of a peneplain, the Highland Rim plain; but that this period was much shorter than the preceding is evident from the fact that this plain was developed only on areas of soft and moderately hard rocks. It was marked, however, by some important drainage adjustments, which will be fully described later. Finally, the region has recently emerged from a third cycle, the time which has elapsed having sufficed as yet only for the sinking of the streams part way down to the newly established base-level. The last cycle was much the shortest of the three, its gradation having been able to develop base-leveled valleys only. The events of this cycle are so recent that they can be grouped in a number of episodes, when the history of the entire province is considered. This, however, is impossible in a restricted area, such as the Chattanooga district, and hence is beyond the scope of the present paper.

FIRST CYCLE.

LENGTH AND COMPLEXITY.

It has been stated above that the cycle which coincides with the formation of the Cumberland peneplain was very long and complex. As to the length of time which it covered there can be little question, since its limits are tolerably well fixed, the beginning being the emergence of the region at the close of the Carboniferous, and the end being the uplift near the close of the Cretaceous. From what is known of other periods of equal or less duration, it would appear highly probable that this long interval was not a simple cycle, but was composed of several quite distinct cycles, in each of which the river passed through the normal changes which mark the development of drainage from youth to old age. Although the records of these intermediate cycles, in so far as they consist of land forms, have been almost entirely obliterated by the final, perfect base-leveling of the region, some evidence of their former existence may be obtained.

If sufficient time were to elapse between two periods of orogenic uplift, the forces of subaerial degradation would reduce a region completely to base-level. This is theoretically possible, but has probably never happened for any considerable area, inasmuch as the process of base-leveling is one which goes on with a constantly decreasing rate as it approaches completion. If it were to occur, however, the final product, so far as the form of the plain is concerned, would be the same whether the uplift which inaugurated the cycle were a single rapid movement of the crust, a single slow movement long continued, or a series of movements separated by intervals of rest. Since, however, the final stage, the perfect plain, is never reached by gradation, the character of the movements by which the elevation was effected may be determined in some measure (1) by the character of the monadnocks—the unreduced, residual masses left projecting above the surface of the base-level plain—and (2) by the character of the stream adjustments which are found to have taken place at the end of the cycle.

Evidence from residuals.—If a region is lifted either rapidly or slowly, the streams first lower their channels nearly to base-level and then reduce the interstream areas. Naturally the two processes overlap to some extent in the same area, since the general lowering of the entire surface begins as soon as the streams are capable of removing the land waste. Also when the whole river basin is considered they overlap still more, since the process of gradation along the lower portion of the river may be well advanced while its upper portion is actively corrading its channel. Nevertheless, there is a natural sequence in the two processes, and the first must necessarily precede the second.

If the uplift within a certain period is accomplished in a single orogenic movement and there is great diversity in the rocks of the region, the residual masses which remain at the end of the given period will consist of the hardest rocks, and their altitude will vary with the erodibility of the rocks and the distance from master streams. Areas of the softest rocks will be continuously attacked until they reach base-level, while those which offer greater resistance will retain proportionate relief. The altitude of any point will thus depend chiefly on the product of the two factors *erodibility* and *location*, and the former will be the more important factor in proportion to the completeness of the base-leveling. Consider now that the same uplift is accomplished within the same period, but, instead of there being only a single movement, by two or more elevations separated by periods of comparative repose. Each uplift stimulates erosion anew; but, however long continued, it can reduce the softest rocks no lower than base-level, for below this level they are perfectly protected. Since the gradation periods are shorter, the effect of rock hardness is less pronounced and that of location is greater. Residual masses are composed not only of the hardest rocks, but also of intermediate rocks favorably located for preservation. If, therefore, the element of location is found to be pronounced in the residuals of any region, it is safe to assume that the peneplain above which they rise is not the product of a single uninterrupted gradation period, but that the uplift was interrupted and the soft rocks, now forming the residuals, were below base-level, and so protected from degradation. This is the condition prevailing to some extent on the Cumberland Plateau. The monadnocks bordering Sequatchie Valley and forming Crab Orchard Mountain are composed of hard rocks, but those away from the valley are composed of comparatively soft rocks, mostly shales and thin-bedded sandstones, which are poorly adapted to resist long-continued erosion. They are, however, far from any large stream, being near the line which was for a long time the main divide of the region, and their preservation from degradation must be ascribed to location rather than to the hardness of their rocks. While they are not sufficiently extensive to establish the position of another peneplain above the Cumberland Plain, their presence makes it probable that such a peneplain was formed from 500 to 800 feet above the present surface of the plateau.

Evidence from stream adjustments.—The second method of determining whether the uplift of this region during this first cycle was accomplished in one or more periods of orogenic activity is a consideration of the drainage adjustment which had taken place at its conclusion. The thickness of strata eroded from the Appalachian Valley belt is at least 10,000 feet, and in many places much more. This enormous degradation was accomplished, in large part at least, in the cycle under consideration. The elevation of the anticlines may have been so rapid that drainage was ponded and turned into synclinal streams, or it may have been so slow that the crests of the folds were worn down as fast as they rose. In either case, so long as the uplift continued, no matter how slowly, the divides would tend to remain upon the axes of elevation, even though these were upon soft rocks. This tendency of divides to migrate toward and remain upon axes of elevation has been demonstrated by Campbell.[1]

If the elevation of the anticlines was rapid, the entire drainage must have been changed from antecedent to consequent; while if it was slow, although the larger streams might have retained their antecedent courses, the secondary drainage at least must have been changed to consequent courses. If the whole of the elevation had been accomplished in a single period, the streams would probably never have been able to escape from these consequent courses, and there would now be a great preponderance of synclinal streams. Since the streams of this region are almost wholly subsequent, there must have been abundant opportunity for their escape from the consequent courses, and the most favorable conditions for this are afforded by repeated base-levelings. At each uplift and consequent revival of drainage upon a base-level plain some streams are more favorably situated than others by reason of their location on soft rocks, and a certain amount of adjustment takes place. With each revival the drainage becomes more perfectly adjusted and to a larger extent subsequent. The very perfect adjustment in this region, therefore, supports the conclusion, reached from a consideration of its monadnocks, that it has passed through several cycles of uplift and reduction to base-level.

EARLY STREAM ADJUSTMENTS.

Paleozoic physiography of the region.—There can be no doubt as to the relation of sea and land in this region during the Paleozoic period. The materials making up the formations then deposited were derived chiefly from the degradation of a land mass to the southeast. It should be stated, however, that at various times during the Paleozoic period considerable areas of land probably existed in the western part of the Appalachian province. Thus probably in Cambrian time, and almost certainly in late Silurian and early Devonian time, the central basin of Tennessee was occupied by a land mass, which may have been continuous northward through Kentucky with the Ohio area. Again, after a submergence in the early Carboniferous, the same region was probably land during late Carboniferous time, forming a barrier between the eastern and western coal basins of Kentucky. This land, however, was low, furnishing but little detritus, and it was probably again submerged at the close of the Paleozoic, so that its influence on subsequent drainage development is only indirect. The streams upon the Appalachian Paleozoic continent must have flowed toward the northwest, and as the interior sea margin was pushed gradually westward by the emergence of successive strips along the coast, the streams doubtless

[1] Drainage modifications and their interpretation, M. R. Campbell: Jour. Geol., Vol. IV, 1896, p. 567.

followed the retreating sea margin toward the northwest by extending their lower courses across the newly emerged land. Different opinions are held as to the length of time these rivers continued in their northward courses.

Theory of early diversion of original streams.—One theory is that the streams were turned from northwestward to southwestward courses comparatively soon after final post-Paleozoic emergence of the interior regions. This was effected in part by the barriers which the rising folds presented midway of their courses, and in part by the favorable opportunities afforded to southwestward streams located upon soft rocks in the axes of the folds for capturing transverse streams. Whichever factor may have been the more important, it is concluded that toward the end of Cretaceous time, when the whole region was reduced to a very perfect base-level plain, the drainage of the Appalachian Valley was southwestward to the Gulf, while the plateau streams continued westward to the Mississippi embayment.

Theory of persistence of original streams.—Another theory, supported by Griswold[1] and others, holds, on the other hand, that the Appalachian continent was continuous toward the southwest with the Arkansas land area, both during the period of Paleozoic deposition in the interior sea and of the subsequent base-leveling when it had become dry land. This theory requires the depression in which the Mississippi now flows to have been formed by the warping of the Cretaceous peneplain. It necessitates the conclusion that during the entire Cumberland gradation period the drainage of the southern Appalachian province was westward across the present Mississippi depression to an outlet in northwestern Texas.

The presence of Cretaceous sediments in central Alabama, however, and the northward extension of these sediments across Mississippi, Tennessee, and Kentucky, indicate clearly that, whatever may have been the southward extension of the Appalachian land in Paleozoic and early Mesozoic time, the Mississippi embayment is older than the Cretaceous peneplain. Hence the first theory, as stated above, must be accepted as the one most in accordance with the facts.

Early consequent stream.—Whatever may have been the effect of the rising folds elsewhere in the Appalachian province, it seems very probable that immediately after the emergence of this region a consequent stream occupied the Walden syncline. This shallow trough has a gentle inclination from the northern portion of the district southward to central Alabama, where it disappears beneath the Cretaceous sediments. Its southwestward inclination has been increased by post-Cretaceous tilting, but is chiefly due to the pitch acquired at an earlier date. No transverse fold or other barrier exists which could have prevented the formation of such a consequent stream, while the Sequatchie anticline must have formed a very effectual barrier to prevent the drainage escaping to the westward from this trough.

[1] Origin of the Lower Mississippi, L. S. Griswold: Proc. Bost. Soc. Nat. Hist., Vol. XXVI, 1895, pp. 474-479.

Diversion of consequent stream from Walden Plateau.—The process of stream adjustment in the particular region under discussion during this first long and complex cycle may now be examined in somewhat greater detail. It may be assumed from evidence stated above that the uplift of the region to the altitude held during the Cumberland base-leveling epoch was accomplished by several periods of oscillation separated by periods of repose. The folds and faults of the valley belt brought many strips of limestone above the successively established base-levels and also placed the beds of sandstone in such attitudes that they were more readily removed than if they had remained horizontal. The earlier axial streams, or those occupying the southern portion of the valley belt, thus possessed at the start a decided advantage over the transverse streams, whose lower courses were upon the comparatively hard horizontal Coal Measure sandstones. The consequent stream in Walden Plateau, flowing throughout its entire course upon sandstones, was at a serious disadvantage compared with a parallel stream subsequently established upon a limestone belt. Hence the eastern axial valleys were lowered more rapidly, and their streams not only continued to intercept and divert the upper portions of additional transverse streams, thus continuously decreasing the volume of the stream to the west, but probably in some gradation period prior to the Cumberland beheaded that stream and diverted its upper portion from the syncline. The two portions of the Walden syncline on opposite sides of the Tennessee line are quite differently situated with reference to ability to protect a consequent stream from diversion. The northern section has immediately adjacent upon the east a broad belt within which the protecting sandstones were not only lifted high above base-level, so that their removal was quickly effected, but were intersected by many faults which must have greatly facilitated erosion. The southern section, on the other hand, has upon the east from one to three comparatively low, unfaulted anticlines, which brought the resistant sandstones during early stages of gradation to the right elevation for protection against streams encroaching westwardly from the valley belt. Hence the diversion of the consequent stream was effected in the unprotected northern section, while the beheaded portion remained in its original position in the southern section till a very much later date.

Influence of Sequatchie anticline.—It is probable that the Sequatchie anticline, which had previously formed a barrier across the path of westward-flowing streams, and, as stated above, had diverted them to a southward consequent course in the Walden syncline, now formed a barrier to further westward encroachment of the subsequent streams. The hard Coal Measure conglomerate, brought above base-level on the Sequatchie anticline, probably held the divide for a long time at the axis of the fold.

Westward encroachment of axial drainage.—Eastward-flowing streams continued working at the divide, and finally, toward the close of the cycle, the barrier was breached and the successful stream began the conquest of territory farther west. Since at each uplift which inaugurated a new gradation period the deepening of the main axial valley progressed toward the northeast, southern tributaries would have an advantage in time over those farther north; that is, the lowering of their outlet to any given level would be accomplished earlier for the former than the latter. Hence North Chickamauga and Soddy creeks were favorably located, and succeeded in capturing territory west of the anticline. Roaring and Richland creeks, on the other hand, were less favorably located, and did not succeed in passing the barrier. Still farther north the anticline flattens out, and the conglomerate, being below the earlier base-levels, ceased to be effective as a barrier against the encroaching streams. Hence Sandy and Berks creeks acquired considerable territory beyond the anticline.

PHYSIOGRAPHY OF CUMBERLAND BASE-LEVELING EPOCH.

At the close of the Cretaceous period of base-leveling the drainage was probably arranged somewhat as represented in green on the maps, Pls. IV and V. The present divides are represented on the maps by brown lines, and the position of the divides then existing by the broken green lines. Wherever no green lines appear on the map the drainage of the epoch is regarded as coinciding with present drainage or there is no evidence for determining its position.

Position of the main divide.—The chief difference in the drainage of the region is seen to be the course of the main trunk stream of the Appalachian Valley southward across the present Tennessee-Coosa divide. The main divide between southward- and westward-flowing streams was near the Sequatchie axis, passing to the west around the heads of the few streams which had been able to capture territory beyond that barrier. It probably crossed the course of the present Tennessee near the Tennessee-Alabama line. Below this point the Sequatchie anticline was probably occupied by a subsequent stream, which may have been either tributary to the consequent stream in the Walden syncline or have flowed westward to the Mississippi embayment.

The Appalachian river.—The main trunk stream of the valley belt, which may be called the Appalachian river, received several large tributaries from the east, only one of which, the Hiwassee, has persisted in its entirety to the present. These were the streams originally flowing westward from the Appalachian continent to the Paleozoic interior sea, first turned southward by the Sequatchie anticline to a consequent course in the Walden syncline, and then intercepted and diverted by a subsequent stream to the course shown on the map.

Growth of the upper Coosa system.—Some of these streams have been again intercepted and diverted southward by the headward encroachment of a favorably located axial stream and now form eastern tributaries of the Coosa system. It is impossible to determine the exact date at which this last diversion took place, and it may possibly have occurred before the epoch represented on the map. The evidence to the contrary is derived from the presence of water gaps through the high valley ridges. It would seem probable that these must have been occupied by larger streams than at present, at least as late as the close of the Cumberland base-leveling epoch; otherwise in the adjustment which followed that epoch the streams would have been unable to cut down the hard rocks of the ridges with sufficient rapidity for their own protection and would have been diverted, leaving wind gaps at the points where they had formerly crossed.

Influence of the Sequatchie anticline.—Although the eastward-flowing streams north of the Tennessee line had diverted the drainage from its consequent position in the Walden syncline and had pushed their head waters some distance to the westward of the original anticlinal divide, they had not completely reduced the territory thus acquired to base-level. The hardest stratum they encountered in the corrasion at the divide was the conglomerate at the base of the Coal Measures. Above this resistant stratum are shales and sandstones, and below are limestones. The upper shales and sandstones were almost perfectly base-leveled east of the anticline and the limestones generally quite reduced wherever the covering of conglomerate was removed. Between the base-leveled limestone belt on the axis of the anticline and the base-leveled shale belt in the syncline there remained a ridge of conglomerate through which the encroaching streams flowed in narrow gaps. These gaps serve to determine the present position of the peneplain, since, as will be explained later, they were deserted by their streams at the end of the base-leveling epoch, and hence have not been cut below its surface. The portions of the ridge left between these gaps formed a series of monadnocks rising above the general level of the plain. By reason of the decrease in height of the anticline toward the northeast the activity of erosion on its crest and sides had there been less active, so that portions of the conglomerate remained, protecting the underlying limestone. Thus the monadnocks which occur along the eastern side of the valley increase in height toward the northeast and pass here directly into the Crab Orchard Mountains. The extent of these monadnocks is shown on the map (Pl. II), on which, as explained on a former page, the most heavily shaded areas represent portions of the surface remaining above the level of the Cumberland peneplain at the present time. They must be considerably smaller now than they were at the conclusion of that base-leveling epoch, for erosion has been active upon them during the succeeding gradation periods.

On the western margin of Sequatchie Valley the monadnocks are inconspicuous, consisting of a few small knobs along the edge of the escarpment. By reason of the fault along the Sequatchie anticline, the beds on the western side are relatively depressed, so that the conglomerate was, for the most part, below base-level while the Cumberland Plain was being formed, and hence not in a position to resist erosion.

Along the eastern side of the valley a monadnock extends continuously from Beatty Gap northward some distance beyond its head. Its upper portion bifurcates and holds Grassy Cove between its divergent branches. It is nearly, though not quite, cut down to the level of the peneplain at Low Gap and also at the head of Swaggerty Cove. The region now occupied by the upper part of the Sequatchie Valley, at least the upper 10 miles, although in part underlain by limestone, was probably not reduced to the level of the Cumberland Plain, and small streams heading upon this unreduced portion of the anticline flowed eastward through Low Gap and through Swaggerty Cove, but were not able to corrade their channels quite to base-level.

From Tollett Mill to Bearden Mountain the anticline has a sharp northeastward pitch, while beyond the fold flattens out and the axis is nearly horizontal for some distance. In this latter portion of the fold, therefore, the conglomerate has a much lower altitude than farther south, and hence was not so early in the cycle an effective barrier to streams encroaching from the east. It appears probable that somewhat early in the Cumberland gradation period, or in one which preceded it, several eastward-flowing streams cut backward across the anticlinal axis, while they were yet upon the comparatively soft shales and sandstones overlying the conglomerate. Having acquired some drainage area beyond the anticline, they were able to hold their courses across the axis when the conglomerate was reached in the process of downward cutting, and to cut through the conglomerate to the limestone beneath. The process of opening a lateral valley upon the axis of the anticline then began, and resulted in the formation of Grassy and Crab Orchard coves.

SECOND CYCLE.

ADJUSTMENTS ALONG THE MAIN DIVIDE.

Effect of uplift.—The long period of base-leveling which resulted in the formation of the Cumberland peneplain was terminated by a series of oscillations, the final effect being an elevation, and this uplift, as shown by the present altitude of different portions of the peneplain, was accompanied by considerable warping of the base-level. The streams had for a long time meandered over a smooth, featureless plain, the interstream areas almost entirely reduced and the active cutting confined entirely to the few monadnocks at their head waters. The uplift terminated one cycle and inaugurated another. Streams which had long been inactive began vigorously to attack their channels, working backward from the sea margin, or from points in their courses where differential uplift was felt by the upper tributaries. Also the axial stream or streams, although in the main located upon soft rocks, found their channels crossing many hard beds which they were compelled to cut through. The streams flowing westward from the plateau to the Mississippi embayment, on the other hand, had a somewhat shorter route to the sea and were more advantageously situated for rapid cutting. During the greater part of the preceding cycle they had been working upon horizontal sandstones and consequently under great disadvantage compared with the axial streams. As a result the axial streams had encroached upon their territory and diverted their head waters to southward courses. The conditions were now to some extent reversed. The sandstones had been removed from at least half the area which they originally covered west of the Sequatchie anticline, and, where not entirely removed, their thickness had been greatly diminished, so that they offered comparatively little resistance to further degradation.

Effect of deformation.—Another condition in their favor was the character of the deformation which accompanied the uplift. As shown in the paper above cited,[1] the greatest elevation was on a longitudinal axis nearly coincident with the Appalachian Valley. Hence the axial streams flowed lengthwise of the uplift and were compelled to cut back the entire distance from their mouths. The westward-flowing streams, on the other hand, were transverse to the uplift, and were accelerated chiefly in the upper portion of their courses. Hence they had a shorter distance to deepen their channels before their upper tributaries were stimulated. By reason of this combination of favorable circumstances the westward streams were able to push back the divide and regain some of the territory lost in the preceding cycle.

Contest for the Sequatchie anticline.—The Sequatchie anticline, so far as base-leveled, was occupied by a narrow belt of easily erodible limestone, entirely surrounded by a rim of resistant sandstone. The limestone could not be reduced more rapidly than an outlet was lowered across the sandstone rim. The sandstone barrier was thinnest in northern Alabama, and here it was first breached, either by a westward-flowing stream, cutting backward at its head under the accelerating influence of its increased grade, or, if this part of the anticline had remained in the western drainage, by the cutting downward of a stream already located across the barrier through the thin protecting cap of sandstone. Having gained unobstructed access to the limestone area, a branch of the aggressive stream was rapidly pushed headward along the axis of the anticline, and by reason of the great advantage which it possessed diverted the streams which it successively encountered in its progress toward the northeast. Before this stream had pushed its conquest of the anticline as far as the present Tennessee line, the Appalachian river had probably cut its channel back sufficiently to stimulate its tributaries in this region. Those farthest south would be the ones first affected, and since these, having been favorably located in the previous cycle, had acquired the largest territory beyond the

[1] Geomorphology of the Southern Appalachians, C. W. Hayes and M. R. Campbell: Nat. Geog. Mag., Vol. VI, 1894, pp. 63–126.

Sequatchie anticline, they were vigorous streams and were able to keep their channels down near base-level. They probably succeeded in cutting nearly or quite through the barrier of sandstone capping the Walden Plateau before they were intercepted and their head waters diverted to the southwest. The one whose head waters occupied the Coppenger Creek Basin may have succeeded in diverting several of its neighbors before they had cut deeply into the rim of conglomerate along the western edge of Walden Plateau. The beheaded streams continued to occupy channels across at least the eastern portion of Walden Plateau, and, since the resistant sandstones had been removed, were able to lower their channels in the limestone quite down to the Highland Rim base-level. Having captured these vigorous streams, the channel of the diverter upon the Sequatchie anticline was still further deepened and its progress was more rapid toward the northeast. The streams flowing eastward from the anticline were successively beheaded before they were able to cut their channels across the hard, upturned conglomerate much below the level of the peneplain. Being thus beheaded, the gaps through the conglomerate ridge became cols where erosion was reduced to a minimum. Consequently these gaps remain practically at the level of the old peneplain. The progress of the diverting stream as it approached the northeastern end of the anticline became slower by reason of its increasing length and the less perfect reduction of the region to the old base-level.

The conglomerate cap upon Bearden and Hinch mountains finally checked further progress, and Swaggerty Cove Creek, which would have been the next capture, was only partly diverted. Meanwhile the streams which had breached the anticlinal barrier farther north and acquired territory to the west in the former cycle continued to flow across the axis toward the east for a long time after the uplift. The coves were considerably enlarged and their channels were deepened at least 300 feet below the level of the old peneplain before these streams were dispossessed of the territory which they had acquired west of the anticline.

The capture of their head waters was finally effected, not by the encroachment of an anticlinal stream, as is most often the case, but by a favorably located synclinal stream. As already stated, the rocks above the lower Coal Measure conglomerate in this region are chiefly shales, which offer slight resistance to erosion compared with the conglomerate. The Emory River, flowing past the northern end of the Sequatchie anticline, was able to acquire a large drainage area on the plateau during the preceding cycle, and when it was accelerated by the uplift it rapidly lowered its channel in the shales above the conglomerate. A tributary, Daddy Creek, entering the Emory west of the anticline, was favorably located for cutting backward into the territory of the transverse streams, obstructed as the latter were by the conglomerate they were obliged to cross at two points, one on either side of the anticline. Possessed of this advantage, Daddy Creek acquired all of the territory west of the anticline previously drained by the streams which occupied Crab Orchard Gap and Grassy Cove. It also acquired the greater part of Crab Orchard Cove, but not Grassy Cove, for another factor intervened to prevent this.

Effect of subterranean erosion.—As stated above, the progress of the aggressive stream toward the northeast along the anticlinal axis was checked by the conglomerate cap of Bearden and Hinch mountains. Although the valley was not extended farther along the axis, its surface was lowered nearly to the newly established base-level, leaving a steep escarpment, limestone below and conglomerate above, along the sides and about the head of the valley. The valley surface was thus 600 feet lower than the surface of Grassy Cove, on the opposite side of Bearden Mountain, while the lowest gap in the intervening ridge was 1,500 feet above the valley. Notwithstanding the great height of this ridge, however, it is not so formidable a barrier as would appear at first sight, inasmuch as its lower portion, all except the upper 500 feet, is composed of limestone.

Wherever surface waters containing carbonic acid and other organic acids taken up from decaying vegetation comes in contact with limestone some of the latter is dissolved. Thus water percolating through minute cracks in the rock enlarges them to underground channels and finally to great caverns. The roofs of these caverns often fall in and give rise to the sinks so common in all limestone regions. Where the strata have been bent and fractured the formation of underground channels is more rapid than elsewhere, since many open fissures are found by the percolating solvent water. The thrust fault which prevails along the western side of the Sequatchie anticline passes at the upper end of the valley into the steep limb of the unsymmetrical fold. Where the rocks have been thus sharply bent they have also been considerably fractured, and hence the conditions have been favorable for the formation of underground channels. These worked backward from the head of the valley along the line of fractured rocks, and finally established a connection between the valley and the northern portion of Grassy Cove. This underground channel quickly diverted the waters of the cove from their course across the sandstone rim to the easier course thus established. They now enter the mouth of a cavern at the northern end of the cove, and after their long underground passage of 8 miles emerge in a large spring near the head of Sequatchie Valley. The land surface within the cove has been lowered about 100 feet since the drainage was diverted to its present course. If the underground passage should by any means become choked up, the cove would be flooded. It seems that in comparatively recent time this has happened, for the floor of the cove is deeply covered by fine silt, which appears to have been deposited in standing water. The course of the underground channel is marked at various points by surface depressions where the cavern roof has fallen in. Something of this kind may easily have choked up the passage for a short time.

The smaller coves are in part tributary to Grassy Cove and in part northward to a branch of Daddy Creek, which has succeeded in holding its course from the limestone area across the edge of the conglomerate to the westward. Crab Orchard Cove is composed of a number of small basins, in each of which the surface water collects into a stream and disappears in a sink to reappear elsewhere as a large spring.

These coves with underground outlets are extremely interesting as illustrating the manner in which the Sequatchie Valley was excavated, while the whole region throws much light on the mode of formation of anticlinal valleys in general. The various stages in the process are shown by typical examples: First, the complete arch, with unbroken covering of the protecting formation, is seen in Luper Mountain; next, the transverse gap cutting through to the easily erodible limestone, but still occupied in part at least by the stream which cut it, as Crab Orchard Gap with the beheaded Berks Creek; then the cove with an underground outlet, and finally the completed, base-leveled valley.

The rapidity with which the axial stream progresses headward is vastly increased by the formation of underground channels. While a col at which two streams are contending is worn down with extreme slowness by reason of the small amount of water which is available for performing the work, the formation of cavities in limestone is no slower there than elsewhere, depending simply on the supply of acidulated waters and the presence of cracks in the rocks. Hence a divide may be penetrated by an underground channel while the intervening col remains practically unchanged, as is the case at the head of Sequatchie Valley. When such a channel is once formed and the diversion of drainage effected, it is only a matter of comparatively little time till an open channel is formed. The frequent caving in of the roof makes a depression on the surface which directs and concentrates the drainage and renders surface erosion much more rapid than it would otherwise be.

DEVELOPMENT OF STREAM BASINS OF TYPE I.

While this contest for supremacy was taking place along the main divide the older peneplain was being dissected on either side and a new plain developed at the lower level. As stated above, erosion in the first cycle had removed the greater part of the sandstone from a considerable portion of the region it originally occupied in the western part of the district. Conditions were therefore favorable for the rapid reduction of this region. The streams, accelerated by the uplift, sank their channels in the soft limestone, and the interstream areas were rapidly lowered, chiefly by solution. The rate at which the stream channels were deepened decreased toward the southeast by reason of their smaller volume and the increasing thickness of sandstone through which they were obliged to cut before reaching the soft limestone beneath. The sandstone cap was thinnest in northern Alabama, and here the new plain reached its greatest development, the plateau being cut through at several points, so that the plain developed west of the plateau was continuous through these gaps with the one developed on the Sequatchie anticline. The width of the plateau increases northward with the increasing thickness of the sandstone left uneroded below the surface of the old peneplain. The western escarpments of the plateau, as well as the sides of the river channels, were kept steep by reason of the arrangement of hard and soft beds. The limestones forming the lower slopes are removed by solution, and the overlying sandstones and conglomerates are thus undermined and break off in large blocks, which form a talus along the lower slopes. The rate of recession of these escarpments depends largely upon the ability of the streams to remove this talus and expose fresh surfaces of limestone to the action of the solvent waters. But even where the surface of the limestone is deeply covered with a mantle of residual and foreign material the percolating waters gain access to the rock beneath and form underground channels and caverns which greatly facilitate degradation.

During this second cycle the westward-flowing streams, that is, those which are now included in the Cumberland River Basin, retained about the same courses they had acquired in the preceding cycle. They lost a little territory through the continued encroachment of streams at first tributary to the Appalachian river and afterwards to the Sequatchie. Having all been stimulated in nearly the same degree by the elevation and warping of the base-level, few opportunities were offered for the capture of drainage area from one stream by another. Doubtless minor adjustments occurred as one stream or the other had slight advantage by reason of the differences in the rocks on which they were flowing, but no considerable reversals or diversions.

DEVELOPMENT OF STREAM BASINS OF TYPE II.

On plateau-belt anticlines.—Considerable space has been devoted to the manner in which the Sequatchie Basin was developed, since this is taken as the type of anticlinal valleys, and also since the process is there incomplete and can therefore be studied to advantage. The development of other anticlinal valleys in the district doubtless followed essentially the course outlined above. Consequent streams upon the sides of the arch cut through to less resistant beds and opened out longitudinal valleys upon the axis. These were developed at the expense of the adjacent synclinal streams, from which successive branches were diverted, leaving wind gaps in the resistant rim of the synclinal basin. An essential factor in the process is the character of the elevation to present altitude. Without halts of sufficient length for removal of most of the resistant bed from the top of the arch, while it was protected below base-level in the bottom of the adjacent syncline, and for the base-leveling of considerable areas upon the anticline, probably few, if any, subsequent anticlinal streams would have been developed. As it is, conditions have been so favorable for this development that every anticline of any magnitude coincides with a valley of this type. The overlapping ends of the Lookout and Wills anticlines are perfectly reduced, and the stream developed in the shorter of the two, in addition to performing its own task, has cut through the intervening narrow syncline and assisted in the reduction of the other.

On valley-ridge anticlines.—Among the valley ridges, already described somewhat fully, are a few anticlines upon which subsequent valleys have not yet been developed. Wherever these folds brought the resistant Silurian sandstone above the Cumberland base-level, there it was reduced during this long gradation period, but portions of the anticlines which were below that base-level have in general persisted to the present. Thus the western portions of Simms and Lavender anticlines brought the sandstone above the Cumberland base-level, and it was removed, permitting the development of subsequent axial valleys during later gradation periods. The eastern portions of these two anticlines, on the other hand, were below base-level, and so protected during the Cumberland epoch. At only one point has later erosion been able to breach the resistant stratum. The head of Beach Creek has succeeded in cutting through the sandstone to softer rocks beneath, in which a small axial valley has been developed, the outlet stream flowing through a narrow gap cut in the outer hard beds. This breach in the Lavender anticline is probably not due simply to the unaided corrasion of a small stream upon its side. It is more probable that the former drainage of Texas Valley and perhaps a much larger area, as shown on Pl. V, was southward by the present course of Beach Creek. When the degradation of the Highland Rim period revealed the resistant sandstones of the Lavender anticline, the stream which found itself thus unfavorably located was robbed of its head waters by streams passing around the end of the obstruction upon soft rocks. The diversion, however, did not take place until considerable work had been done upon the sandstones at the summit of the arch, probably sufficient to cut entirely through it, so that the beheaded stream had only to reduce the soft rocks below and cut down its outlet across the southern limb of the fold.

DEVELOPMENT OF STREAM BASINS OF TYPE III.

In plateau synclines.—Coincident with the growth of the subsequent anticlinal valleys has been the diminution of the consequent synclinal basins. These, as indicated by the maps showing late Cretaceous drainage (Pls. IV and V), were then much larger than at present. The northern portion of the Walden syncline had been robbed of its consequent stream in a previous epoch, and in the period which followed successive areas were abstracted from its southern portion by the aggressive stream developed on the Sequatchie anticline. In like manner the Lookout synclinal basin was greatly diminished. By the lowering of adjacent limestone areas to the Highland Rim base-level it was left in high relief. Its streams, flowing at an elevation several hundred feet above base-level, were subject to capture on every side. They were to some extent in a state of unstable equilibrium. The eastern rim of the basin was breached and its upper portion captured by a tributary of Chattanooga Creek, while a tributary of the Coosa intercepted the main trunk stream near the middle of its course and diverted it from the basin, leaving Black Creek as its shrunken representative.

In valley synclines.—The several branches of Armuchee Creek are examples of synclinal streams which have probably not persisted in their consequent courses, but are, to a certain extent at least, subsequent, having reached their present position by a process of adjustment. In the case of Texas Valley, the original consequent stream was diverted from the syncline of hard rocks, now represented by a small mesa in the center of the basin, to soft rocks upon adjacent anticlines. When, by further degradation, resistant beds were reached upon these anticlines, the streams followed the soft beds down the slopes toward the center of the syncline. There are at present, therefore, two monoclinal streams with a synclinal mesa between them, and when the latter is entirely removed the two streams will combine near the center of the syncline. This final stage has already been reached in the North Armuchee Basin.

These subsequent synclinal streams are, under present conditions, stable and safe from diversion, since the resistant bed forming the rims of the basins passes below base-level. If, however, the region should be elevated so as to bring the Silurian sandstone above base-level, they would become unstable and again subject to diversion, exactly as are those upon Lookout Mountain.

DEVELOPMENT OF STREAM BASINS OF TYPE IV.

The final class of stream basins to be considered is that of which the Hiwassee forms the type. This class is confined to the valley belt, and its best development is in regions where the Appalachian type of structure prevails. The two most important factors in producing this drainage type have been the presence of Appalachian structure and the recurrence of several well-marked gradation periods.

During each base-leveling epoch the streams were sluggish, the interstream areas had slight relief, and the effects of structure and rock character were reduced to a minimum. The streams were nicely balanced at their divides, which had remained practically stationary for a long time, no stream having sufficient advantage over its neighbor to effect conquest of territory. With the uplift which inaugurated the next gradation period the streams were accelerated and the delicate balance between the opposing streams was disturbed. In the consequent struggle for ascendency between rival streams advantage was taken of structure and rock character, factors whose importance in drainage adjustments is proportional to the acceleration. Streams which found themselves located upon soft rocks had great advantage over those on harder rocks, and their capture of territory from the latter rapidly followed. Streams which succeeded in holding their courses across hard beds were compelled to cross them in the most economic manner; that is, at right angles to the strike. There resulted from these conditions the peculiar rectangular arrangement of drainage so well developed in this portion of the Appalachian Valley. The master streams of the region, determined by the broad structural features of the province, are axial. Into these flow a few large transverse streams, such as the Hiwassee, which, by reason of their size, have been able to hold their courses across the hard beds. Into the transverse streams flow many axial streams, each located upon a strip of soft rock. Finally, these have tributaries joining them at right angles from the harder rocks on either side, and in some cases a third set of axial streams is developed tributary to the second set of transverse streams. Thus in its typical development the drainage shows five classes of streams in descending order, as follows: First, the primary axial streams, e. g., the Tennessee; second, the primary transverse streams, e. g., the Hiwassee; third, the secondary axial streams, e. g., Candy and Rogers creeks; fourth, the secondary transverse streams, e. g., Bigsby, Potter, Short, Brush Shoal, and Rock creeks; and finally, the tertiary axial streams, e. g., the numerous small tributaries of those last mentioned.

The extent to which this adjustment has been carried is best shown in the Hiwassee Basin. The formations which make up the valley west of the Chilhowee Range, when classified with reference to erodibility, show considerable diversity within certain limits. The Hiwassee River pursues a very direct course from its junction with the Ocoee northwestward, across hard and soft formations alike, to the Tennessee. Its tributaries, the secondary axial streams, are almost without exception located upon the most easily erodible formations, the upper part of the Knox dolomite and the overlying Chickamauga limestone, while the greater number of their branches come from the side on which the next softer formations lie. Thus Rogers Creek is located upon the Conasauga shale and receives many tributaries from the increasingly harder Rome shale and sandstone on the west, but almost none from the Knox dolomite on the east. The same is true of Price, Spring, and North Mouse creeks. The Chestuee is located on a broader belt of soft rocks, and hence flows in broader curves, while its tributaries come in about equal numbers from the east and the west.

Eastanaula Creek is peculiar in that it appears to retain for a short distance south of Athens its consequent course in the syncline. North of Athens and south of Riceville the consequent stream has migrated from the axis of the syncline to the slightly more advantageous location upon the limestone. The stream encounters no obstacles in its present course, except the Tellico sandstone, where it enters and leaves the syncline. This had not retarded it enough to enable the subsequent stream to quite complete the capture, although, if the drainage were greatly accelerated, this would probably soon be accomplished. The subsequent tributary east of Riceville would easily cut back along the limestone belt and capture the head of the tributary which flows into the syncline, since the latter is retarded by the Tellico sandstone. It would then be separated only by a low limestone divide from the Eastanaula at Athens, and if the acceleration were sufficient, this might be cut through and the latter diverted to a subsequent course. Its present channel would then be occupied by several small tributaries flowing westward from the syncline, such as the present Meadow Fork, which doubtless occupies a part of the deserted consequent course of the Eastanaula, from which it has been recently diverted.

By no means all of this very perfect adjustment was accomplished in the second cycle. The process had been going on since the first emergence of the region, and was doubless well advanced at the close of the preceding cycle. Also some of the adjustment has been effected since the close of the second cycle, and a few streams, as the Eastanaula, above described, persist in their consequent courses, from which they may yet be diverted.

STREAM BASINS OF WALDEN PLATEAU.

A less complicated effect of structure on drainage is seen in the streams flowing eastward from Walden Plateau. The arrangement of this drainage is intermediate in character between that west of the Sequatchie and that in the valley belt. The upper tributaries of these eastward-flowing streams show the same irregular branching as the tributaries of Collins and Caney rivers. Along the eastern side of Walden Plateau, however, the effect of structure was pronounced. It will be recalled that this plateau is a broad, shallow syncline, sharply upturned along its eastern side. Thus the resistant sandstone beds are nearly horizontal throughout the greater part of its extent, but are steeply inclined and in some places vertical along the eastern edge. These upturned beds offer exceptional resistance to stream corrasion. Hence only the largest streams have been able to hold their courses across the barrier of hard rocks, while the smaller ones have been turned aside by the barrier and converted into tributaries of those which were able to pass it. Thus the lower tributaries of the latter flow toward the escarpment and then turn parallel with it until they reach the master streams. Although the steeply dipping conglomerate ledge at the plateau escarpment appears to have turned these streams aside to new courses, the process which resulted in the present arrangement was indirect. When the drainage of this region was stimulated by uplift, some streams, by reason of their greater volume, cut their channels through the conglomerate more rapidly than others. Small tributaries of the larger streams, which join them on the comparatively soft rocks back of the upturned conglomerate, by reason of the rapid lowering of their outlets and their favorable location, cut backward at their heads parallel with the escarpment and tapped the smaller streams which were held at higher levels at the obstruction formed by the upturned conglomerate.

THIRD CYCLE.

The second cycle, although extending over a vast period of time, was much shorter than the first. It sufficed only for the development of a peneplain upon areas of comparatively soft rocks, leaving those which were protected by sandstone, as the plateaus, forming extensive unakas. It was brought to a close and a new cycle inaugurated by a series of oscillations, the final result of which was elevation with some warping of the surface. The effect of the elevation was to accelerate the streams and start them to corrading their channels. The effect of the warping was to bring about important stream adjustments. These were confined chiefly to the largest streams of the region, as the minor drainage had become in general well adjusted in the preceding cycle.

Diversion of the Appalachian river.—The large axial stream in the Appalachian Valley continued to flow southward across the present divide for a short time after the uplift, but it was able to cut its channel less than 100 feet in the peneplain before it was diverted to a westward course. The process by which this westward diversion was most probably effected has been fully explained by Campbell and the present writer in the paper already cited. The conclusions there stated are accepted in all essential points, and the details of the process need not be repeated here. It was practically a repetition of the process by which the westward-flowing streams, in the preceding cycle, had pushed their head branches eastward and recaptured a portion of the territory lost in an earlier cycle. In both cases an important advantage possessed by the captor was derived from the deformation which accompanied the elevation of the peneplain. The axial streams were in the line of maximum uplift, and were thus obliged to lower their channels throughout the whole of their courses, while the acceleration was distributed over a long distance, and hence was not highly effective at any one point. The transverse streams, on the other hand, flowed away from the axis of uplift and hence the acceleration was concentrated in a small part of their courses and was correspondingly effective in causing rapid corrasion of their channels. In both cases, also, erosion in the preceding cycle had prepared the way for conquest in the one which followed. The sandstone barrier was either entirely removed or greatly weakened, and the accelerated aggressive stream on the Sequatchie anticline found itself separated from its field of conquest only by a comparatively feeble barrier, while its opponent in both cases had many difficulties to contend with.

Minor consequent adjustments.—The diversion of the Appalachian river to a new course through the plateau brought about some readjustments in the minor drainage. The valley, originally fitted to the main trunk, was later occupied in part by a reversed tributary, South Chickamauga Creek, and in part by a beheaded stream, Chattooga River. In general, however, the minor drainage retained the very perfectly adjusted form it had acquired in the preceding cycle. In all portions of the region in which the streams had not brought their channels down near base-level in the preceding cycle the drainage was scarcely at all affected by the new uplift. They were slightly accelerated in their lower portions, but for the most part continued as before.

Sequatchie meanders.—The Sequatchie River had reduced its immediate valley to a very perfect plane, across which it meandered from side to side. The uplift caused it to sink its channel rapidly in this plane, and it thus preserved the meanders it acquired in the preceding cycle. From the arrangement of the rocks forming the Sequatchie anticline comparatively hard beds come to the surface in a belt through the center of the valley, giving rise to a low ridge on which remnants of the peneplain formed in the preceding cycle are preserved, while softer rocks form narrow valleys on either side. The meanders of the base-leveled stream led it across both hard and soft belts and its present channel thus has the peculiarity of crossing back and forth from one side valley to the other through gaps in the ridge between.

Dissection of Highland Rim plain.—West of the Chattanooga district, in middle Tennessee, the strata rise in a low dome which had brought the hard beds at the base of the Carboniferous, the Fort Payne chert, above the Highland Rim base-level, so that they were removed from a large oval area during the second cycle, while they were below the base-level, and hence preserved, in a broad belt entirely surrounding it. Degradation following the uplift was rapid in the central area, where the hard beds had been removed, and resulted in the formation of the central basin of Tennessee. It was retarded in the surrounding region, where the hard beds preserved the previously formed peneplain now forming the Highland Rim. The large streams draining the central basin, Cumberland and Duck rivers, flow westward through the Highland Rim in narrow valleys. Their tributaries from the east have cut deep, narrow channels to varying distances back into the hard beds of the rim, whose western escarpment they are now pushing eastward exactly as streams from the plateau are wearing back the corresponding plateau escarpment.

Probably some stream adjustments have taken place upon this portion of the Highland Rim in the present cycle. Since the strata, as stated on a previous page, dip eastward at a low angle, the hard beds forming the surface of the rim toward its outer edge pass below the surface as they approach the plateau escarpment and are replaced by the overlying limestones. The stream which first succeeded in lowering its channel across the outer portion of the rim would have a decided advantage in contending with its neighbors on the softer rocks to the east. The successful stream was Caney Fork, which, by reason of its greater size, lowered its channel most rapidly, and sending out side branches upon the soft rocks near the foot of the plateau intercepted the smaller westward-flowing streams and diverted them to the east and northeast. Thus Barren, Charles, Mountain, Sink, Pine, and Falls creeks are probably, in part at least, reversed streams, formerly flowing westward, but diverted by Caney Fork to their present courses.

Condition of divides unfavorable for adjustments.—The drainage adjustments of this cycle, indicated above, were rendered possible in large measure by the great extent of base-leveled surface produced in the previous gradation period. Subsequent adjustments have been insignificant by reason of the small areas base-leveled during this period. Only soft rocks were reduced, and these only where favorably located, so that practically all divides remained at or above the former base-level and the streams when stimulated by the last uplift were not in a condition favorable for readjustments. Hence, in most cases, they have simply lowered their channels, preserving the meanders acquired in the previous cycle.

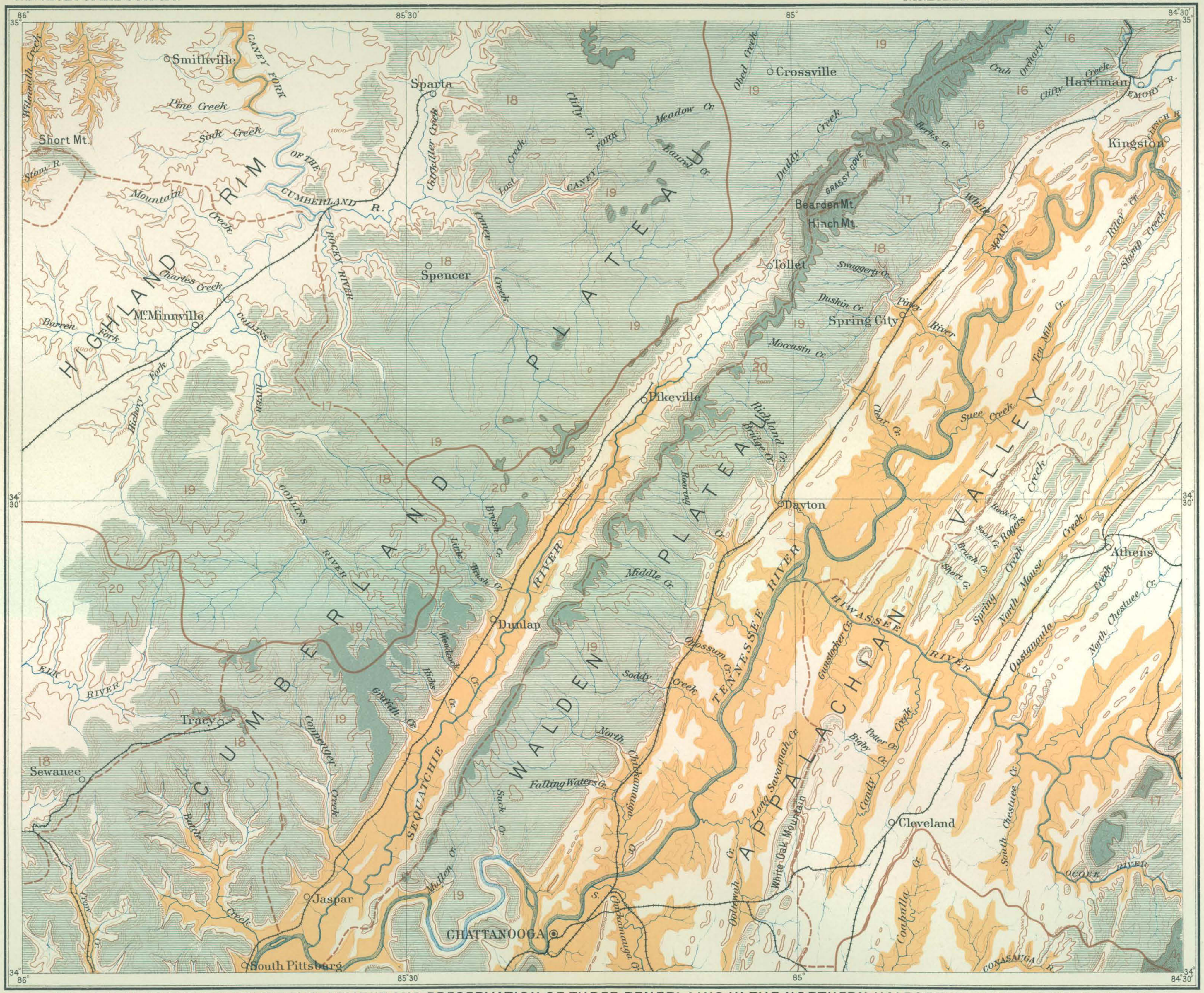
Aggrading streams.—Although by far the larger number of streams in the district are at present corrading their channels, a few are aggrading them. This results from the peculiar relations existing between supply of load and carrying power. The uplifts which have taken place since the completion of the Cumberland peneplain have produced abrupt slopes by reason of the great difference in erodibility between rocks forming adjacent areas, such as the Coal Measure sandstones and the limestones of the valley. The limestones were lowered perhaps nearly to base-level before corrasion of stream channels had deeply notched the sandstone escarpments, and hence the greater portion of the stream in this early stage of development would be flowing in a shallow depression upon the standstone of the highland and would be inefficient as a corrading agent. Thus while the stream was in this condition the supply of load remained small and the lower portion was able to transport all furnished it, and so continued to corrade its channel to a very low gradient. With the gradual lengthening of the marginal notch into a canyon the area of supply increases. A long line of cliffs bordering the stream channel yield at this stage, by the process of sapping, an abundant supply of coarse material to the stream, which is unable to transport the whole of it, and hence forms an alluvial deposit where it embouches upon the lowland. When the canyons are somewhat broadened and extended nearly to the head of the streams, although the cliff line may be much longer, the sapping is less active and less débris is furnished to the stream. It is then able to remove the material which it had previously deposited along its lower course. The alluvial fans are thus seen to be merely temporary deposits associated with a particular stage in the development of the stream basin.

The plateaus have been in strong relief for so long a time that most of the streams heading upon their surfaces and flowing to the lower plain have passed through the first stage and are well advanced in the second or third. The best examples of aggrading streams are those of intermediate size which flow eastward from the Walden Plateau. They are unable to carry the heavy load of sandstone which they acquire in the plateau canyons across the lowland plain, and have built up sometimes extensive deposits where they emerge upon the valley. In some cases the streams, except during freshets, disappear from the surface in crossing their own deltas. Most of the large streams, such as Emory River and Crow and Battle creeks, are sufficiently mature to be able to carry all the load furnished them, and are no longer aggrading, but have removed the greater part of the alluvial deposits previously formed, leaving only an occasional terrace which indicates their former extent.

CONCLUSION.

The geographic development of this region is thus brought down to the present and its topographic forms are shown to be the complex product of several factors, each in some measure modifying the others. Some conditions have been practically uniform over the entire region, while others vary widely in different portions, and the effects of each factor can be, to some extent, detected in the final product.

The drainage of the region in the process of reaching its present maturely adjusted form has had a curious pendulum-like motion; first, westward to the interior sea by antecedent streams, then diverted southward to consequent courses, and, finally, westward as subsequent streams. Further, it is quite conceivable that the drainage of the Appalachian Valley may again be diverted southward to the Gulf, for it is manifest that the Coosa has a decided advantage over the Tennessee in its more direct course to the sea; it is only necessary that the Tennessee should encounter slightly harder rocks than the Coosa and that future elevations of the region should lift the Mississippi Valley as much as the Appalachian Valley, or tilt the surface slightly eastward. The latter is perhaps the most important condition, and the careful student of geography in this region is constantly impressed with the important part which slight differences in uplift play in drainage adjustment. Effects due to differences in rock character and in structure are generally more striking and are first detected, but the broad modifications of drainage are most apt to be produced by the slight warping of the land surface which appears to accompany all uplifts.



MAP SHOWING THE RELATIVE DEVELOPMENT AND PRESERVATION OF THREE PENEPLAINS IN THE NORTHERN HALF OF THE CHATTANOOGA DISTRICT

BY C.W. HAYES 1897.

Scale

6 0 6 12 18 MILES

CONTOUR INTERVAL 250 FEET

Topography generalized from published sheets of U.S.Geological Survey by C.W.Hayes.

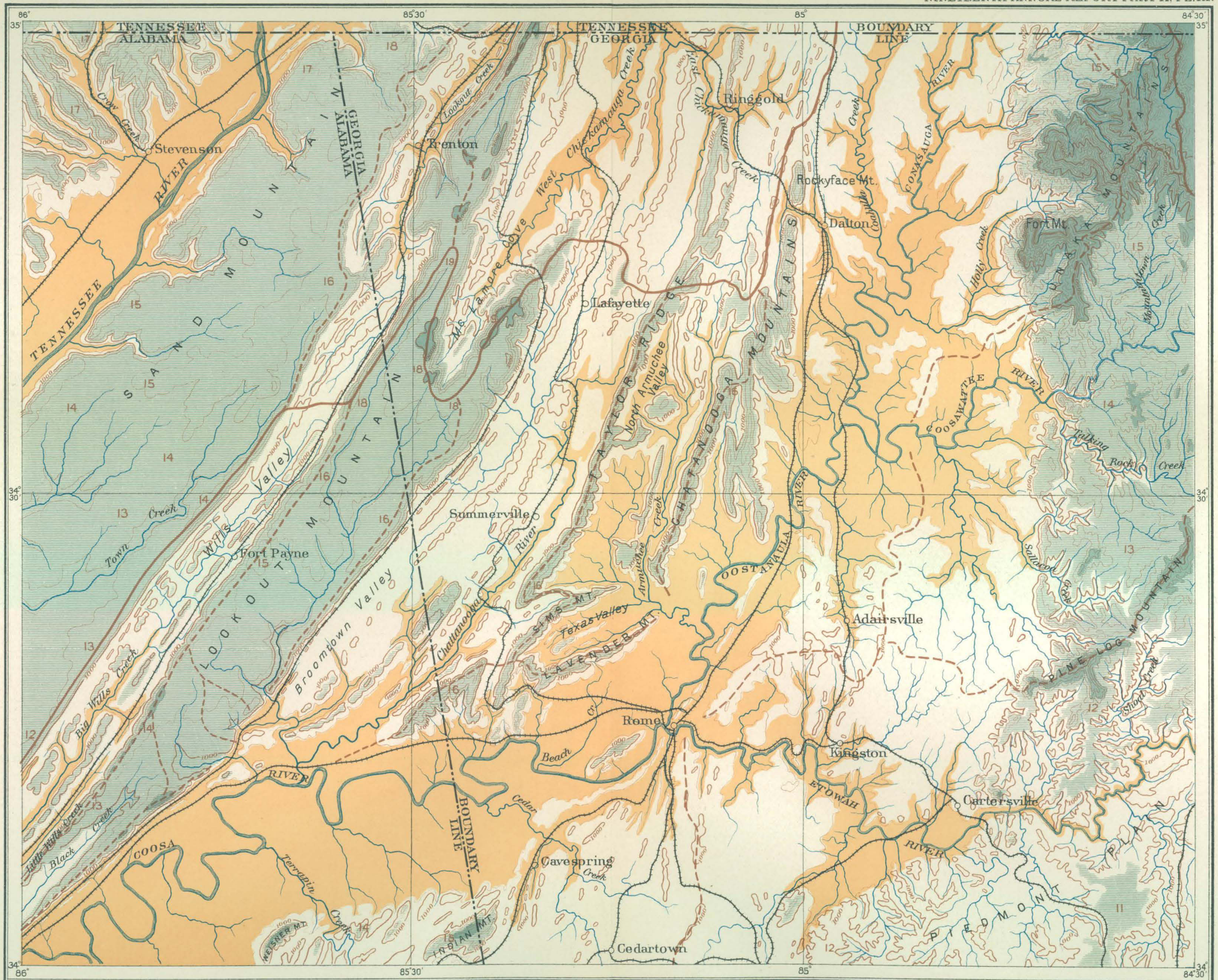
Residuals, Monadnocks above The Cumberland peneplain

Residuals, Monadnocks and Unakas above the Highland-Rim peneplain

Base-leveled areas of the Coosa peneplain

Note: Figures indicate the altitude of the Cumberland peneplain in hundreds of feet.

A.Hoen & Co. Lith. Baltimore.



MAP SHOWING THE RELATIVE DEVELOPMENT AND PRESERVATION OF THREE PENEPLAINS IN THE SOUTHERN HALF OF THE CHATTANOOGA DISTRICT

BY C. W. HAYES 1897.

Scale

6 0 6 12 18 MILES

CONTOUR INTERVAL 250 FEET

Topography generalized from published sheets of U.S. Geological Survey by C. W. Hayes.

Residuals, Monadnocks above The Cumberland peneplain

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Base-leveled areas of the Coosa peneplain

Note: Figures indicate the altitude of the Cumberland peneplain in hundreds of feet.

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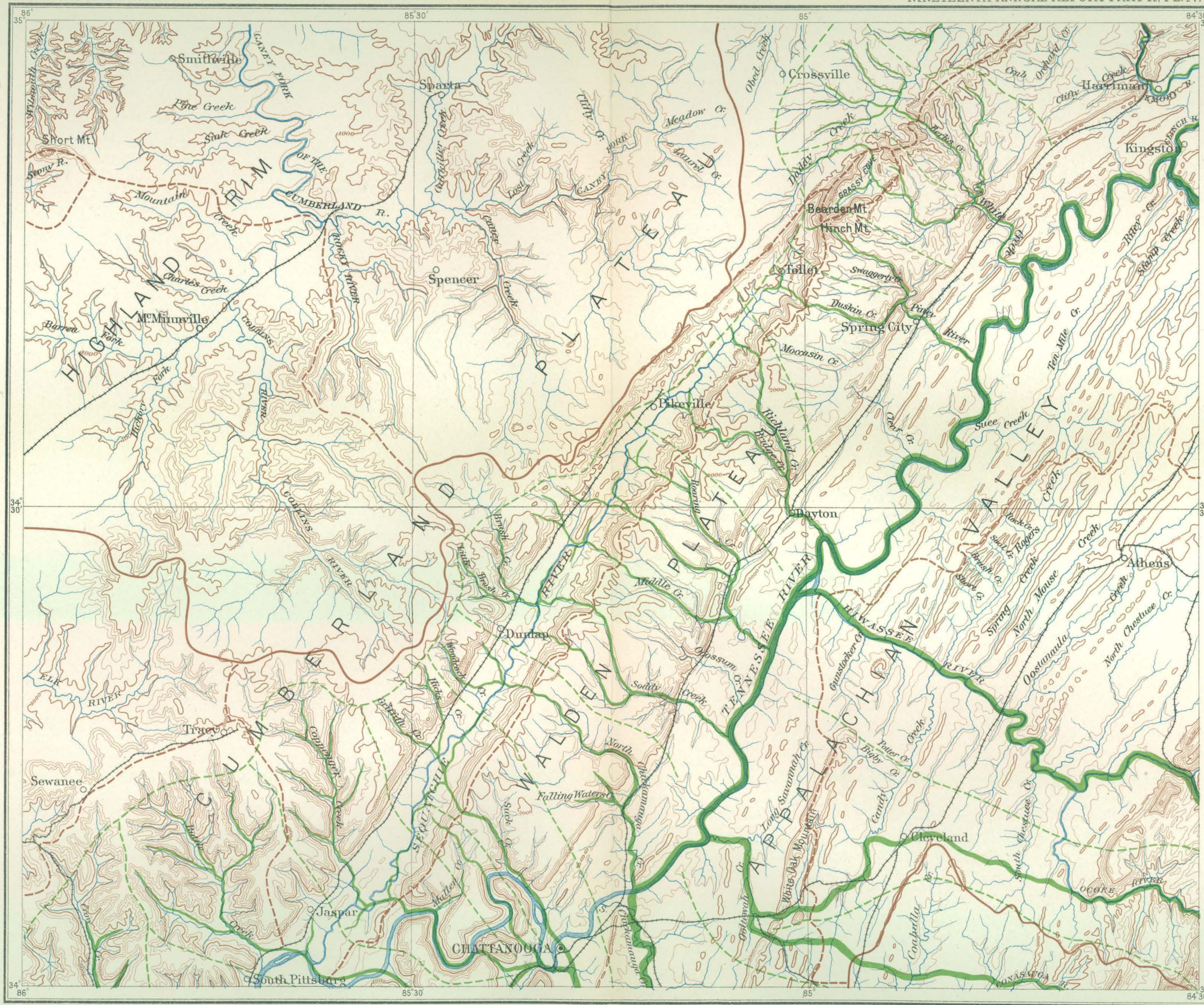


MAP SHOWING THE DRAINAGE AT THE CLOSE OF THE CUMBERLAND GRADATION PERIOD IN THE NORTHERN HALF OF THE CHATTANOOGA DISTRICT

BY C.W. HAYES 1897.

Scale

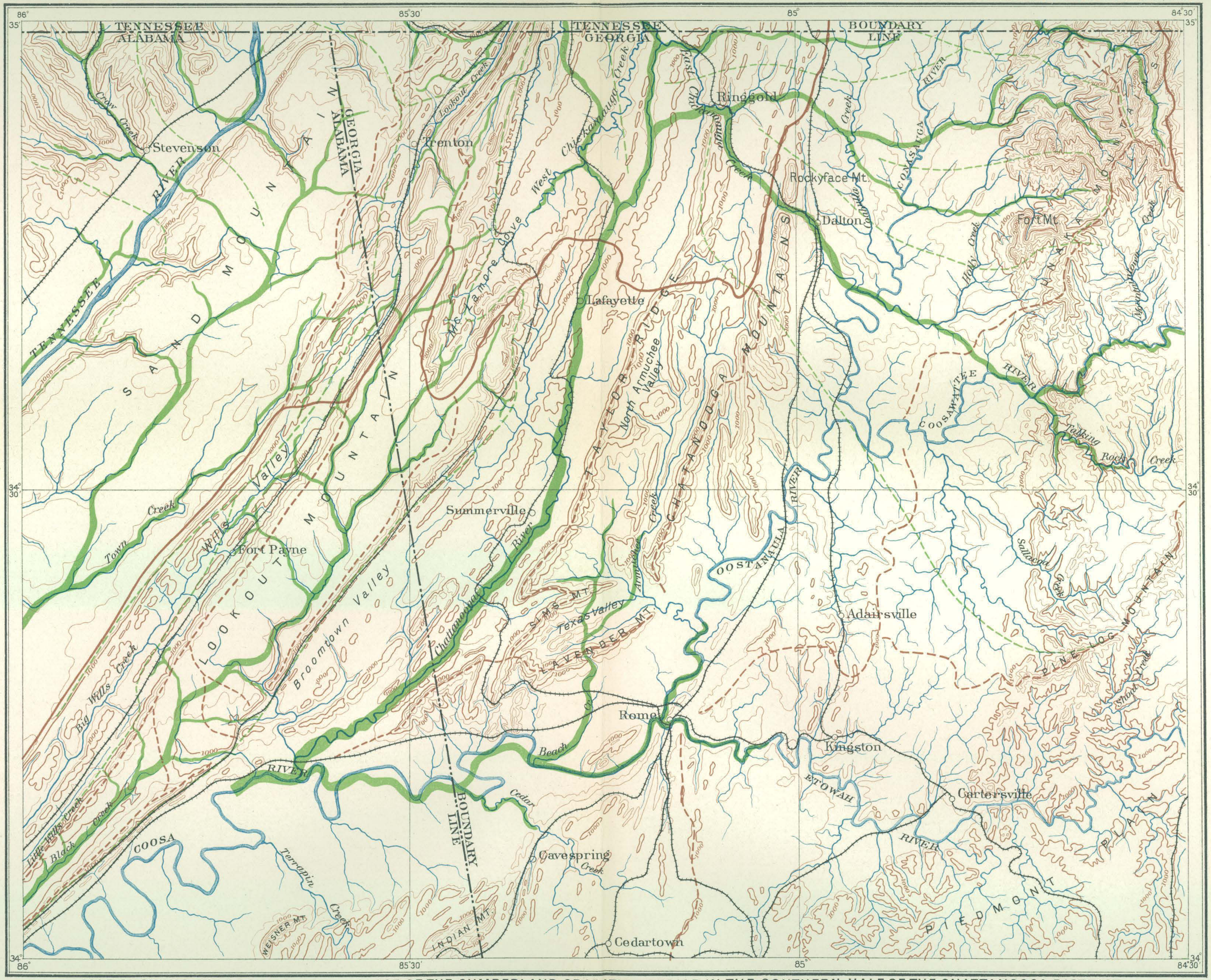
6 0 6 12 18 MILES

CONTOUR INTERVAL 250 FEET

Topography generalized from published sheets of U.S. Geological Survey by C.W. Hayes.

Note: Cretaceous drainage in Green
Present drainage in Blue

A. Hoen & Co. Lith. Baltimore.



MAP SHOWING THE DRAINAGE AT THE CLOSE OF THE CUMBERLAND GRADATION PERIOD IN THE SOUTHERN HALF OF THE CHATTANOOGA DISTRICT

BY C.W. HAYES 1897.

Scale

6 0 6 12 18 MILES

CONTOUR INTERVAL 250 FEET

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PRINCIPLES AND CONDITIONS OF THE MOVEMENTS OF GROUND WATER

BY

FRANKLIN HIRAM KING

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By F. H. King.

INTRODUCTION.

During our earlier investigations regarding the flow of water through soils, it appeared that if the laws of capillary flow apply to the movements of water and of air through soil, it ought to be possible to arrive at the sizes of soil grains from a knowledge of the flow of water through the samples under known conditions. Such great difficulties, however, were encountered in duplicating results with water that air was substituted as the medium whose flow was to be measured. The handling of the air proved so much simpler and expeditious and results could be duplicated so closely that in 1894 the plan was laid before Professor Slichter for his judgment as to the possibility of placing the method on a quantitative basis. This seemed to him possible, and he kindly consented to undertake a preliminary investigation, which resulted in the formula for computing the effective sizes of soil grains, presented in the first portion of his paper in this volume. When it was found that computed results agreed with observations more closely than had been hoped at first, a return was made to water as a means of checking the accuracy of the method and the formula. It was found that the flow of water used in the formula gave results quite comparable with those computed from air.

At this stage Mr. Newell proposed, in 1896, to assist financially in an investigation of the movement of ground water, and the writer consented to undertake the work, with permission to secure Professor Slichter's services in the development of certain theoretical phases of the subject. The work was prosecuted during the year, but as the results which could be submitted at the close were quite incomplete, an extension of time and assistance was granted. In order to bring Professor Slichter's theoretical investigations into as close touch as possible with the concrete phases of our study, the writer formulated for his investigation, and discussed with him, a series of 17 definite problems, the most important of which are here given and are in part discussed in the last portion of his paper.

Series A, Problem I.—Given a uniform bed of unfissured sandstone 100 feet thick, lying between impervious layers and dipping 5 feet per mile. Given further—(*a*) a uniform temperature of 10° C.; (*b*) a pore space of 30 per cent; (*c*) an effective size of grain of 0.15 mm.; (*d*) an effective head of 10 feet, and (*e*) supposing no cementing or clogging material between grains, required the possible discharge in cubic feet per minute per foot of vertical section into a vertical fissure extending at right angles to the dip and constantly filled with water, when the fissure is 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 miles from the border of the collecting area. The rainfall on the catchment area is sufficient to maintain a constant overflow across its border.

Series A, Problem II.—With conditions of Problem I, what is the rate of discharge in cubic feet per minute from a 6-inch well extending entirely through the sandstone when the well is situated 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 miles from border of collecting area?

Series A, Problem III.—With conditions of Problem I and an extent of sandstone equal to 200 miles at right angles to the dip, what is the minimum distance apart of wells on a line at right angles to the dip so that there shall be an interference to the extent of 1 per cent of the flow of Problem II and when the line of wells is situated at 20, 40, 60, etc., miles from the border of the catchment area?

Series A, Problem IV.—The same as III, except that the line of wells is along the line of strike.

Series A, Problem V.—Required the maximum number and distribution of 6-inch wells under conditions of I and II on an area 200 miles square so that there shall be a mutual interference of 1 per cent; of 20 per cent.

Series A, Problem VIII.—With the conditions of I, but with the upper impervious layer removed and a vertical cliff at the 200-mile line, required the rate of rainfall over the whole area which will just make surface streams impossible.

Series B, Problem I.—Given 200 feet of sandstone with grains having an effective size of 0.25 mm. and a pore space of 32 per cent filled with water and uniform temperature of 10° C., required the capacity of a 6-inch well 100 feet in rock when the water in the well is lowered 4, 8, 12, 16, and 20 feet.

Series B, Problem II.—With the conditions of I and the water lowered by pumping 20 feet, required (*a*) the flow when the diameter of the well is 2, 4, 6, 8, 10, 12 inches, (*b*) when diameter is 20 feet and 22 feet deep. (*c*) Required the flow when (*b*) has one, two, and three 6-inch wells extending through the water-bearing rock.

Series B, Problem III.—With the conditions of Problem I and a head of 10 feet, required the capacity in cubic feet per minute when the well enters the water-bearing bed 4, 8, 12, 16, 20, 40, 80, 100, and 200 feet.

Series B, Problem IV.—With the conditions of I except depth of sandstone, and well 20 feet in sandstone, required the capacity of the well when the water-bearing rock extends 0, 1, 2, 4, 10, 20, 40, 100, 200, and 400 feet below the bottom of the well.

Series B, Problem V.—With the conditions of I and water lowered 20 feet, required the capacity when the effective size of the grains are 0.02, 0.04, 0.06, 0.08, 0.1, 0.2, 0.4, 0.6, 0.8, 1.2, and 3 mm. in diameter.

Professor Slichter's solutions of those of these problems which he has made directly or in modified form have been very helpful in this investigation, and, it is hoped, will enable further study along these lines to be more intelligently prosecuted.

CHAPTER I.

GENERAL CONSIDERATIONS.

There is no single substance entering into the structure of the earth which has played and is playing so important a part as water. Its aggregate quantity is large. It has the widest distribution. It is everywhere in relatively rapid motion. In the gaseous form it escapes from the bosom of the ocean, from the surface of the soil, from the foliage of vegetation, and from the bodies of animals, to rise to varying altitudes above the earth's surface and to be precipitated as rain, hail, or snow. So rapid is this movement of moisture in the atmosphère that it has been estimated that 6 per cent of the land area receives more than 75 inches of rain annually, 16 per cent receives from 50 to 75 inches, 25 per cent from 25 to 50 inches, over 30 per cent from 10 to 25 inches, while only 20 per cent receives less than 10 inches a year. On one occasion in Japan a fall of rain measuring 29.5 inches in a single day was recorded, while in India no less than 39.5 inches fell during twenty-four hours.

Of the water which falls upon the land, one portion finds its way by surface flow into the drainage channels at once, a second portion is evaporated from the place where it fell, while a third portion enters the ground.

The water which evaporates from the earth's surface and is again periodically precipitated upon it maintains that moisture of the soil which is essential to plant life, and that constant seepage which feeds perennial springs and streams, and without which animal life in its higher forms could not exist upon the land areas. Further than this, it is the constant evaporation of water from the sea and its return to the land in sufficient amounts to maintain a heavy leaching of the soil that keeps both the soil and the water at that standard of purity which is essential to the life of land areas; the salts formed by the water as it moves through the soil and the rock go with it to the sea and are there left, when, after evaporation, the water returns fresh and pure through the atmosphere above.

AMOUNT OF WATER STORED IN THE GROUND.

In sandstone.—The water which penetrates the soils, the sands, and the rocks of the land areas does so in such large quantities that sands and sandstones lying below drainage outlets may contain as high as 38 per cent of their volume of water. Broad sheets of sandstone, like the Potsdam, St. Peters, and Dakota, underlying as they do many square miles of territory, have become storage reservoirs of vast capacity. The Dakota sandstone, for example, stretching from the foothills of the Rocky Mountains eastward beneath the plains of the two Dakotas, Nebraska, and Kansas, apparently in one nearly or quite continuous sheet, may be likened to a submerged inland sea or lake, for wherever this formation lies beneath the zone of saturation it carries within itself from 15 to 38 feet of water on the level for every 100 feet in thickness of the sandstone itself, and from it water may be drawn wherever it lies close enough to the surface to be reached by wells. The Potsdam sandstone is a formation of much wider distribution than the Dakota, and in southern Minnesota and Wisconsin and in Illinois and Iowa it has a measured thickness of 500 to 1,000 feet, all lying beneath the surface of saturation, so that in this great bed there has been stored away a quantity of water equal to a sheet not less than 10 to 38 feet in depth for each 100 feet in thickness, and 500 feet of this water-bearing rock may store the equivalent of an inland submerged sea having a mean depth of 50 to 190 feet of water.

In soil.—Even the mantle of soil, sand, gravel, and clay which nearly everywhere covers the surface of land areas carries a surprisingly large amount of water wherever it occurs outside of arid regions. A saturated sand carries from 20 to 22 per cent of its dry weight of water, while the soils and clays range all the way from these values up to 40 and even 50 per cent of their dry weights. Since a cubic foot of dry sand weighs from 102 to 110 pounds, while the soils, clays, and gravels range between this and 79 pounds, we have a ready means of expressing quantitatively the water which is continually stored in this mantle of loose materials where it lies below the plane of saturation.

An actual determination of the water-holding capacity of natural soils under natural conditions gives the results which are shown in the following table:

Table showing the water capacity of undisturbed soils when lying below the plane of saturation.

Kind of soil.	Depth of layer.	Per cent of water.	Inches of water.
	Inches.		
Marly loam	0 to 12	41.3	5.88
Reddish clay	12 to 24	28.1	5.03
Reddish clay	24 to 36	28.4	5.07
Clay with sand	36 to 48	24.8	4.67
Very fine sand	48 to 60	17.4	3.76
Total			24.41

It will be seen from this table that the storage capacity of soil is in round numbers at the rate of 2 feet of water for 5 feet of soil or 40 feet of water on the level for every 100 feet of soil. Where soil does not lie below the plane of saturation it usually contains 75 per cent of the amount required for full saturation, except during dry times in a surface layer 1 to 5 feet thick, so that even where the plane of saturation lies below a large thickness of soil there is still a large storage capacity provided for water if the mantle of loose materials is thick. The water thus stored above the plane of saturation will vary all the way from about 4 per cent of the dry weight for coarse mixed sands, such as are used for plastering, up to as high as 32 per cent in clays of fine texture.

In other rocks.—But the water stored in the upper strata of the earth's surface is not confined to the beds of sand, sandstone, and soils which have been referred to above. All other rock beds contain more or less of water, either in the interstices of the rock itself or in the fissures which have been formed in them. Even the compact and close marbles and granites absorb measurable quantities of water; for example, a marble measured by Newell was found to absorb 0.23 per cent of its weight of water, which, with a specific gravity of 2.701, gives a weight of water per cubic foot of rock amounting to 0.3878 pound, and for a column of rock 5,000 feet long, 30 cubic feet of water. That is to say, so small an amount of water as 0.0023 of the weight of 5,000 feet of the earth's crust is large enough to form a continuous sheet about the globe 30 feet deep.

DEPTH TO WHICH GROUND WATER PENETRATES.

There are many reasons for believing that water penetrates the fissures and interstices of the earth's crust to depths even exceeding 10,000 feet, and if the water so inclosed formed no larger part than 1 per cent of the weight of the material, then with a specific gravity of 2.65 the amount of inclosed water would be quite sufficient to form an envelope 265 feet thick. Considerations like these make it evident that water has a distribution in the rocky interior of the earth quite as remarkable as is that upon its surface and in the atmosphere above, while the parts which it there plays are both very numerous and extremely important.

GENERAL MOVEMENTS OF GROUND WATER.

Daily observation teaches us that the water of the ocean and of the atmosphere is never at rest, and so it is with that which occupies the interior of the earth's crust; it, like the others, is constantly in motion, and these motions are at once numerous, extended, and very complex, but may be brought together under three categories—(1) gravitational, (2) thermal, and (3) capillary movements.

GRAVITATIONAL MOVEMENTS.

SEEPAGE.

Among gravitational movements by far the most important is seepage, and the term as here used is intended to express the movement of water through the fine pores of soil or rock under the stress of gravitation. Seepage begins where the water enters the soil and ends where the water again escapes into passageways which are larger than capillary or which lie above the surface of the solid crust. The chief motive power in seepage is the hydrostatic pressure of the water itself, but the effects of hydrostatic pressure are intensified or reduced in various ways. It has long been a matter of common remark among observing farmers that springs flow more rapidly on the approach of a storm or when the wind is from the east, and the writer

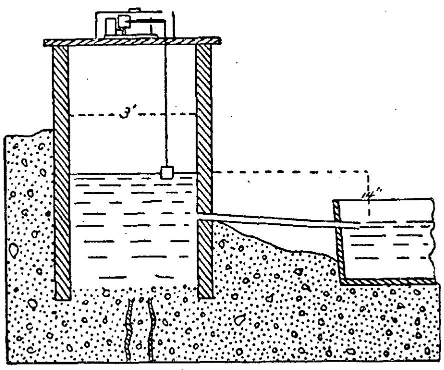


FIG. 2.—An ordinary spring curbed, with autographic instrument recording changes in rate of discharge.

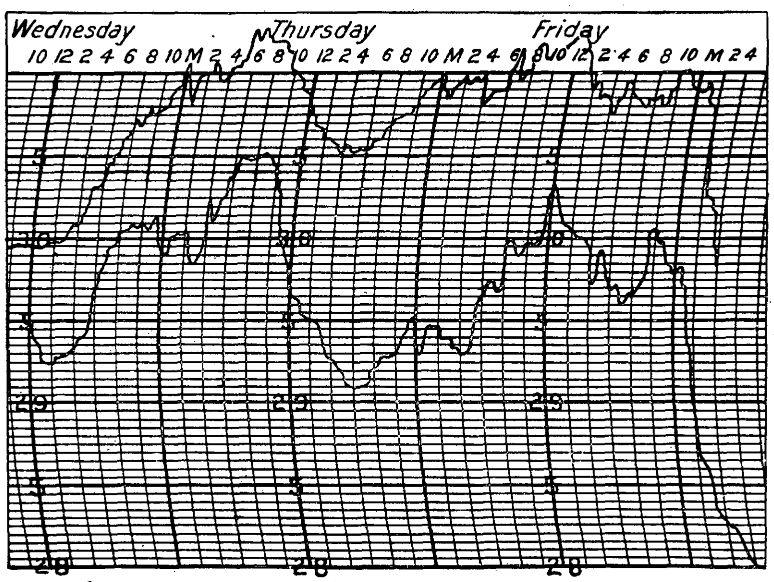


FIG. 3.—Autographic record of changes in rate of flow from spring and also from artesian well one-half mile distant, produced at the same time Upper curve for spring; lower curve for well.

has shown in Bulletin No. 5 of the United States Weather Bureau that the passage of a low barometric depression across a section of country is always associated with a more rapid discharge of water from springs, flowing wells, tile drains, and seepage outlets of all kinds.

Influence of barometric changes on the discharge of water from drainage outlets.—A more definite idea of the magnitude and character of the disturbances imposed upon the discharge of water from the seepage channels will be gained from a study of figs. 2, 3, 4, 5, and 6.

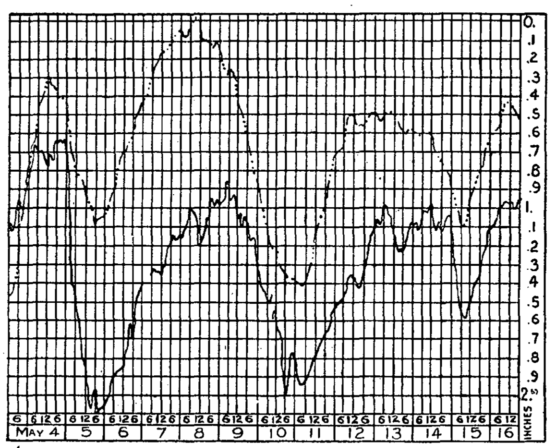


FIG. 4.—Autographic record of changes in flow of spring and of changes in atmospheric pressure occurring at the same time, the barograph being 45 miles west of the spring. Upper curve, air pressure; lower curve, flow of spring.

Fig. 2 shows an ordinary spring which has been curbed so as to force the water to rise and discharge into a trough, and upon which an automatic recording instrument has been placed for the purpose of measuring the changes in the head of the spring. Fig. 3 is a copy of a curve produced by the rise and fall of the water level of the spring in question during three days. The lower curve in the same figure is a record of the changes of level in an artesian well situated about one-half mile distant and produced at the same time. Fig. 4 shows the larger changes which occurred in the flow of water from the spring during the period of May 4 to May 16, together with the curve of barometric pressure which was associated with these changes. Fig. 5 shows the variations in the rate of discharge from a system of tile drains during one week and the barometric changes to which these variations are chiefly due. And fig. 6 shows a remarkable change in the level of the water of the reservoir of the city waterworks at Whitewater, Wisconsin, which occurred during one of those sudden and pronounced barometric depressions so frequently associated with thunder showers.

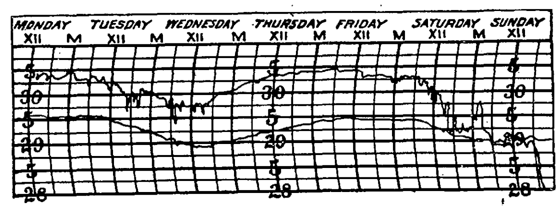


FIG. 5.—Autographic record of changes in atmospheric pressure and in rate of discharge from tile drains during one week. Upper curve, atmospheric pressure; lower curve, discharge from tile drains.

The reservoir in which this sudden increase of head occurred has a diameter of 106 feet, and from it water was discharging over the top of a standpipe leading out through the bottom and having an opening at the top 9.75 inches in diameter, this being an expansion on the end of a 6-inch pipe: The artesian well which supplies this reservoir has a depth of 979 feet and was discharging at the time of this change at the mean rate of about 14 cubic feet per minute. It will be seen that the head in the reservoir increased rapidly during about fifteen minutes and then fell away more gradually during about seventy-five minutes, when the original head was again attained.

There was a heavy shower at the time this curve was obtained, but it does not seem possible that it could have produced any considerable part of the change recorded, particularly since it lasted but for a few moments. Then, too, as the overflow pipe was situated within 3 feet of the float of the recording instrument, it does not appear that any action of the wind could have been steady enough and strong enough to bank the water about the instrument to such an extent as to produce the effect which was recorded, particularly since the curve is so regular as it is.

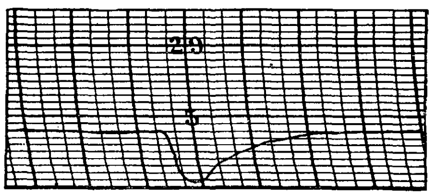


FIG. 6.—Autographic record of sudden change in the rate of discharge from well at city waterworks, Whitewater, Wisconsin.

The observed variations in the head of the spring showed that the influence of barometric changes are great enough to modify the rate of flow by as much as 8 per cent of the full normal rate of discharge. The observed changes in the case of the tile drains amounted to as much as 15 per cent, while the curve obtained from the reservoir of the city waterworks at Whitewater indicates changes much greater than these. Indeed, during ten consecutive days measurements were made of the rate at which the reservoir filled up after it was pumped down for the purposes of the city, and it was found that during that time the mean rate of flow per minute changed through as wide limits as from 15.441 cubic feet to 13.947 cubic feet per minute, a variation of fully 10 per cent, where the volume of flow is itself large.

It is clear, therefore, that barometric changes do exert a far-reaching influence upon underground drainage coming from any and all depths, and the magnitude of this influence, it is believed, is so great and so far-reaching as to be capable of registration on streams and lakes with suitable instruments properly placed. Indeed, records have already been obtained from the Wisconsin and Fox rivers in Wisconsin, and from Lake Mendota, which appear to support this belief, but the data procured are not extended enough to establish the point.

Rate of seepage modified by diurnal changes in soil temperature.—During the same series of investigations which led to the results just cited it was also established that the diurnal changes in soil temperature which occur in mid- and late summer have a sufficiently marked influence upon the rate of seepage to be recorded by the device used upon the spring and referred to under fig. 2. The effects are brought out clearly in fig. 7, where the upper curves show diurnal changes in the level of water in shallow wells, while the lower curve, marked "drain," shows variations in the rate of flow of water from a system of tile drains, the two wells in question being in the same piece of land.

These variations in the height of water in the wells and in the rate of discharge of the tile drains are due not so much to changes in the viscosity of the ground water as they are to variations of pressure due to the expansion and contraction of the gas confined in the soil with and above the water.

Reaction of barometric pressure on ground water.—The evidence now at hand is insufficient to show in a conclusive manner just how changes in atmospheric pressure do produce those variations in the rates of seepage to which reference has been made; but there are two radically different modes of action, by either of which we may suppose the changes in the rate of flow are brought about.

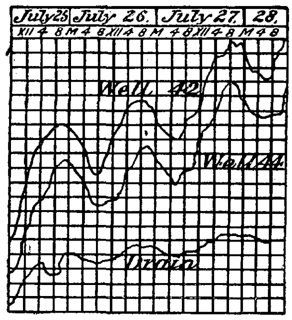


FIG. 7.—Autographic record of diurnal charges in rate of seepage into tile drain.

In the first place it may be supposed that the general level of the ground-water surface is depressed or elevated bodily, as the case may be, by barometric changes, the loading of the air upon a region depressing the ground-water surface of that region, and the unloading of it permitting the level to be partly or wholly restored again. In the second place it may be supposed that, through an unequal permeability to air of the soil above standing water in the ground, the changes in atmospheric pressure are more quickly felt by the water surface at some points than they are at others, and as a consequence a rising barometer will cause the water to be depressed in wells and in the more open soils, the water being forced into both the capillary and noncapillary spaces of the adjacent less permeable areas, while a reduced air pressure would permit the confined air in the soil of the more permeable regions to react and force the water out into drainage channels, thus producing the phenomena of increased flow of springs and artesian wells during times of low barometer as they are observed to occur.

If differences of barometric pressure amounting to 1 inch develop on opposite sides of the Atlantic Ocean, then the ocean surface, as a result of this unequal loading, will be depressed over the region where the pressure is high, while it will rise over regions where the pressure is low, and a deformation of the ocean's surface to the extent of 1.13

feet would be the result. So, if we suppose a continental ground-water surface in a state of drainage equilibrium to be similarly circumstanced, its surface would be deformed in like manner, and as a result of this deformation the water would stand higher in wells and discharge more rapidly from springs and other drainage outlets where the atmospheric pressure is low, while the converse would be true under the high area.

If Mr. G. H. Darwin[1] is correct in his estimate that if the barometer rises 1 inch over Australia the increased pressure is sufficient to depress the continent 2 or 3 inches, and that the tides which twice a day load the shores of the Atlantic may cause the land to rise and fall as much as 5 inches, there seems to be no physical reason why the ground-water surface, being more mobile than the rigid earth and at the same time capable of moving through its interstices, should not suffer a deformation greater than the land itself when subjected to a similar load.

If a horizontal canal be conceived to extend a distance of 2,000 miles and to lie wholly above the general drainage plane, so that water might discharge through gates of equal capacity at the two ends, it is evident that were a low barometric pressure to pass over one end while a high pressure came upon the other, the water would begin discharging more rapidly under the low pressure and less rapidly under the high. In like manner it appears possible for changes in barometric pressure to depress the ground-water surface in one section and to permit it to rise in another so as to change the relative rates of seepage in the two regions, the discharge becoming more rapid in the region of low pressure and less rapid in the region of high.

Studies made regarding the rate of change of level of water in wells during 1888, 1889, and 1890 show that in 1888 the level of the ground water fell at the mean rate of 0.235 inch daily when the barometer was rising, while it rose at the mean daily rate of 0.141 inch during the days when the barometer was falling. In 1889 the mean daily rates were 0.143 inch of fall under rising barometer and 0.046 inch of fall under falling barometer, while in 1890 the changes were a fall of 0.295 inch for the former and 0.098 inch fall for the latter, making the mean fall of the ground water per day during the three years 0.224 inch for periods of rising barometer and 0.001 inch during periods of falling barometer; relations such as these should be expected if the changes in barometric pressure are capable of affecting the general level of the ground water. It should be stated that the observations here referred to were made during that portion of the year when the ground water is as a general rule falling rather than rising.

Turning now to the second hypothesis stated, the following conditions furnish a foundation for it: The capacity of water to retain air condensed within itself increases with the pressure to which it is subjected; and, again, air does not readily escape from the interstices of a fine-

[1] Nature, Vol. XXVIII, p. 367.

grained soil, especially if it is saturated or nearly saturated with moisture.

Under these conditions it may be assumed that when an area of low barometer passes over a district the equilibrium between the confined gases in the soil water and surface tension is destroyed, and a part of the absorbed air escapes to unite with the air already in the interstices of the soil with the water, and by the expansion of these two volumes of air it reacts upon the underground water, tending to augment the hydrostatic pressure and thus to increase the rate of discharge into drainage channels.

On the other hand, when the conditions of barometric pressure become reversed, then the permanent rarefication which the soil air has sustained by a withdrawal of a portion of the water and also of the air from the interstices of the more impermeable soils will permit the increased barometric pressure to force back into the soil interstices a part of the water which had reached the more open regions and drainage channels, thus lowering the water in wells, and, by offering a greater resistance to the discharge of water into drainage channels, actually decrease the rate of seepage by establishing what amounts to the same thing—a less steep gradient or difference of pressure.

This hypothesis, however, appears much more applicable to the short-period fluctuations which the records often show than to those which are more gradual and which involve the movement of so much water, as in the case of the spring at Whitewater, which, as the record shows, continued to flow under an increased head for days in succession with a falling barometer, producing a curve very nearly parallel with that of a barometer situated 45 miles distant.

In the case of those fluctuations in the diurnal rate of drainage which have been referred to and which are expressed by the curve in fig. 7, it is quite clear that the increased flow as the temperature rises must be due to the pressure developed by the expansion of the air confined in the soil above the zone of saturation, resulting in a pressure which augments the hydrostatic pressure due to difference of level.

MOVEMENTS OF GROUND WATER DUE TO CRUST DEFORMATION AND ROCK CONSOLIDATION.

Another phase of the gravitational movements of ground water must always have been associated with those slow subsidences of the earth's crust which have occurred in regions where deposition has been going on, the major movement of the ground water taking place toward the region of elevation, where denudation has been in progress.

Amount of water laid down with sediments.—We know that when sediments are laid down on the borders of the ocean or over the bottom of inland seas, gulfs, or bays there becomes locked up with them large volumes of water, quantities varying from 25 to 50 per cent of the volume of the sediment, according as the pore space in the sediment is large or small.

It will be seen in another part of this paper that the pore space of loose sands, when packed as closely as tamping and jarring will secure, amounts to from 30 to 38 per cent, while the pore space of clays and finer soils runs up as high as 45 and even above 50 per cent, and there is no reason to suppose that the sediments, whether they be sands, clays, or limestone débris, will be laid down with greater compactness than we have been able to secure in our experimental work.

Seelheim[1] has shown that when an emulsion of fine clay and water is allowed to stand quietly for some time under conditions where no jarring can take place the clay subsides, assuming a stratified condition, but containing a large amount of water. He found where no jarring took place that the upper layers contained more water than the lower ones, the proportion being 1 volume of clay to 3.84 volumes of water in the upper strata and 1 volume of clay to 1.78 volumes of water in the lower strata. That is to say, in the loosest settling 79.34 per cent of the volume of the sediment was water and in the closer packing there was still 64.03 per cent of pore space.

Where the settling was allowed to take place under frequent jarrings Seelheim secured a uniform texture throughout and greater compactness, but the ^ was still a pore space of 54.54 per cent. He further showed that there was no sensible reduction of pore space when the sedimentation was caused to take place under a pressure of 102 feet of water instead of a few feet. Further than this, there is no reason to suppose that the pore space of sediments laid down under water will not be filled very largely with the water in which they are deposited.

Movements of inclosed water due to settling.—When fine sediments are being laid down over beds of a coarser character there is a tendency for a part of the entangled water to escape downward. The finer sediments, as first laid down under water, have a relatively very large pore space, but in the course of time this becomes reduced, partly by slow segregation and partly by compression with the accumulation of sediment above, but before such consolidation can take place a portion of the water must be expelled, and this necessitates a flow of water either upward, downward, or laterally.

In the experimental studies made in connection with this investigation it has been necessary to adopt methods of freeing the samples of sand or of soil from air before introducing them into the apparatus in which the capillary or other movements of water were to be studied, and in doing this for one series of experiments one of the classes of movements of water here under consideration was incidentally demonstrated.

The apparatus is represented in fig. 8, and consisted of a cylinder 1 foot in diameter and 4 feet high, which contained a layer of sand and

[1] Methoden zur Bestimmung der Durchlässigkeit des Bodens: Zeitschrift für analytische Chemie, Vol. XIX, p. 387.

gravel in the bottom and was provided with an opening, to which a piece of rubber tubing was attached, intended to provide a means of admitting water at the bottom, so as to permit study of the rate of capillary movement upward through a medium to be placed in the cylinder above the sand and gravel.

In order to insure the absence of air from the sand or soil in which the capillary movements were to be studied, the cylinder was first partly filled with water and then the material to be studied was worked up in small lots under water to free it from air and then poured in until the cylinder was filled. While working in this way, whether with fine sand or with soil, it was found that during several days a considerable settling would take place, and new quantities of the material needed to be added.

At the time this settling was going on water flowed in considerable quantities out of the upper end of the rubber tube and back into the reservoir above the water, rising to a height of 4 inches above the top of the tank and 6 inches above the level of the soil and water in it. The rising of the water 6 inches higher than its head while flowing out of the bottom of the tank and back into it above seemed paradoxical at first, but became plain enough after a little reflection. So long as the material in the cylinder continued to settle, the water which was in the sand or soil must necessarily move, which of course it did, taking the path of least resistance. A portion of the water no doubt worked its way upward through the subsiding sediment and reached the surface in that way, but another portion found the line of least resistance to be downward through the sand and gravel and thence up through the rubber tube, the resistance to flow upward the other way being great enough to overcome an increased head of 6 inches.

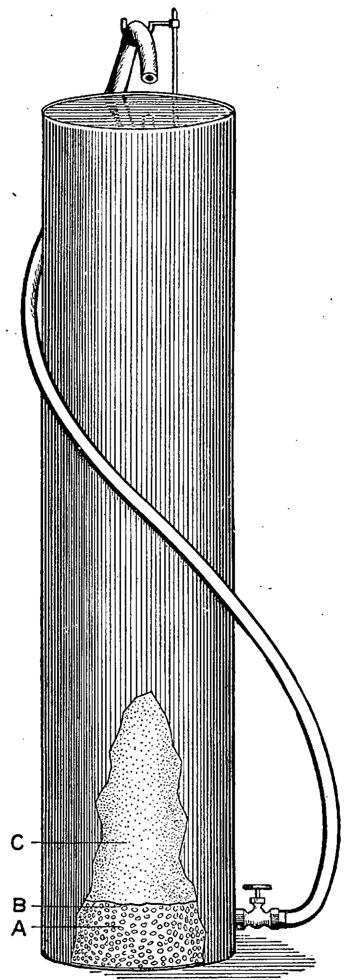


FIG. 8.—Apparatus demonstrating flow of water due to settling of sediments.

This principle must have come prominently into play during the process of sedimentation in all geologic ages, and most prominently where heavy deposits of fine sediments have been laid down over those of a coarser texture. Fig. 9 illustrates the nature of this movement under one of many possible conditions.

We have no quantitative measure of the amount of compression which, under the conditions of natural sedimentation, takes place where beds of shale and limestone are formed, but in these experiments both those with very fine sand and those with ordinary soil, the compression amounted to as much as 4 inches in as many feet, and while the amount of water which escaped through the sand at the bottom was not measured, it is believed that it was much more than enough to have covered the surface of the cylinder 1 inch deep.

But this movement of water, although of considerable magnitude when measured by the time during which it has taken place and the wide areas over which it has occurred, is yet very small when compared with other movements in the same category. Such consolidation of sediments and displacement of water as may have taken place by the ordinary processes of sedimentation unaided by other agencies must still have left large volumes of inclosed water to be deeply buried in districts like the Appalachian region, where, during Paleozoic time,

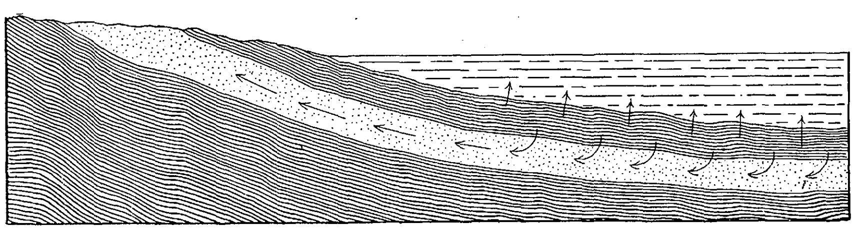


FIG. 9.—Diagrammatic section showing flow of ground water due to consolidation of sediments.

if the estimates of Dana are accepted, an aggregate subsidence and sedimentation of 36,000 feet must have taken place.

Movements due to consolidation.—When these rock materials were first laid down the pore space containing water could hardly have been less than 33 per cent, so that at one time they have contained in the aggregate more than 1,200 feet of water. But as most of the rocks of the Appalachian region have been greatly consolidated and very many of them highly metamorphosed and crystallized, the present pore space compared with its original volume is very small. In much of these beds we know the pore space to be less than 1 per cent. If we suppose the average pore space of the Paleozoic rocks of the Appalachian region to be as high as 23 per cent and this to be still occupied by water, there would yet have been a displacement of water for the whole series amounting to a depth of 3,600 feet. The actual pore space of these rocks is now very much less than 23 per cent, so that there has certainly been a very large movement of water out of them since their deposition, a movement which must have been twice, if not thrice, the amount stated above, if such depths of sediments were formed.

In the interior region of the North American continent, where but little metamorphism has taken place, there has been a very large consolidation of sediments, particularly of those of a calcareous nature, for many of the limestones have at the present time an extremely small pore space, some of them being among the most compact rocks, so that from them there must have been a large expulsion of water.

Even our sandstones have lost in pore space until many of the open ones contain as low as 25 to 15 per cent, which means that their original storage capacity for water has been reduced 10 to 20 per cent and that this amount of water has been expelled from them during the period when these reductions of pore space have been taking place.

These large volumes of water which have been carried beneath the earth's crust as a phase of the process of sedimentation must in part have reappeared at the surface in one place or in another, and there must of necessity be an underflow of the entrapped sedimentary waters from beneath the ocean toward the land, just as there has been and now is a large movement of the sediments themselves in the same direction, as was pointed out in May, 1885.[1]

It is plain that in those regions where large and long-continued subsidence is taking place there must of necessity be a lateral movement which will provide the space in which the subsiding materials may find room; and as the inclosed water is so extremely mobile and capable of being readily driven through the interstices and fissures of the rock mass this is the material which will suffer the first and the largest displacement, and hence be driven in whatever direction exit may be found; thus we have here one of the profound gravitational movements of ground water, and one whose magnitude is seen to be very great when the geologic time and the geographic area through which it has occurred are considered.

THERMAL MOVEMENTS.

The thermal movements of ground water belong to two classes; first, those which are the result of direct expansion and contraction due to changes of temperature; and, second, those which are represented by the phenomena of diffusion, osmosis, and solution.

Displacement of water by expansion.—When during the process of subsidence water-bearing sediments are carried downward through several thousand feet, one of the first results of this displacement is a large increase of volume by expansion due to rise in temperature, and whatever increase in volume may take place in such region, whether it be in that of the water or of the sediments themselves, it becomes a measure of displacement, and a flow of water in some direction is the result. At the same time the movement of the water is greatly facilitated by the mere rise in temperature, for the resistance to flow—the

[1] Internal chemical and mechanical erosion a factor in continent and mountain building: Am. Nat., 1886, p. 56.

internal friction—is much less in hot water than in cold water. Poiseuille found that water at a temperature of 45° C. flowed 2.5 times as fast under otherwise like conditions as water at 5° C.

Displacement of water by growth of grains and filling of pore space.—The second type of thermal ground-water movement is much more important in the results which it produces than the first, and while the movement, when measured in feet traveled in a given time, is small, the sum total of work done by it is very large. It is this movement, associated with the final consolidation of such rock as the quartzites, which must have been one of the chief means of transporting to the places of deposition about the original sand grains the materials which have so completely filled the interstices of the sandstone as nearly to have annihilated the once large pore space.

As the gravitational streams of water flow through the interstices of the rock the movement is chiefly along the most direct and most open channels. Indeed, except under very high pressures and very rapid flows, there is surrounding each grain a layer of water which has become stationary and does not move with the rest; and it is in this film of stationary water that the growth of the old sand grains takes place, producing that interlocking which converts a friable sandstone first into a good building stone and finally into a hard and impervious quartzite almost devoid of pores of any size.

As the processes of crystallization and precipitation go forward upon the surfaces of the sand grains beneath the films of stationary water the amount of solids which it is holding in solution is reduced and the water becomes purer than that of the current which is passing, and it is at this stage that the second type of thermal ground-water movement comes into play.

Were it not for the processes of solution, diffusion, and osmosis each grain of sand would come to be invested with a film of pure water which would effectually prevent further change; but as it is, no sooner is there a portion of the material held in solution in the stationary film laid down upon the sand grains than the energy of diffusion forces a new supply out of the moving current into the stationary film, and so long as the inward diffusion is sufficiently rapid to maintain a state of saturation consolidation of the rock mass goes forward by the growth of the sand grains. On the other hand, if a change in the character of the current passing the stationary films surrounding the sand grains occurs, so that its water is less saturated than is that of the film, solution may be set up and the pore space of the rock be increased. It is this latter condition which is everywhere maintained in humid soils, where the frequent precipitation of new supplies of fresh water maintains a nearly constant solution of the soil grains and a leaching away of the products dissolved.

But in those regions of the earth's interior where a constant saturation of the water is maintained growth may be going forward and a reduction of the pore space steadily taking place. As the sand grains become larger, as the growing faces of crystals push out into the stationary film of water which invests them, this film is itself pushed forward, and a repetition of the process steadily reduces the internal surface of the rock to which the water film may adhere; thus each addition to the permanent rock structure forces an equal volume of the stationary water of the film to enter the moving current.

It is evident, therefore, that a thousand feet of sandstone, covering many thousand square miles and containing 20 per cent of its volume of water, may lose by this method of thermal ground-water movement 19 per cent of its volume of water, while at the same time being converted into a firm rock containing a pore space of but 1 per cent.

Amount of rock consolidation a measure of ground-water movement.—The final or nearly complete consolidation of 50,000 square miles of sediment 1,000 feet deep, having a pore space of 33 per cent, filled with water, involves the actual transfer to a different region of the equivalent of a sheet of water 50,000 square miles in area and 300 feet deep, when there is still left within the mass a pore space of 3 per cent filled with water; and this thermal ground-water movement, large as it is, is an amount over and above whatever volume of gravitational flow may have been required to transport the materials held in solution necessary to do the work of making so prodigious a fill as is here implied, namely, the equivalent of covering 50,000 square miles to a depth of 300 feet with a solid rock material almost devoid of pores. It is only when we consider these slow and long processes of nature in their quantitative relations that we can realize how large and how important they have been and still are.

Mr. T. M. Read has estimated that the Mississippi River carries to the sea annually 150,000,000 tons of rock materials held in solution, equivalent to 1,848,000,000 cubic feet of solid rock, having a specific gravity of 2.6; but with water of this degree of saturation it would require the volume of the Mississippi River in continuous flow more than 60,000 years to make the fill referred to above, supposing all of the solids in solution were laid down.

If, then, it is true that the sandstones, limestones, and shales which have been deposited over the sea bottom have reached their present degree of consolidation by the movement of cementing materials through the agency of ground water, we can see how great and how long continued these movements must have been. Even if it is held that a large part of the reduction of the pore space in sedimentary deposits has in metamorphic regions been brought about through mechanical compression and flowage, there must still have been even here a large movement of ground water, both thermal and gravitational.

Then again, if the extremely small pore space of limestones which are not metamorphic owe this condition to the interstitial deposition of carbonates and to growth about the sedimentary granules, here, too, a very large work must have been done through the thermal and gravitational movements of ground water; for whether the original sediments which have been converted into limestone were fine or coarse grained, they must have been laid down with an associated volume of water equal to from 30 to 50 per cent of that of the original sediments.

But the limestones as now taken from the quarries have, as a rule, a pore space varying from less than 1 per cent to 7 or 8 per cent at most; so that the final formation of every 1,000 feet of compact limestone means an expulsion of water from those beds during the process of growth and consolidation amounting to not less than one-fourth, and possibly as much as one-half, of the present volume of limestone rock.

If it be assumed that nonmetamorphic limestones have reached their present compact condition through a segregation which has resulted in a shrinkage to the extent of the consolidation, rather than by the growth of the original grains through a deposition of materials from solution, the water of deposition must still have been expelled, and there must even then have been a ground-water movement to the extent at least of the interstitial water taking the place of developed fissures and other cavities resulting from such a segregation.

In the case of the extensive beds of clay deposits which have given rise to shales and rocks of that type, it is not improbable that the extremely large original pore space of 40 to 50 per cent in these sediments has been reduced to its present small proportions through compression; but be this as it may, there must even then have been a ground-water movement measured by the actual reduction of pore space which has taken place, for the water of sedimentation must of necessity have been expelled before the reduction of volume could have occurred.

It may be supposed that under certain conditions the water of sedimentation may have been converted into the gaseous state and expelled from the rock structure as steam, or possibly even separated into its elementary constituents and driven out as another chemical substance; but if this has been the case, here, too, there has been a ground-water movement equal to the volume of the water of sedimentation and expressed by 20 to 40 per cent of the cubic measure of the rock mass involved.

When we pause, therefore, to contemplate the gigantic thickness of sedimentary and metamorphic rock of world-wide distribution which the investigations of geologists have disclosed, and remember that any reduction of the pore space in these rock materials means a movement of ground water out of them to the extent of that reduction, we realize that the movement must have been very great, and if we attempt to assign dimensions to the volume of water moved nothing less than sheets of continental proportions and several hundreds of feet thick for the various land areas will answer the requirements. And if the materials which have closed the pore spaces in these beds of rock have been borne to their places in solution in the water flowing through them, then, indeed, has there been a great game of give and take, go and come, played by the grains of sand, always wearing out and ever forming anew, and the water, which knows no rest on land or sea.

CAPILLARY MOVEMENTS.

The capillary movements of ground water are mostly confined to the superficial deposits of land areas. Indeed, it may be said that they are almost exclusively limited to the unconsolidated soils which lie above the surface of saturation. There can be no capillary movements of water either in loose sediments or in indurated rocks where the pore spaces are already filled with water. On the contrary, capillary movements of ground water take place in directions leading away from pore spaces which are wholly or partly filled with water and toward those which are entirely empty or are less nearly filled than those from which they move.

Direction of movement.—Capillary movement may take place upward, downward, or laterally. Immediately after and during rains, when the surface soil is more moist than that below, capillary action aids gravity and hastens the penetration of water into the ground; but as soon as the surface soils become drier than those below the capillary currents are reversed and the flow is upward. In a zone of soil occupied by feeding roots the movement will be toward the roots from all sides where the adjacent soil has its pore spaces more highly charged with water than that in the vicinity of the roots themselves.

Extent and rate of movement.—The rate of capillary movement varies with the distance the water must be raised and with the character of the pore space through which the water must move. Where the movement is vertically upward through a distance of 1 foot it has been found by experiment that the rate for a fine sand was 2.37 pounds per square foot per day of twenty-four hours; when the lift was increased to 2 feet the movement became 2.07 pounds; at 3 feet it was 1.23 pounds, and at 4 feet only 0.91 pound per square foot. A similar trial with medium clay loam gave a movement of 2.05 pounds for a lift of 1 foot, 1.62 pounds for 2 feet, 1 pound for 3 feet, and but 0.9 pound where the lift was 4 feet.

There are as yet no sufficiently exact data relating to field conditions to show through what distances vertical capillary movements of water take place. But the observations quoted show that it is quite rapid at 4 feet; so rapid indeed that were it maintained throughout the year it would deliver at the surface the equivalent of 63.85 inches of water and almost prevent any part of the rain from sinking deeply beneath the surface over much the larger part of the United States.

Diminution of ground water by capillarity.—The most general effect of capillarity upon the ground water is to diminish its quantity by bringing the recently precipitated water to the surface of the soil or to the roots of plants, where it is lost by evaporation, and were it not for this action of capillarity the volume of streams flowing into the sea would be greatly increased. Capillarity exerts its least influence in the direction under consideration in regions where the surface soils are coarse and sandy and where they are underlain with coarse sand and gravels having great thickness above the ground-water surface. Under such conditions as these rain water finds its way to the ground-water surface with the greatest dispatch, and very little returns by capillarity to the surface.

Amount of water retained by capillarity.—The variations in the rate of percolation, or the rate at which water moves downward, are well brought out in the following experiment, which had for its primary object measurements of the water-holding power of long columns of soil.

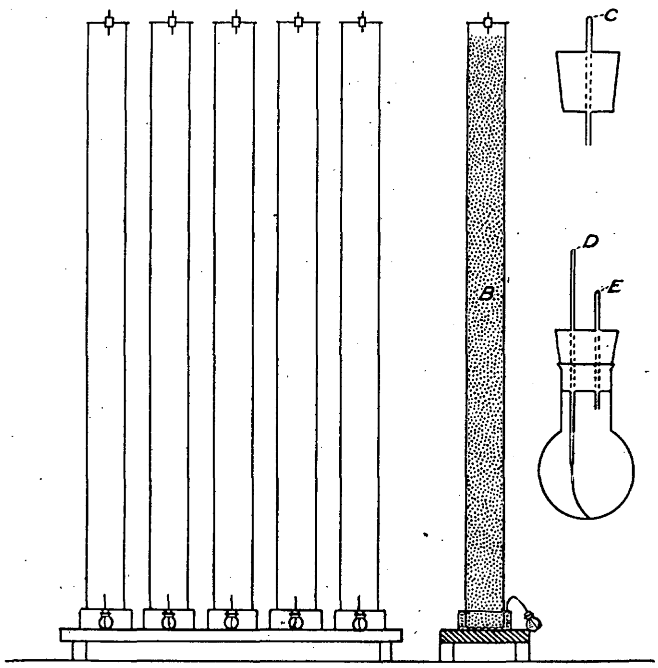
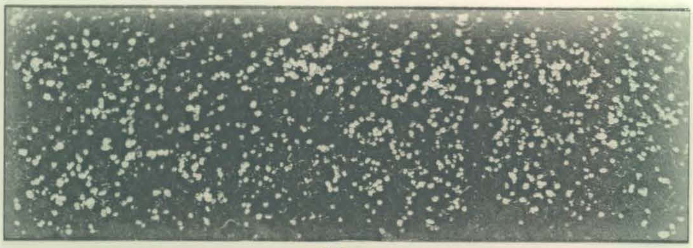


FIG. 10.—Apparatus used to demontrate the water retained by soils after long drainage without rainfall. *A*, tubes; *B*, section of tube; *C*, cork with glass tube drawn to a fine point to prevent evaporation; *D*, collecting flask; *E*, vent.

Five galvanized-iron cylinders, 8 feet long, 5 inches inside diameter, with the construction illustrated and explained in fig. 10, were filled with sorted and chemically dry sands of five degrees of fineness. The effective sizes of these grains are given in the table which follows, and the actual size is shown in Pl. VI.

When the apparatus was filled with sand, water was slowly introduced from the bottom, so as to expel the air, until the pieces were full, and then percolation was started in all at the same time, the water



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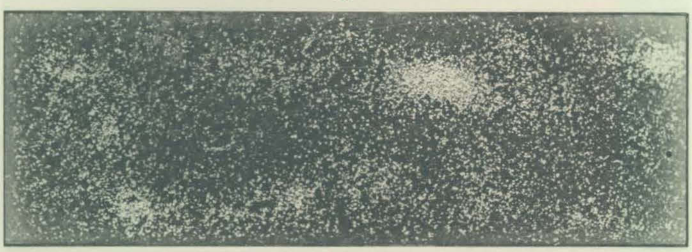

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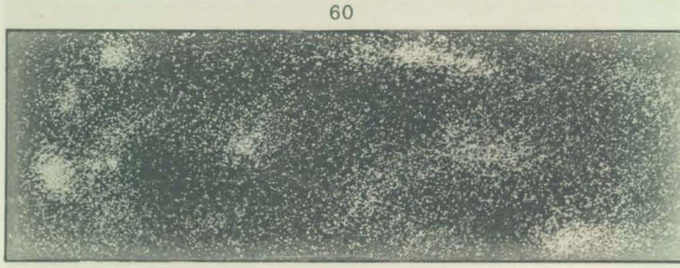

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100

SANDS USED IN APPARATUS, FIG. 10. NATURAL SIZE

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being received in flasks placed beneath the cylinders. The rate of percolation was measured by readings at intervals during nine consecutive days, and in the following table are given the amounts of water which were discharged between the intervals of weighing.

Amount and per cent of water which percolated from columns of sand 8 feet long during 190 hours 44 minutes.

	Sand No. 20.	Sand No. 40.	Sand No. 60.	Sand No. 80.	Sand No. 100.
Dry weight of sand, grams	50,050.0	49,060.0	48,490.0	48,650.0	49,340.0
Per cent of pore space	38.86	40.06	40.76	40.57	39.77
Effective size of grains, millimeters	.4745	.1848	.1551	.1183	.08265
Total discharge:					
Grams	7,499.2	7,042.7	6,234.4	4,873.5	4,154.0
Per cent	15.29	14.35	12.86	10.02	8.42

Detailed report of experiment giving above results.

Time.		Sand No. 20.		Sand No. 40.		Sand No. 60.		Sand No. 80.		Sand No. 100.	
		Grams.	Per cent.	Grams.	Per cent.	Grams.	Per cent.	Grams.	Per cent.	Grams.	Per cent.
H.	*M.*										
	30	3,298.3	6.59	2,427.1	4.95	1,730.0	3.57	486.0	.999	390.0	.791
	30	1,506.5	3.01	1,687.5	3.44	1,451.9	3.00	416.7	.856	278.2	.564
1	7	713.7	1.43	837.3	1.71	531.2	1.10	551.0	1.132	330.7	.670
1	32	486.8	.97	478.3	.97	763.4	1.57	541.7	1.113	353.7	.717
1	34	229.3	.46	289.6	.59	376.2	.78	476.7	.980	305.2	.619
2	33	193.7	.39	212.3	.43	249.0	.51	507.3	1.043	375.8	.762
15	0	463.3	.93	489.1	1.00	579.0	1.19	944.3	1.945	1,103.3	2.033
23	0	250.8	.50	211.0	.40	217.9	.45	410.2	.843	499.4	1.012
24	0	85.0	.17	94.6	.19	123.7	.26	184.5	.379	161.0	.326
24	9	68 8	.14	78.3	.016	46.9	.10	99.3	.204	149.8	.304
24	5	66.8	.13	23.5	.05	33.8	.07	49.7	.102	59.0	.120
23	35	27.0	.05	26.1	.053	1.9	.004	26.8	.055	38.6	.075
49	55	10.92	.22	188.0	.38	129.5	.27	179.3	.369	209.3	.042

After these measurements were made the flasks were weighed from time to time as water percolated into them, and the dates of weighing and the amounts of water discharged between the intervals are given in the table which follows.

Table showing downward percolation in columns of sand 8 feet long under conditions of no surface evaporation and no addition of water.

Date.	Sand No. 20.	Sand No. 40.	Sand No. 60.	Sand No. 80.	Sand No. 100.
1894.	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*
February 7	0.6	0.8	13.1	20.5	21.5
February 8	.0	.0	11.2	12.4	.0
February 9	19.2	24.3	.0	22.7	20.1
February 12	1.1	14.8	28.2	8.5	23.2
February 13	.0	14.8	7.8	17.3	27.1
February 14	11.3	8.4	19.1	8.7	12.7
February 17	7.5	1.2	9.7	1.0	5.0
February 19	10.2	1.3	37.3	19.9	13.8
February 20	.0	.0	.0	45.0	15.7
February 20, p. m	40.7	57.3	.0	.0	32.9
February 21	.0	.0	16.8	.0	.0
February 23	.0	.0	.0	43.5	17.8
February 26	44.7	1.8	47.0	35.9	45.5
February 27, a. m	.0	.0	.0	20.2	.0
February 27, p. m	.0	48.5	.0	.0	16.8
February 28	.0	.0	72.8	.0	11.7
March 4	51.3	.0	.0	.0	.0
March 12	.0	.0	.0	12.5	.0
March 18	42.0	38.0	.0	.0	31.5
March 22	.0	.0	.0	3.0	7.3
April 16	48.0	40.8	.0	7.0	.0
April 17	.0	.0	.0	7.9	.0
April 19	.0	.0	52.5	35.2	.0
May 10	42.7	.0	.0	.0	25.3
May 15	.0	38.8	.0	6.5	.0
May 17	46.9	.0	.0	18.2	41.0
June 12	57.5	40.0	55.3	25.9	28.1
June 13	.0	.0	.0	15.8	.0
July 13	2.0	37.9	2.5	31.6	43.0
July 29	44.6	.0	1.5	6.9	.0
August 8	.0	35.3	.0	15.0	.0
October 3	.0	48.3	.0	.0	.0
October 24	69.7	.0	.0	.0	.0
December 16	.0	48.3	.0	.0	.0
1895.					
January 16	17.7	.0	4.5	67.0	.0
January 21	.0	52.8	.0	.0	.0
February 20	.0	.0	65.8	.0	.0
March 14	39.0	27.7	1.2	20.7	.0
April 15	20.5	8.3	63.9	.5	.0

Table showing downward percolation in columns of sand 8 feet long, etc.—Continued.

Date.	Sand No. 20.	Sand No. 40.	Sand No. 60.	Sand No. 80.	Sand No. 100.
1895—Continued.	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*
May 6	27.2	10.2	0.3	21.7	0.0
May 31	22.5	10.8	69.3	11.0	.0
August —	36.7	.0	.0	46.4	....
1896.					
April 12	.0	49.0	.0	74.0	....
August —	19.6	17.2	.0	.0	....

The water which was finally left in these sands at the end of more than two years and a half is given in the next table, where not only the total quantity left in the sand, but also the distribution throughout the column is given. These results were obtained by cutting the tubes down in 3-inch sections and removing and drying the sand at 110° to 120° C. until constant weight was reached.

Percentage distribution of water left in columns of sand 8 feet long after percolation had continued two and one-half years.

Height of section above ground water.	Sand No. 20.	Sand No. 40.	Sand No. 60.	Sand No. 80.	Sand No. 100.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
96-93	0.27	0.17	0.22	1.26	3.44
93-90	.22	.17	.23	1.16	3.44
90-87	.23	.16	.29	1.34	3.82
87-84	.22	.15	.32	1.61	3.83
84-81	.23	.18	.61	1.98	3.93
81-78	.29	.19	1.07	2.32	4.19
78-75	.44	.26	1.33	2.61	4.38
75-72	.89	.58	1.57	2.90	4.92
72-69	1.18	1.16	1.80	3.12	4.94
69-66	1.48	1.45	1.85	3.36	5.70
66-63	1.71	1.67	2.03	3.56	5.91
63-60	1.80	1.80	2.18	3.92	6.43
60-57	1.83	1.86	2.26	4.22	6.77
57-54	1.93	1.87	2.27	4.53	7.72
54-51	1.98	1.98	2.30	4.88	8.59
51-48	2.02	1.92	2.38	5.42	9.42
48-45	2.03	2.12	2.46	6.03	10.50
45-42	2.02	2.07	2.71	6.99	11.34
42-39	2.06	2.18	3.08	7.47	12.58
39-36	2.17	2.29	3.46	8.71	13.00
36-33	2.31	2.48	4.10	10.54	14.95

Percentage distribution of water left in columns of sand 8 feet long after percolation had continued two and one-half years—Continued.

Height of section above ground water.	Sand No. 20.	Sand No. 40.	Sand No. 60.	Sand No. 80.	Sand No. 100.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
33-30	2.36	2.65	5.09	11.77	15.90
30-27	2.63	3.14	6.36	12.95	17.20
27-24	2.86	3.63	8.74	15.05	17.96
24-21	3.42	4.71	13.52	17.24	18.92
21-18	4.26	6.76	23.57	19.08	20.49
18-15	6.41	9.38	27.93	19.37	21.34
15-12	9.77	14.66	23.61	21.44	21.63
12-9	16.08	21.31	22.46	22.69	22.68
9-6	19.33	22.39	22.76	23.20	23.39
6-3	20.96	23.52	22.88	24.22	30.28
3-0	21.58	24.61	23.54	25.07	24.08

Summary of results of experiment tabulated above.

	Sand No. 20.	Sand No. 40.	Sand No. 60.	Sand No. 80.	Sand No. 100.
Total water retained:					
Grams	2,121.4	2,474.9	3,515.0	4,576.2	5,831.5
Per cent	4.24	5.05	7.25	9.41	11.82
Percolation in first 9 days:					
Grams	7,499.2	7,042.7	6,234.4	4,873.5	4,154.0
Per cent	14.98	14.35	12.86	10.02	8.42
Percolation after first 9 days:					
Grams	804.6	838.6	579.7	839.9	621.3
Per cent	1.61	1.71	1.20	1.73	1.26
Total water recovered:					
Grams	10,425.2	10,356.2	10,329.1	10,289.6	10,606.8
Per cent	20.83	21.11	21.30	21.15	21.50
Total weight of dry sand	50,050.0	49,060	48,490	48,650	49,340

The data presented in these tables are of fundamental importance in showing how the ground-water surface in humid climates is fed through precipitation by slow percolation or seepage.

Rate of loss of water from sands.—It will be observed in the first place that when the pore space of the sand was entirely filled with water the water escaped very rapidly. Indeed, it is quite likely that the first flow, especially from the coarser sands, represents a rate of movement too small on account of the fact that the discharge tube had an inside diameter of only one-eighth of an inch, and so offered a material resistance to the escape of the water from the columns of sand. As it was, however, the water contained in 8 feet of fully saturated sands escaped from them at the following mean rates during the first and second thirty minutes and under its own head.

Table giving the rate of percolation from sands under the gravitational head of the inclosed water.

Size of sand.	Effective diameter of grain.	Per cent of pore space.	Weight of sand per 8 cubic feet.	Amount of water percolated in— First 30 minutes.		Amount of water percolated in— Second 30 minutes.	
	Mm.		*Pounds.*	*Pounds.*	*Inches.*	*Pounds.*	*Inches.*
No. 20	0.4745	38.86	809.28	53.33	10.25	24.36	4.683
No. 40	.1848	40.07	793.28	39.27	7.549	27.35	5.258
No. 60	.1551	40.76	784.00	29.99	5.674	23.52	4.522
No. 80	.1183	40.57	786.64	7.86	1.512	6.73	1.294
No. 100	.08265	39.73	797.76	6.31	1.213	4.40	.845

It will be seen from the above table that the rate at which the water moved downward through the coarsest or No. 20 sand was such as to average during the first thirty minutes 497.9 inches per twenty-four hours, while for the finest or No. 100 sand the mean rate was 58.16 inches. Such facts as these make it plain that a ground-water surface lying beneath a catchment area made up of as coarse materials as are presented by this series must be fed by almost the entire precipitation when that is in the form of rain, even were it to reach the maximum amounts which have been recorded in Japan and India for twenty-four consecutive hours.

The gain to the underground supply of water, through precipitation, is intensified by the extremely small amounts of water which are retained upon the surfaces of the sand grains, as illustrated by the data of this set of tables. It will be seen that in the end all of the sands became extremely dry throughout the upper 4 feet, so dry that the lower 3 inches of the surface 4 feet in the finest sand retained but 9.42 per cent, when its full capacity is 21.50 per cent of the dry weight; while in the surface 3 inches only the two finest sands retained as much as 1 per cent of water. Indeed, it must be understood that this extremely dry condition of the surface sands was reached very early in the period covered by the experiment. This statement is proved by the fact that after the first nine days the entire loss in any case did not equal 1.75 per cent of the dry weight of the sand, and under such conditions the loss of water by surface evaporation is necessarily very small.

In illustration of the possible rate of evaporation from such sands as those in question, the results of a series of measurements are cited.

A series of cylinders, represented in fig. 11, each having an area of cross section of 0.1 square foot, was filled with the same sands used in the preceding experiments, but unassorted; that is, the several sizes of grains were mixed in the natural proportions.

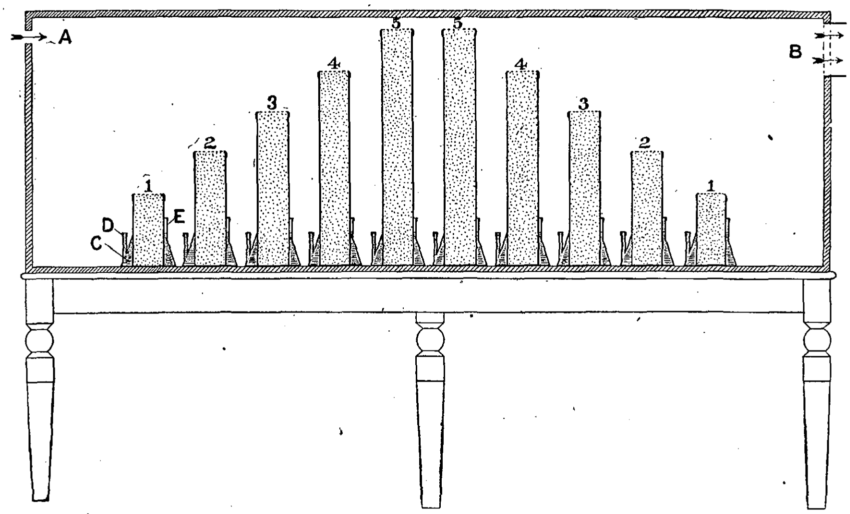


FIG. 11.—Apparatus used in measuring the loss of water from coarse sands by evaporation from surface different distances above plane of saturation. A, intake for air current; B, exit for air current; C, water reservoir; D, supply tube; E, vent.

In the two shortest cylinders water was maintained in the reservoir at a level of 6 inches below the surface, while the other pairs of cylinders had the water level maintained at 12, 18, 24, and 30 inches, respectively, below the surface. The total evaporation during forty days was found to be as follows:

Evaporation from sand.

Capillary lift.	Total evaporation.	Mean evaporation per day.
Inches.	*Inches.*	*Inches.*
6	4.56	.114
12	4.45	.111
18	3.19	.08
24	1.36	.034
30	.78	.0195

These rates of evaporation took place in the laboratory, where the temperature of the air was about 70° F., and where the relative humidity was very low.

It is evident, therefore, from these two series of observations, that in regions where the surface soils are very coarse and where the ground-water surface has a depth exceeding 8 feet, nearly the whole precipitation passes at once below the level at which it is possible for capillarity to return it to the surface.

Even over regions where much finer soils prevail at the surface the total possible percolation may be quite large and the amount of water contributed to the ground-water supply may be important, provided the indurated rock below is capable of receiving it.

Using cylinders having a cross section of 0.1 square foot, it was found that when water would percolate through 14 inches of No. 40 sand at the rate of 301 inches in twenty-four hours, and through No. 100 sand at the rate of 39.7 inches, a clay loam would allow but 1.6 inches to pass in twenty-four hours. These flows occurred after the soils were fully saturated and when the surface was kept covered with 2 inches of water.

It should be understood with reference to percolation through clayey and other fine and close textured soils that the rate of flow through the surface 4 feet is greatly augmented ordinarily by the borings of earthworms and animals of various kinds, as well as by passageways left by the decay of the roots of plants and by shrinkage checks which are developed during times of drought.

A steady percolation of so slow a rate as 0.1 inch per day of twenty-four hours would provide for the entrance into the ground of 36.5 inches on the level during the year if water were continuously supplied; but the rains do not fall in such manner as to permit all the water to enter the ground, even where the topography is quite flat, and besides, through the conjoint action of capillarity and the roots of vegetation, a large part of the moisture which falls during the growing season upon fertile soils fails to penetrate beneath the surface more than 1 to 4 feet before it is recovered and brought back to the surface and lost by evaporation.

Then again, during seasons of drought in humid climates and at nearly all times in arid climates another important factor comes in to prevent even moderate showers from entering the soil deeply. When the soil becomes nearly air dry to any considerable depth the pore space becomes entirely filled with air, and this must always be expelled before percolating waters can make an entrance. In coarse sands and sandy soils the pore spaces are so large that the water has little difficulty in displacing the air and making an entrance as fast as the rain is likely to fall; but where the surface is covered by this finer soil even a moderate shower is likely to fill up the surface pores so completely as to prevent almost entirely the escape of the soil air, and this at the same time prevents the entrance of the water. Under these conditions heavy rains may cause an immense amount of surface erosion, and the little moisture which finds entrance to the soil penetrates so short a distance under the great hindrance from entangled air that it is quickly returned to the surface by capillarity and lost by surface evaporation.

PERCENTAGE OF PRECIPITATION WHICH PENETRATES THE SOIL.

Of the water which falls upon land areas one portion finds its way by immediate surface flow directly into drainage channels; another portion is retained upon the surface of the soil and the foliage of plants and is returned at once by evaporation to the atmosphere from which it came; while a third portion penetrates the interstices of soil and rock to varying depths, but ultimately reappears again in drainage channels.

Newell has pointed out, as a result of his studies, that the mean annual run-off in the United States exceeds 20 inches in the States of Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, New York, New Jersey, Pennsylvania, Maryland, Delaware, the Virginias, North and South Carolina, Florida, Georgia, Alabama, Louisiana, Mississippi, Tennessee, and Kentucky, together with the southern portions of Ohio, Indiana, and Illinois, most of Arkansas, and a small portion of eastern Texas and Indian Territory. Throughout this region the rainfall for the year amounts to from 40 to 60 inches, reaching 60 to 70 inches in a few comparatively small areas. This makes the run-off about 50 per cent of the total precipitation, or perhaps a little more. In all of Wisconsin and Michigan and in parts of Ohio, Indiana, Missouri, Indian Territory, Texas, Iowa, and Minnesota the water which finds its way into streams is placed by Newell at 10 to 20 inches, while the mean annual rainfall is between 28 and 42 inches, making the run-off from 36 to 47 per cent of the rainfall; but in a narrow strip extending nearly north and south across the central portion of the United States, taking in parts of Minnesota, Iowa, and the Dakotas on the north and crossing central Texas on the south, the run-off is 5 to 10 inches, while the rainfall for the same region is not far from 20 to 30 inches, making the percentage relations 25 to 33. That is to say, from one-fourth to one-third of the water which falls as rain and snow is ultimately gathered into streams and borne away.

West of the region just referred to, as far as the extreme Northwest, in western Washington, Oregon, and the mountainous parts of California, the water which annually finds its way into streams measures from 5 inches to none; but in an area bordering that, where the run-off is 5 to 10 inches and widening out in the north so as to cover the balance of the Dakotas and the eastern portions of Montana and Wyoming, Newell's maps show that 2 to 5 inches of water (from 20 to 25 per cent of the mean annual rainfall) finds its way into streams.

It appears, therefore, that in the more level districts of the United States, where the rainfall ranges from 10 inches to more than 70 inches, from one-fifth to one-half of the water which falls as rain and snow finds its way into streams, but by far the larger portion of this water has penetrated the soil to the ground-water level and has emerged again from beneath the earth's surface before it reaches river channels.

The water of rivers which does not take the course through soil and rock is (1) that which falls directly into water courses in the form of rain or snow, and this would bear such a ratio to the total rainfall of the drainage basin as the superficial area of the streams and lakes bears to the total area of the district drained by them; (2) that which falls in heavy showers near the water courses where the slopes are steep and for lack of time does not enter the ground; and (3) the heavy snows which melt rapidly upon steep slopes near drainage channels. Just how large a percentage of the total run-off these three factors make we do not know, but it is certainly much smaller than a first judgment without reflection would be likely to place it, and it may be laid down as a broad proposition that nearly all of the water of rivers and small lakes is that which is slowly but constantly seeping through and from the soil.

HOW SEEPAGE WATERS FIND THEIR WAY INTO DRAINAGE CHANNELS.

Whenever rain falls upon a field, no matter of how steep a slope, its first tendency is to continue the course it was pursuing when it fell and to pass directly beneath the surface in a straight line, and it is only when the rate of precipitation exceeds that at which percolation takes place that there is any surface movement toward drainage channels.

The water which enters the ground in excess of capillary saturation moves directly downward until the ground-water surface has been reached, when it raises that level and at once augments the pressure. If the land were everywhere level the effect of percolation would be simply to raise the level of the ground-water surface; no lateral movement would be possible except under such conditions as permitted the ground-water level to be lowered more rapidly in one place than in another by surface evaporation aided by capillarity. With the differences of level, however, which are always associated with topographic forms and with the far greater resistance which is opposed to lateral flow, as compared with that which impedes percolation directly downward, it is evident that the water which sinks beneath the surface of land areas must tend to accumulate beneath the places where it has fallen until a sufficient pressure has been developed to force it to flow through the soil and rock toward whatever drainage outlets may exist.

There is a widespread general belief that the level of standing water in the ground is indicated by the level of the water in the rivers and lakes of the district in question, and that wells must be sunk to those levels before water will be reached by them. It is even commonly thought that the water which supplies the local wells of a region actually seeps into the soil and rock from the beds of rivers and lakes.

So far is this common impression from being true that its exact opposite is the real expression of the facts. The surfaces of rivulets, brooks, creeks, streams, rivers, and lakes, with but very few exceptions, lie below the level of standing water in the ground adjacent to them, and from which almost everywhere water is steadily but usually slowly flowing into them. Rivers generally receive new acquisitions of water at every point along their banks, there being a slow but general seepage from the surrounding higher lands. The same is true of lakes. Springs, it is true, are feeders of both lakes and streams, but these are only underground extensions of channels in which the same type of slow seepage occurs, the water oozing through the walls of the subterranean channels as water is gathered into a system of tile drains, not at any one point, but little by little all along the course.

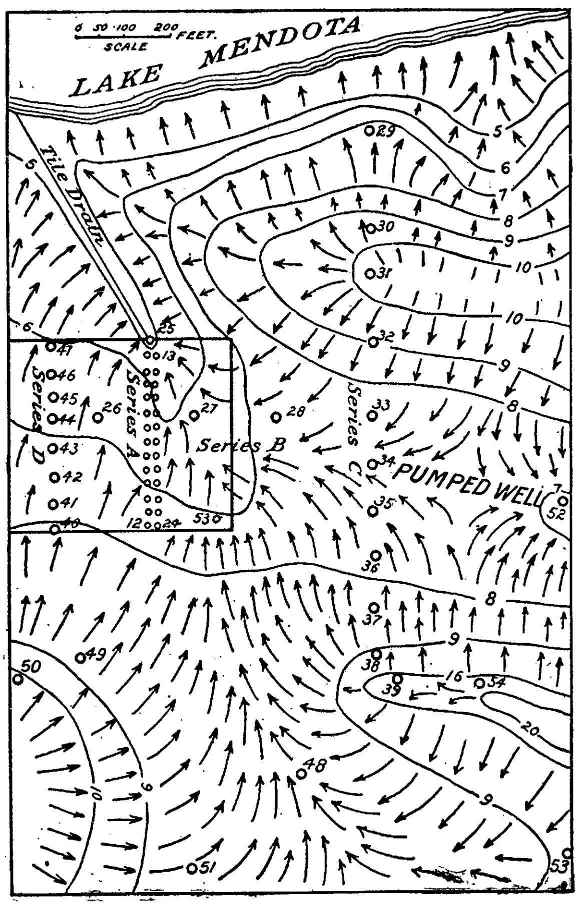


FIG. 12.—Contour map of surface of ground water. Numbered circles, location of wells; figures in lines, elevations of contours; arrows fly with direction of current.

There are cases, it is true, where mountain streams flow out upon arid plains, in which the direction of seepage is reversed and the water wastes outward, ultimately leaving the bed of the stream dry; but in these cases such portions of these waters as are not lost by evaporation are certain to reappear again farther down the valley, adding to the growth of rivers there.

In other cases rivers may move down upon a sandy plain, perhaps underlain by a sandstone formation which is deeply underdrained, so that the ground-water level lies below the bed of the stream; and in such instances the stream loses in volume rather than increases as it moves along its course. In still other cases a shallow soil may be spread out upon a much-fissured limestone formation which, by reason of slope or cliff exposures, is so thoroughly drained that no ground-water surface can be maintained above the stream beds; and here, too, the water may slowly waste away, or in some cases the brook may disappear abruptly beneath the surface, only to reappear again farther down the valley in the form of a powerful spring.

CONFIGURATION OF THE GROUND-WATER SURFACE.

In order to gain a clear conception of the conditions which determine the flow of ground water it will be helpful to know the actual configuration of the ground-water surface in a particular case, and one of the simplest examples is represented in fig. 12, where the contour lines show how far the surface of the ground water departs from a horizontal plane and also how high it lies above the level of the lake into which the water is draining. Fig. 13 is a contour map, showing the topographic features of the same locality.

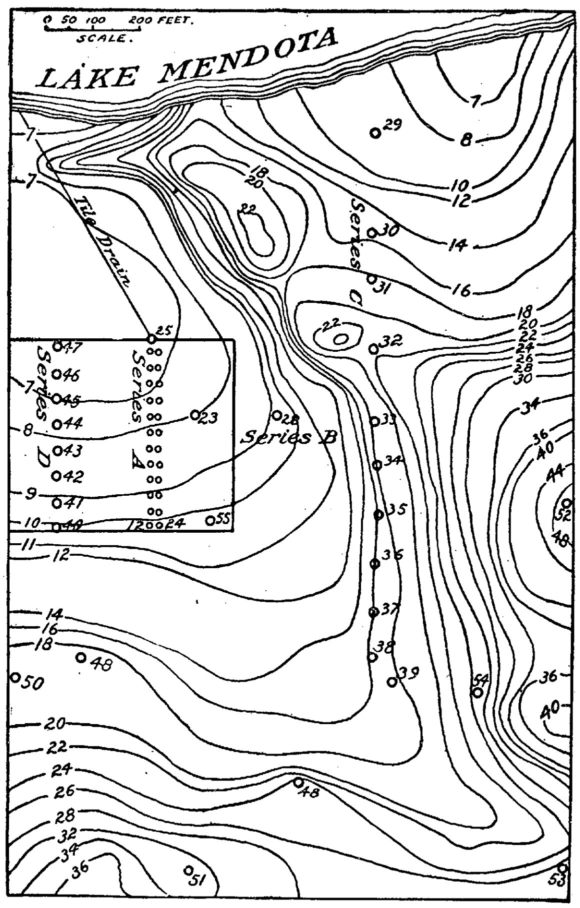


FIG. 13.—Contour map of surface of ground above the ground water of fig. 12

The variations in level of the ground-water surface in this case were secured through measurements of the height of the water in 52 wells, designated on the maps by numbers, against which small circles are placed.

The area mapped is a portion of the Wisconsin Agricultural Experiment Station farm, and lies just within the terminal moraine of the second Glacial epoch. The glacial till, into which the water percolates and through which it flows to the lake, is laid down upon the very unevenly eroded surface of the Madison sandstone. The till is quite heterogeneous in character in its upper portion, but is much more uniform at the level of the ground water and below, through which the drainage to the lake takes place.

The whole area is mantled with a stratum of reddish clay 2.5 to 4 feet thick, containing pebbles and bowlders irregularly and generally sparsely distributed through it, the pebbles and bowlders being coarser and more numerous on the higher ground. Beneath this mantle there is usually a rapid transition to a sand of varying degrees of coarseness, but generally quite free from gravel and clay, everywhere below the 9-foot contour.

The effective sizes of the grains in these sands are given in the table below, as shown by a section taken at 55:

Effective sizes and pore spaces of sands underlying the locality shown on fig. 13.

Depth in feet.	Pore space.	Effective size.	Depth in feet.	Pore space.	Effective size
	Per cent.	*Millimeter.*		*Per cent.*	*Millimeter.*
1			7	35.32	0.1312
2	38.57	0.06745	8	34.57	.1818
3	39.38	.07579	9	34.37	.1738
4	39.45	.1875	10	33.08	.2191
5	37.94	.1746	11	30.25	.1470
6	38.50	.1673	12	28.76	.1055
			13	29.32	.0566

At a point near 52 the finer sand and gravel in the heterogeneous superficial till has an effective size of grain and pore space expressed by the figures below:

Fine material of mixed till.

Pore space.	Effective size.
Per cent.	*Millimeter.*
33.65	0.0338
33.76	.04144
33.88	.04084
34.37	.05261

These figures show the diameter of the mean sand grain and the per cent of open space in these sands through which the water must move.

By referring to fig. 12 it will be seen that the surface of the ground water is very far from level, and that near well 54 the water stands 20 feet above the level of the lake and has a gradient of 12 feet in 200, or 1 foot in 16⅔ feet. Even at well 29, only 150 feet from the lake, the water stands 7.2 feet above the suface of Lake Mendota, making a fall here of 1 foot in about 20 feet to force a flow of water toward the lake.

In another well sunk in the same hill, shown on the map, but about 3,600 feet to the east, where the surface of the ground is 88 feet above the lake, the level of the water stood 52 feet above the lake 1,200 feet distant, and this gives a fall of about 1 foot in 23 feet.

The area here under consideration lies between two lakes, making it impossible for seepage waters from long distances to reach it, and there is no opportunity for artesian waters to furnish any part of the supply, so that we have here a perfectly simple case of local precipitation sinking directly into the ground and raising the level of the water in the glacial till until pressure enough has been developed to cause the water to flow into the lake in directions and along lines indicated by the arrows (fig. 12).

The contours of the ground-water level show that this surface presents the features of hills and valleys approximately conformable with the relief forms of the surface above, the water being low where the

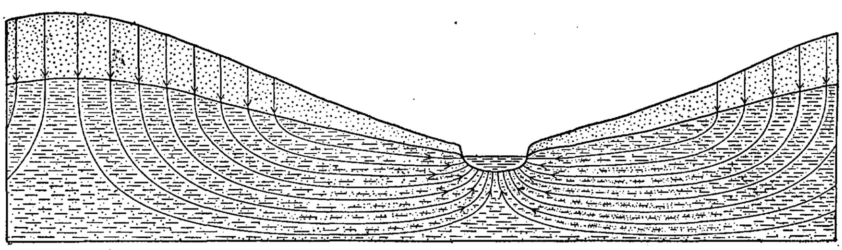


FIG. 14.—Diagrammatic section illustrating seepage and the growth of streams. Lines with arrows are lines of flow.

surface of the ground is low, and high where the surface of the ground is high. It will be further noted that the water moves outward from the higher areas of ground water in directions essentially the same as those which would be taken by water flowing down natural surface slopes, and this gives rise to a concentration of water movement along the valley lines beneath the surface of the ground, just as happens with flood waters.

It is plain, therefore, that streams winding through the lowest levels of valleys in regions of humid climates must receive increments to their volume of water step by step as they move along.

It is further evident that low-lying flat areas between higher ground may be made and kept wet by the slow rise of water from beneath as it is forced upward under the hydrostatic pressure developed by the accumulation of water percolating down through the surrounding higher land, and in fig. 14 is represented in diagrammatic form the direction of movement of the ground water as it passes downward through the porous soil and outward from beneath the higher areas to seek an outlet in river channels or in the bed of lakes.

ELEVATION OF THE GROUND-WATER SURFACE DUE TO PRECIPITATION AND PERCOLATION.

We have already given the amount of water which may be retained by columns of sand of varying degrees of coarseness after a period of percolation exceeding two years had expired. The data presented in those tables may be used to compute the amount of elevation of the ground-water surface which a given amount of precipitation is capable of bringing about, and as the rate of drainage depends in part upon the height of the ground water above the drainage outlets this becomes a matter of fundamental importance.

In the table on page 87 is given the amount of pore space in the several sands under experiment, and by referring to this table it will be seen that the unoccupied space is about 40 per cent as an average of the five cases. This means that each cubic foot of sand had a capacity for water amounting in round numbers to 0.4 of a cubic foot, and that 12 inches of rain would completely fill the voids of 30 inches of these chemically dry sands.

Under field conditions, however, the sand is never chemically dry, so that a rise of the ground-water surface amounting to 2.5 inches for each inch of water which reaches it does not express the full magnitude it may have. Further than this, as the sands were filled into the cylinders without jarring or tamping, they possessed under the trials made about as large a pore space as it is possible to give them, so that it may safely be said that an inch of rain will never fail to raise the ground-water surface more than 2.5 inches.

But after the long period of drainage to which the sands were subjected under conditions where little or no evaporation was possible they still retained the amounts of water stated below in percentages of their dry weight.

No. of sand.	Per cent.
20	4.24
40	5.05
60	7.25
80	9.41
100	11.82

As this water occupies a portion of the pore space of the sand it must augment the elevation of the ground-water surface in proportion to the space occupied, and as these amounts of retained water represent from more than one-fifth of the full saturation capacity in the case of sand No. 20 to more than one-half in the case of No. 100, it is plain that 1 inch of rain must raise the ground-water surface from 3 to 5 inches.

But the water when it drains from a soil or sand does not do so in such a manner as to leave the retained water uniformly distributed. On the contrary, the sand just above the ground-water surface is still almost completely filled with water, so that but little needs to be added here to raise the ground-water surface a large amount. Indeed, in the case of the reservoir of sand described on page 264, we found that a single pound of water added to a wet surface of 14.5 square feet of sand was sufficient to raise the ground-water surface 0.025 foot. That is to say, the depth of water added to this nearly saturated sand was augmented some thirtyfold on falling into the narrow, nearly filled pore spaces, and raised the ground-water surface at the rate of nearly 30 inches for each inch of rain.

If we compute the full saturation capacity of the five sands under consideration from their observed pore space, expressing the water in per cent of the dry weight of the sand, and then subtract from these the observed percentages of water which were retained at the different levels, the differences will give the percentages of water which will be needed to fill completely the respective sands at each of the thirty-two different levels above the ground-water surface where the determinations were made.

The results of such a computation are given in the following table, and fig. 15 represents graphically the amounts of unoccupied space in the several sands at the various levels.

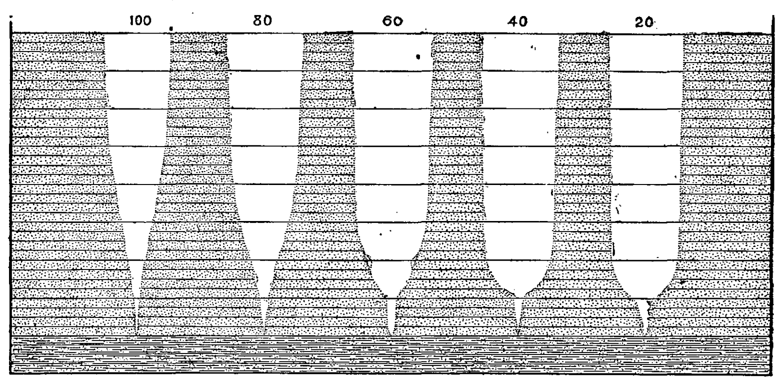


FIG. 15.—Diagram showing unoccupied space in sands after two and one-half years of seepage without rain or evaporation. Numbers designate grade of screen; horizontal lines drawn at distances of 3 inches; open space in each case applies to whole section; lower shading is ground water.

Table showing the per cent of water required to fill completely five grades of sand after being permitted to drain more than two years.

Height of section above ground water.	No. 20.	No. 40.	No. 60.	No. 80.	No. 100.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
96–93	23.71	25.06	25.76	24.49	21.43
93–90	23.76	25.06	25.75	24.59	21.43
90–87	23.75	25.07	25.69	24.41	21.05
87–84	23.76	25.08	25.66	24.14	21.04
84–81	23.75	25.05	25.37	23.77	20.94
81–78	23.69	25.04	24.91	23.43	20.68
78–75	23.54	24.97	24.65	23.14	20.48
75–72	23.09	24.65	24.41	22.85	19.95
72–69	22.80	24.07	24.18	22.63	19.93
69–66	22.50	23.78	24.13	22.39	19.17
66–63	22.27	23.56	23.95	22.19	18.96
63–60	22.18	23.43	23.80	21.83	18.44
60–57	22.15	23.37	23.72	21.53	18.10
57–54	22.05	23.36	23.71	21.22	17.15
54–51	22.00	23.25	23.68	20.87	16.28
51–48	21.96	23.31	23.60	20.33	15.45
48–45	21.95	23.11	23.52	19.72	14.37
45–42	21.96	23.16	23.27	18.76	13.53
42–39	21.92	23.05	22.90	18.28	12.29
39–36	21.81	22.94	22.52	17.04	11.87
36–33	21.67	22.75	21.88	15.21	9.92
33–30	21.62	22.58	20.89	13.98	8.97
30–27	21.35	22.09	19.62	12.80	7.67
27–24	21.12	21.60	17.24	10.70	6.91
24–21	20.56	20.52	12.46	8.51	5.95
21–18	19.72	18.47	13.06	6.67	4.38
18–15	17.57	15.45	11.59	6.38	3.53
15–12	14.21	10.57	7.93	4.31	3.24
12–9	7.90	3.92	3.52	3.06	2.19
9–6	4.65	2.84	3.22	2.55	1.48
6–3	3.02	1.71	3.10	1.53	.81
3–0	0.00	0.00	0.00	0.00	0.00

	No. 20.	No. 40.	No. 60.	No. 80.	No. 100.
Effective diameter of sand grains ..... mm	0.4745	0.1848	0.1551	0.1183	0.08265
Per cent of pore space	38.86	40.06	40.76	40.57	39.72

In the diagram the stippled area is intended to represent a section of sand 96 inches high and having any unit width, while the unshaded areas represent the amounts of space in such a volume of sand which were found unoccupied by water after drainage had taken place throughout a period of over 2.5 years; that is to say, the amount of space left in a column of sand 8 feet long above the plane of saturation, and having the sectional dimensions shown in the figure, is represented by the unshaded areas for each of the five grades of sand shown in Pl. VI, and when rain enough has fallen upon the surface of the whole section to fill any one of the cavities represented, this amount will bring the ground-water surface to the top, or raise its level through 8 feet.

It will be observed that the drained space both in sand No. 20 and sand No. 40 increases rapidly until a distance of about 27 inches above the ground-water surface is reached, but that higher up the increase of space is small. In the other three sands, however, the space capable of drainage widens upward much more uniformly and at the same time more slowly, so that the rise of the ground-water surface with the same amount of rain is very different in the different grades of sand.

In the following table is given the number of inches of rain which is required to raise the level of the ground water 1, 2, 3, and 4 feet after thorough drainage has taken place:

Table showing amount of rain necessary to raise level of ground water after thorough drainage.

Grade of sand.	1 foot.	2 feet.	3 feet.	4 feet.
	Inches.	*Inches.*	*Inches.*	*Inches.*
No. 20	0.874	4.379	8.550	12.81
No. 40	.433	3.551	7.795	12.19
No. 60	.579	2.701	6.454	10.80
No. 80	.370	1.592	4.080	7.573
No. 100	.242	1.030	2.635	5.131

Thus it becomes evident that relatively large rises in the level of ground water may be produced by small amounts of precipitation, and the case becomes more emphatic when it is recalled that nowhere except in extremely arid regions can so complete drainage ever occur as these sands were subjected to.

If reference is again made to the table of percolation, page 90, it will be seen that an amount of water equal to about 1.5 per cent of the dry weight of the sand was left to percolate after the first nine days of drainage, and as the water in the upper portions of the sand columns was all the time flowing down into spaces in the lower sections, it is plain that at the expiration of the first nine days the open space in the lower 4 feet, and particularly in the lower 2 feet, was much smaller than that which finally came to exist, and hence that ordinarily the rise in the ground-water surface for given amounts of rain will be greater than the amounts stated in the last table.

As the rate of seepage into drainage channels increases with the height of the ground-water surface, the facts here presented show that not only must the rate of seepage increase after heavy rains, but also that the rate of increase will be relatively more rapid in soils of close texture than in those more open. That is to say, the swollen condition of streams during wet seasons of the year is in large part due to the fact that the effective head which forces the water into drainage channels is at such times greatly increased, and the water drains out of the soils of closer texture relatively faster than out of the coarser soils, because the same amount of precipitation raises the ground water higher in the finer soils, and thus makes their effective drainage head relatively greater.

There is still another factor influencing the rate of seepage after rains which needs to be taken into account when these problems are studied—the depth of the stratum of soil above the ground-water surface; for when a considerable interval has occurred between rains, the longest columns of soil, other things being equal, will be most completely drained, and hence will possess both the largest water capacity above the plane of saturation and the longest distance for the percolating waters to move before reaching the ground water to raise its level. That is to say, a low-lying area, where the ground water is near the surface, may easily have its empty pore space nearly filled and the effective drainage head much increased by a given rain several days before the same rain shall have been able to reach the ground water under adjacent higher land, where the empty space is not only larger because of more complete drainage but of greater extent vertically, and hence the ground-water surface may reach its highest level on the low ground and begin to fall again before the water percolating through the longer columns of soil on the higher land shall have had time to reach the plane of saturation.

The effects here under consideration are brought out clearly in fig. 16, which represents the changes in the level of the ground water following a rainfall of 3.19 inches, these changes being determined by measurements made in wells at the stations and times there designated. The distribution of the rainfall in time was as follows: June 2, from 7.30 a. m. to 9 p. m., 1.38 inches; June 3, 7 a. m. to 2 p. m., 0.41 inch; 9 p. m., June 3, to 7 a. m., June 4, 1.18 inches; 9.15 p. m., June 4, to 6.30 a. m., June 5, 0.22 inch, thus covering an interval of three days.

The measurements of the water level were made June 2, before the rain; then June 3 at 3.30 p. m.; June 4 at 9 a. m., 2 p. m., and 7 p. m., and finally, June 6 at 1 p. m., and the profiles of the water level are shown in the figure and numbered in the order they were made from 1 to 6.

The surface of the ground at well 40 is 3.3 feet higher than it is at well 47, as shown by the contour map (fig. 13), and the texture of the soil increases in fineness from well 40 toward well 47. It will be seen that the water rose rapidly at first at the lower end, attaining its greatest height June 4 at 9 a. m. in wells 43 to 47, but that in wells 40 and 41 the water continued to rise until June 6 at 1 p. m., but at this time the water in well 47 had reached its highest point and had fallen through a distance equal to that through which the water in well 40 had risen.

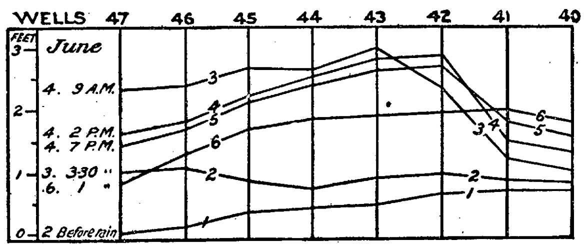


FIG. 16.—Diagram representing changes in the level of ground water following a rain of 3.19 inches.

At the time these observations were first discussed[1] it did not appear to the writer probable that the observed changes in level of the water in the wells could give a true measure of the change in the level of the general surface of the ground water in the locality, the indications then seeming to point to large local percolation of water into those wells which showed such large and prompt changes in the level of the water in them, and the cause of this difference in percolation into the wells was explained (see fig. 17) in the following language:

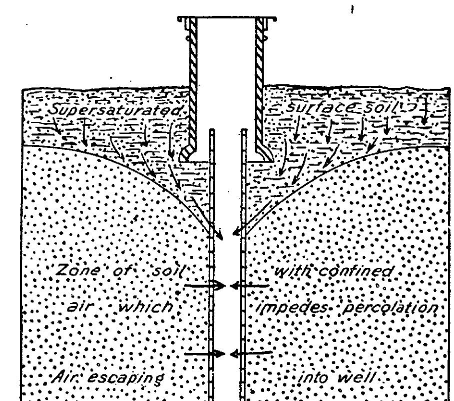


FIG. 17.—Diagram illustrating the influence of soil air in increasing seepage into wells.

The rise of water in wells above the general drainage surface during times of heavy rains is due to the inability of the soil air to escape readily upward through the supersaturated surface, for so long as it can not escape it prevents the water from entering the soil spaces occupied by it; wells, however, which are not curbed with impervious tubing furnish an easy avenue of escape for the air, and it is forced out into the wells, allowing the water to follow it, so that there comes to be established during times of percolation a movement of water and air in the soil about the well something as represented by the arrows in fig. 17.

[1] Bull. U. S. Weather Bureau, No. 5, p. 20.

In the sandy and more open soils, where the interspaces near the surface do not readily become closed with fine sediment moved by the water, there is not so great a lateral flow of water toward the wells, and the water does not rise in them very much more than the general water level in the ground is raised during such times, and it is because the soil about wells 40 and 41 is much more sandy and open than it is about the others of this series that there is less rise of water in them at such times.

Since it has been demonstrated by this investigation that the unoccupied space in partly saturated soils is so small, and especially since it has been shown to be so much smaller in the fine soils than it is in the coarse ones, it is clear that the amount of water which had percolated into the wells under consideration had been overestimated and that their water levels did much more nearly represent the true level of the ground-water surface than was supposed.

The rapid fall of the ground-water surface in the region of wells 47 and 46 is to be attributed in part to the fact that tile drains occupy the area and offer much shorter drainage lines than would otherwise have to be traversed by the water. In the region of wells 40, 41, and 42 the lines of tile are entirely above the level attained by the ground-water surface on June 6, so that here only a small portion of the early falling away of the water could have been directly influenced by the artificial drainage.

It is of course true that the normal rate of fall of the ground water of this particular locality was increased by the increased pressure due to the rise of the water in the ground at this time, so that the full rise of water in the ground produced by the 3.19 inches of rain can not be stated without applying a correction which allows for the amount of water which drained away during the interval under consideration.

The rate at which the level of the ground water did change in the locality under consideration was 13.95 inches during eighty days, from June 8 to September 17, 1889, or a mean of 0.174 inch per day. During one hundred and thirty-one days, from May 27 to October 29, the total fall was 20.495 inches, or a daily mean of 0.156 inch per day, and during one hundred and twelve days, from June 9 to October 7, 1890, the total fall was 20.086 inches, or a mean daily rate of 0.179 inch, the three cases together giving a general mean daily rate of fall amounting to 0.173 inch.

The mean daily rate of change of 0.173 inch would amount for the year to a total fall of the ground-water surface equal to 63.145 inches, and thus, according to the table on page 103, must represent a run-off somewhere between 6 inches and 14 inches, according as the pore space is greater or less than that of the samples experimented with, which is 20 to 40 per cent of the mean annual rainfall.

CHAPTER II.

EXPERIMENTAL INVESTIGATIONS REGARDING FLOW OF FLUIDS THROUGH POROUS MEDIA.

Since the investigations of Graham, Poiseuille, Meyer, and others regarding the flow of fluids through capillary tubes and of Darcy regarding the percolation of water through soils, it has been generally assumed that the flow of water through soils, sands, and porous rock obeys the laws which govern the flow of fluids through capillary tubes. It is generally believed that doubling the pressure upon water moving through sand will double the quantity which will pass through that sand in a given time, while doubling the length of the sand column or the thickness of the sand or rock stratum will reduce the amount of water passing through in a unit of time just one-half; in other words, that the flow is directly proportional to the pressure and inversely proportional to the depth or thickness of the stratum.

In view of the careful and extended work which had been done, both experimental and analytical, regarding the viscosity of fluids and the laws of capillary flow, it occurred to the writer, in 1890, that an apparatus might be devised to utilize the results of some of these studies in determining the size of soil grains.

Since the diameter of a capillary tube should be capable of determination, by calculation, when its length and the amount of water flowing through it in a given time under a stated temperature and pressure are known, it seemed possible that a knowledge of the amount of water flowing through a column of soil of known cross section and length under given pressure and temperature might also be used in computing the diameter of the mean capillary pore through which the water had passed, and that it then might be possible to work from this to the diameter of the sand or soil grains which massed together would produce the capillary pore that had been determined.

Studies in this line were begun by experimenting with the flow of water though sands, but such great difficulties were found in the way of duplicating results from day to day with the same or slightly different apparatus that it became clear that the method with water would be impracticable.

But as air is held to obey the same laws as water in moving through capillary tubes, investigations were made with air; and it was early found that here the difficulties in the way were very much less than had been encountered with water, and that it was easy to get good duplicate results in much less time than was possible with water.

When this stage had been reached, the writer sought the assistance of Prof. Charles S. Slichter, professor of applied mathematics in the University of Wisconsin, and after the matter was laid before him, he kindly consented to undertake a mathematical investigation of the problems involved. He devised a preliminary formula which enabled a practical test of the matter to be made, and a large amount of work was done with sorted sands whose grains were large enough to be counted in sufficient numbers to weigh, so that from their weight, number, and specific gravity their mean diameter might be computed.

While these two methods of determining the diameter of sand grains could not be expected to give identical results, they did give results which agreed quite closely, and means were then sought for putting the methods to a more rigid test.

As it is impossible to get the true diameter of the mean grains in a given sand or soil either by microscopic measurement or by counting and weighing and computing the diameter from the number, weight, and specific gravity, it seemed likely that a more rigid test might be had and a safer standard of accuracy obtained if the amount of water which should flow through the sand were computed from the amount of air which was observed to flow through the same sample. When this test was made with the apparatus represented in fig. 40 the results were again closer than had been expected.

But as E. Wollny[1] holds, as a result of some recent investigations made by himself, that the flow of water through soils does not increase directly with the pressure, it was necessary to undertake an investigation of the same problem, and this has led to the results here presented.

FLOW OF FLUIDS THROUGH RIGID POROUS MEDIA.

In the earliest efforts made in this investigation to determine the flow of water through sands it was found extremely difficult to set up an apparatus for measuring the flow in which it was possible to secure a long series of measurements extending over a range of pressures or temperatures and then to recur to the original conditions and find the same amount of flow as was at first observed.

It appeared that unless the surface of the sand grains was scrupulously clean the movement of water over them would dislodge particles of silt and move them along until they would lodge in another place in such a manner as to alter in a measurable way the volume of water discharged per unit of time.

Marked changes of temperature on account of the different coefficients of expansion of the walls of the apparatus and its contents would seem to permit a rearrangement of the sand grains as the

[1] E. Wollny: Forschungen auf dem Gebiete der Agricultur-Physik, 1891, Vol. XIV, p. 128.

water flowed through to such an extent that it was impossible to perform a series of measurements of flow at one temperature, then to change abruptly to another temperature for a second series, and finally to recur to the first and find that the same rate of flow would again be established; and, this being true, it became inadmissible to permit any important changes in temperature to occur in the apparatus during the time a particular point was being investigated.

Then, again, it is extremely difficult to use a carefully filtered distilled water over and over again for a long series of observations and keep it entirely free from dust particles, whose introduction into the sand tends to establish progressive changes in the rate of flow, and thus to obscure the law under investigation. It is further difficult to entirely expel all air from a sand, so as to leave the full cross section available for the flow of water through it, and as air so entangled is liable to be progressively removed by the water moving past it, here is a source of error which must be carefully guarded against.

On account of these difficulties it seemed desirable to do some work with an apparatus which possessed the rigid characteristics of a capillary tube, but at the same time embodied some of the peculiarities of a soil or which had capillary passages lacking the regularity and directness of capillary tubes, with which most of the careful investigations regarding capillary flow have been made.

FLOW OF WATER THROUGH WIRE GAUZE.

In order to eliminate the possibility of change of texture in the porous medium there was first set up the apparatus represented in fig. 18, consisting of three sections of brass tube 0.709 inch in diameter filled with circular disks of brass-wire gauze, woven out of wire 0.17 mm. in diameter and having rectangular meshes 0.39 by 0.34 mm. These disks were of such a diameter that they fitted the tube very closely and were rammed down one upon another until each 12-inch section was entirely filled with them. The results which were obtained from four sets of trials under pressures varying from 1 to 18 cm. of water are given in the table which follows.

Table showing the relation of pressure to flow of distilled water through 3 feet of disks of wire gauze fitted into a brass tube.

Pressure.	Temperature.	Amount of flow in 10 minutes.				Mean flow.	Computed flow.
		First trial.	Second trial.	Third trial.	Fourth trial.		
Cm.	°*C.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*
1	22.8	22.7	22.7	23.7	22.3	22.9	22.9
2	22.8	51.4	51.8	51.0	49.0	50.8	45.8
3	22.9	76.8	80.4	79.8	76.5	78.3	68.7
4	23.0	110.4	109.2	110.0	105.6	108.8	91.6
5	22.0	138.0	128.0	139.5	134.0	134.5	114.5
6	21.7	164.4	156.6	....	163.2	161.4	137.4
7	21.8	189.7	182.7	200.2	191.8	191.1	160.3
8	21.9	218.4	212.8	229.6	222.4	220.8	183.2
9	21.4	241.2	240.3	....	252.9	244.8	206.1
10	21.5	266.0	268.0	290.0	284.0	277.0	229.0
11	21.8	292.6	295.9	319.0	319.0	309.1	251.9
12	21.7	319.2	328.0	348.0	348.0	337.2	274.8
13	21.6	343.2	358.8	377.0	372.2	365.3	297.7
14	21.7	369.6	389.2	403.2	413.0	396.2	320.6
15	21.9	397.5	423.0	429.0	450.0	424.5	343.5
16	21.8	424.0	454.4	452.8	478.4	452.8	366.4
17	21.9	452.2	484.5	472.6	513.4	481.1	389.3
18	21.9	480.6	518.4	500.4	540.0	509.4	412.2

This table shows very clearly that the flow has increased in a ratio which is greater than the increase of pressure, the departure from the law of capillary flow varying from 10.92 per cent at the pressure of 2 cm. to 23.58 per cent for the five highest pressures. No corrections have been applied for temperature; but these would be very much smaller than the departure from the law. It should be said that the temperatures given in the tables are the mean of the four temperatures observed for the four trials.

The pressure gauge used consisted of a glass tube inclined, as represented in the figure, so that the readings were magnified tenfold, the scale being divided so that one-tenth of a millimeter had a length of 1 mm. The diameter of the gauge tube was nearly 5 mm. at the lower end and 4 mm. at the upper end, so that there would be a small correction which should be applied; the gage tending to make the higher pressures a very little less than they are recorded. No correction for this has been made, but were it applied the departure from the law would be made a little more than shown in the table.

There were, of course, errors growing out of errors of judgment in starting and stopping and occasionally slight changes in head would occur during the run, but the value of these are, in a measure, shown in the table.

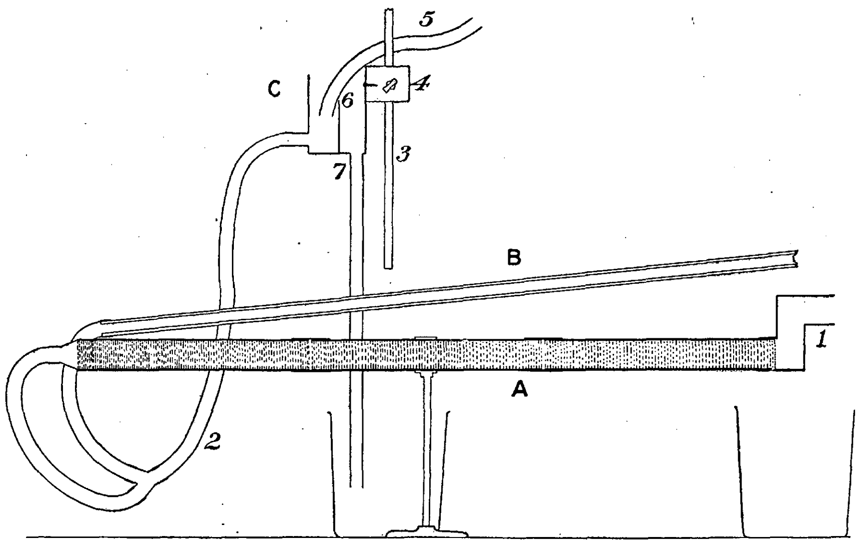


FIG. 18.—Apparatus used in studying the flow of fluids through rigid porous media. A, tube filled with wire gauze; B, pressure gage; C, overflow.

Below are given consecutive duplicate readings, which will show the variations that actually occurred.

	Pressure.	Flow in 10 minutes.	Pressure.	Flow in 10 minutes.
	Cm.	*Grams.*	*Cm.*	*Grams.*
First	1	22.6	6	164.2
Second	1	22.7	6	165.0
First	2	51.4	7	189.8
Second	2	51.4	7	189.8
First	3	77.0	8	218.3
Second	3	77.1	8	219.1
First	4	110.5	9	240.8
Second	4	110.5	9	240.8
First	5	137.9	10	265.3
Second	5	138.0	10	266.4

It is evident, however, from an inspection of the amounts of flow which occurred under corresponding pressures that from some cause a progressive change was taking place which permitted larger flows the longer the apparatus was used. This might be explained on the supposition that some air still adhered to the meshes of the wire gauze and that as the water flowed through this was being absorbed little by little.

If it were true that air still remained in the apparatus and this was the cause of the departure from the law, then the difference between the flow during the first trial and the flow during the last, under corresponding pressure, should equal the percentage departure of 23.58, which has been pointed out. The difference, however, represents only 12.4 per cent in the course of the first and last flows under a pressure of 18 cm.

It may be further supposed that if air was still adhering to the meshes of the gauze in some part of the apparatus, under the higher pressures this air would be more compressed than under the lower ones, and hence would obstruct the passage of the water less when the pressures were high and thus give rise to the phenomena observed of the flow increasing faster than the pressure. It is evident that entangled air would tend to produce a variation of the rate of flow with increase of pressure, but the differences of pressure here are too small to account for the remaining 11 per cent.

If we assume an atmospheric pressure at the time of the experiment equal to 740 mm., the increase of pressure due to the water column would be 170 mm. of water, equal to 12.5 mm. of mercury, which, added to 740, makes 752.5 mm., and this increase in pressure could reduce the volume of the air if present only about 1.69 per cent; but this could effect an increase of 1.69 per cent in the flow only when the air was actually obstructing one-half of the passageway, a condition which does not seem probable.

The next experiment consisted in shortening the same piece of apparatus to 24 inches by removing one section. In order to eliminate the influence of any progressive change which might occur there was a return to the original pressure each time after measurement of flow under a new pressure was made, and the results are given in the table which follows.

Table showing the relation of pressure to flow of distilled water through 2 feet of wire gauze contained in a brass tube.

Pressure.	Temperature.	Flow in 10 minutes.		Pressure.	Temperature.	Flow in 10 minutes.	
		Observed.	Computed.			Observed.	Computed.
Cm.	°*C.*	*Grams.*	*Grams.*	*Cm.*	°*C.*	*Grams.*	*Grams.*
18	22.1	754.3	754.56	18	21.6	672.7	652.95
17	22.2	712.6	....	8	21.6	290.2	....
18	22.2	743.7	737.89	18	21.4	663.7	642.6
16	22.2	655.9	....	7	21.4	249.9	....
18	22.0	731.9	712.08	18	21.4	656.7	636.60
15	21.9	593.4	....	6	21.2	212.2	....
18	21.8	721.8	714.34	18	21.2	653.1	632.52
14	21.7	555.6	....	5	21.1	175.7	....
18	21.7	717.5	705.19	18	20.9	640.8	618.75
13	21.7	509.3	....	4	20.8	137.5	....
18	21.7	703.4	692.1	18	20.7	638.9	588.8
12	21.7	461.4	682.2	3	20.4	99.8	....
18	21.6	692.3	....	18	20.5	627.2	584.1
11	21.6	416.9	666.0	2	20.6	64.9	....
18	21.8	677.9	....	18	20.8	634.1	592.2
10	21.9	370.0	....	1	20.8	32.9	....
18	21.8	674.7	660.8	......	....	....	....
9	21.8	330.4	....	......	....	....	....

It will be seen that here too there is an increase of flow which is more rapid than the increase of pressure, the observed flow at a pressure of 18 cm. being 7.08 per cent greater than that computed from the observed flow at 1 cm., while the percentage difference between the observed and computed flow is only 0.79 when the observed flow at 16 cm. pressure is used to compute what it should be at 18 cm.

The apparatus was again shortened until it had a length of one foot, and it was further modified by the introduction of two pressure gages 1.5 inches from either end of the tube, and the results obtained appear in the table which follows.

Table giving loss of head between gages A and B and flow of water through 12 inches of wire gauze in brass tube.

First trial.				Second trial.				Third trial.			
Temperature.	Pressure, water.	Loss of pressure between A and B.	Flow in 10 minutes.	Temperature.	Pressure, water.	Loss of pressure between A and B.	Flow in 10 minutes.	Temperature.	Pressure, water.	Loss of pressure between A and B.	Flow in 10 minutes.
° *C.*	*Cm.*	*Cm.*	*Grams.*	° *C.*	*Cm.*	*Cm.*	*Grams.*	° *C.*	*Cm.*	*Cm.*	*Grams.*
14.1	1	0.76	62.9	14.55	1	0.79	62.8	15.00	1	0.82	63.0
14.2	2	1.50	126.1	14.65	2	1.52	124.5	14.90	2	1.69	126.6
14.3	3	2.24	189.3	14.90	3	2.31	189.9	14.90	3	2.39	188.4
14.4	4	3.01	249.8	14.80	4	3.08	251.7	15.00	4	3.21	251.5
14.4	5	3.77	324.9	15.00	5	3.79	320.6	15.00	5	4.00	314.8
14.4	6	4.52	395.0	15.00	6	4.65	384.6	14.90	6	4.78	377.3
14.4	7	5.31	450.1	15.00	7	5.43	450.0	14.90	7	5.52	439.9
14.42	8	6.07	517.0	15.00	8	6.19	514.8	14.90	8	6.32	504.4
14.5	9	6.82	581.0	15.00	9	6.97	578.7	14.60	9	7.07	562.1
14.5	10	7.57	646.2	15.00	10	7.73	642.5	14.70	10	7.85	623.2
14.6	11	8.33	712.2	15.00	11	8.54	705.5	14.80	11	8.63	685.8
14.75	12	9.16	778.1	14.80	12	9.33	762.6	14.80	12	9.47	749.7
14.75	13	9.91	843.4	14.90	13	10.13	826.0	14.85	13	10.26	810.0
14.85	14	10.68	907.5	14.95	14	10.88	888.0	14.85	14	11.01	873.2
14.70	15	11.47	973.4	15.00	15	11.67	948.9	14.90	15	11.85	934.0
14.70	16	12.26	1,037.5	15.00	16	12.47	1,012.1	14.90	16	12.53	994.2
14.70	17	13.03	1,104.0	15.00	17	13.23	1,082.2	14.90	17	13.33	1,055.8
14.75	18	13.83	1,165.8	15.00	18	14.00	1,143.5	14.95	18	14.12	1,118.5
14.80	19	14.63	1,231.6	15.00	19	14.79	1,206.5	14.95	19	14.92	1,178.0
14.80	20	15.43	1,296.2	15.05	20	15.59	1,269.1	15.00	20	15.68	1,238.6
14.85	21	16.23	1,357.4	15.10	21	16.38	1,329.1	15.00	21	16.47	1,302.3
14.90	22	17.04	1,421.8	15.05	22	17.18	1,390.7	15.00	22	17.28	1,359.9
14.80	23	17.85	1,487.3	15.05	23	17.99	1,454.2	15.05	23	18.03	1,420.5
14.85	24	18.63	1,550.0	15.10	24	18.79	1,513.8	15.00	24	18.82	1,480.1
14.90	25	19.42	1,614.6	15.10	25	19.57	1,574.1	15.05	25	19.63	1,540.3
14.95	26	20.26	1,675.6	15.10	26	20.38	1,634.4	15.05	26	20.40	1,599.2
14.95	27	20.89	1,740.4	15.10	27	21.25	1,695.5	15.05	27	21.28	1,660.2
14.95	28	21.92	1,802.4	15.10	28	22.06	1,757.1	15.10	28	22.08	1,718.2
15.00	29	22.72	1,866.9	15.10	29	22.90	1,816.8	15.10	29	22.85	1,779.6
15.00	30	23.57	1,929.4	15.20	30	23.70	1,880.7	15.10	30	23.67	1,839.1

In these experiments and the foregoing the temperature was taken with the thermometer placed in the receptacle for maintaining the constant head shown in fig. 19, and the work was done in a constant temperature room built in a subcellar under the center of the physical laboratory, the light coming from electric lamps. The water used was distilled and kept in a closed copper reservoir suspended near the ceiling of the room and having a capacity of about 1.5 cubic feet. The discharge from this reservoir was controlled by a cock, and the water discharged first into a filter of coarse sand and then into the overflow vessel shown in the cut. The water, after passing through the apparatus, was caught in glass beakers, weighed on a pair of torsion balances sensitive to 0.1 gram, and then returned to the reservoir to be used again.

To assist in making the fine adjustment of head, the bar carrying the overflow was provided with a joint which permitted it to be flexed, and thus to be raised or lowered very small amounts after the desired level had been nearly secured with the set screw. The pressures in the internal gages were read directly from the tubes, which carried a scale made from paper ruled in centimeters and millimeters, the same paper being used to make the scale on the long inclined gage tube. The errors in reading the two internal gages are therefore likely to be greater than those for the other gage.

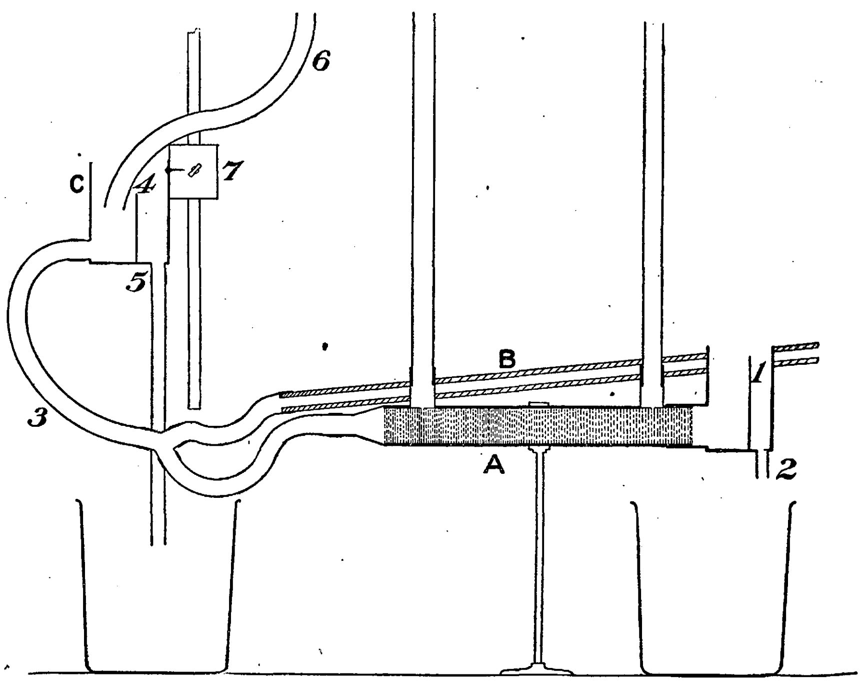


FIG. 19.—Second apparatus of wire gauze, with two internal pressure gages; A, tube with wire gauze and internal gages; B, pressure gage; C, overflow with wier 4 and outlet 5; 7, set screw for adjusting head; 6, supply tube; 1, discharge wier with outlet 2.

It will be observed from the table that there were still progressive changes going on in the apparatus, but these were not nearly so large as they were when the 2 feet of tube was used, the changes being in the opposite direction from those which occurred during the trials made with the full length of tube.

We will now bring into another table the computed and observed flows, and also the computed and observed losses of pressure between the two internal gages.

Table showing mean temperature, pressure, loss of pressure between internal gages, and mean flow for ten minutes, together with the computed flow and loss of head between internal gages.

Mean temperature.	Mean pressure, water.	Mean loss of pressure between internal gages.		Mean flow.		Departure from law of Poiseuille.	
		Observed.	Computed.	Observed.	Computed.		
°C.	Cm.	Grams.	Grams.	Grams.	Grams.	Grams.	Per cent.
14.55	1	0.79	0.79	62.9	62.9	0.0	0.0
14.58	2	1.57	1.58	125.7	125.8	— .1	.0795
14.70	3	2.31	2.37	189.2	188.7	.5	.2650
14.73	4	3.10	3.16	251.0	251.6	— .6	.2385
14.80	5	3.85	3.95	320.1	314.5	5.6	1.7810
14.76	6	4.65	4.74	385.6	377.4	8.2	2.1730
14.76	7	5.42	5.53	446.6	440.3	6.3	1.4310
14.77	8	6.19	6.32	512.0	503.2	8.8	1.7490
14.70	9	6.95	7.11	573.9	566.1	7.8	1.378
14.73	10	7.72	7.90	637.3	629.0	8.3	1.320
14.80	11	8.50	8.69	701.1	691.9	9.2	1.330
14.78	12	9.29	9.48	763.4	754.8	8.6	1.139
14.80	13	10.10	10.27	826.4	817.7	8.7	1.064
14.88	14	10.86	11.06	889.5	880.6	8.9	1.011
14.86	15	11.65	11.85	952.1	943.5	8.6	.9115
14.86	16	12.42	12.64	1,014.6	1,006.4	8.2	.8151
14.86	17	13.20	13.43	1,080.6	1,069.3	11.3	1.057
14.90	18	13.98	14.22	1,142.6	1,132.2	10.4	.9187
14.91	19	14.78	15.01	1,205.4	1,195.1	10.3	.8619
14.95	20	15.57	15.80	1,268.0	1,258.0	10.0	.7949
14.98	21	16.36	16.59	1,329.6	1,320.9	8.7	.6586
14.98	22	17.17	17.38	1,390.8	1,383.8	7.0	.5058
14.96	23	17.96	18.17	1,454.0	1,446.7	7.3	.5045
14.98	24	18.75	18.96	1,514.6	1,509.6	5.0	.3311
15.01	25	19.54	19.75	1,576.3	1,572.5	3.8	.2416
15.03	26	20.35	20.54	1,636.4	1,645.4	1.0	.0612
15.03	27	21.14	21.33	1,698.7	1,698.3	.4	.0236
15.05	28	22.02	22.12	1,759.2	1,761.2	— 2.0	.1136
15.06	29	22.82	22.91	1,821.1	1,824.1	— 3.0	.1645
15.10	30	23.65	23.70	1,883.1	1,887.0	— 3.9	.2067

The loss of head between the two internal gages, it will be seen, was very regular throughout the whole series. This fact is brought out clearly by column 4 in the table, which is computed on the supposition that the loss of head within the tube is directly proportional to the pressure as measured by the outer gage, and the 29 values in the column headed "Computed" are obtained by multiplying the first number (0.79) by the pressures from 1 up to 30.

It will be seen that these computed values agree very closely with those which were observed, but in every case are somewhat larger, though not uniformly so. In the column of computed flows the values are derived from the first observed flow by multiplying by the successive pressures under which the observed flows were produced.

It will be seen that while the flow of water through this section conforms quite closely to the law of Poiseuille there is nevertheless a measurable departure from it which is too regular and persistent to be attributed to errors of observation.

It is noteworthy that under pressures of 1, 2, 3, and 4 cm. of water the departure from the law of Poiseuille is not greater than 0.2 of 1 per cent, but beyond this, and until a pressure of 22 cm. is reached, the flow is on the average 1 per cent faster. The flow then comes closer and closer to the law, until finally a nearly complete agreement is reached at a pressure of 27 cm. Beyond this point, however, although the agreement is very close, a departure from the law in the opposite direction is evidently setting in, and while this change is due in part to the slight apparent progressive decrease in flow through the apparatus, which is shown by the table of original data, this can hardly be responsible for the whole of the change.

At a later time measurements were made of the flow of water through this section under much higher pressures, but these also differed among themselves through quite wide limits. In order to eliminate the effect of any progressive change which might occur, the flows were measured under alternately high and low pressures, but the results are placed in the table in the order of the pressures and are numbered from 1 to 19 in the order of the experiment. Clear well water was used, filtered through the apparatus represented in fig. 30, and the pressures were taken as there described, but are here expressed in centimeters for comparison with the other results.

The table which follows contains both the observed flows and those computed from the mean of the flows under the lowest pressure, assuming Poiseuille's law to hold good for the full range of pressures.

Table showing the flow of water through 12 inches of wire gauze in brass tube.

Number of trial.	Pressure of water.	Tempera-ture.	Observed flow per minute.	Computed flow per minute.	Percentage departure in—	
					Grams.	Per cent.
	Cm.	°*C.*	*Grams.*	*Grams.*		
2	88.16	15.1	360.6	360.6	....	....
20	115.9	14.0	493.5	474.0	19.5	4.16
4	147.4	15.4	707.6	602.8	104.8	17.39
6	176.3	15.1	772.0	721.2	50.8	7.04
8	201.6	14.9	881.3	824.6	56.7	6.88
10	229.3	14.5	994.7	938.0	56.7	6.05
12	259.9	14.7	1,111.6	1,063.2	48.4	4.55
14	290.2	14.8	1,212.0	1,186.6	25.4	2.14
16	322.2	14.7	1,315.0	1,318.2	— 3.2	— .24
18	490.9	14.5	1,876.0	2,008.1	—132.1	— 6.58
17	525.7	14.7	1,999.0	2,155.1	—156.1	— 7.24
15	564.2	14.8	2,103.0	2,307.5	—204.5	— 8.89
13	581.6	15.1	2,212.0	2,378.7	—166.7	— 7.01
11	639.1	15.1	2,326.0	2,614.1	—288.1	—11.02
9	679.7	15.2	2,406.0	2,780.1	—374.1	—13.46
7	714.5	15.4	2,504.0	2,922.1	—418.1	—14.31
5	750.5	15.5	2,606.0	3,069.5	—463.5	—15.10
3	785.6	15.3	2,679.0	3,213.3	—534.3	—18.66
1	88.16	14.2	....	....	....	....
19	785.6	13.8	....	....	....	....

At a still later time, when freshly boiled water was being used to avoid the possibility of air clogging, the flow of water was again measured through two sections of the brass tube filled with the gauze. The water when used was still quite hot, as the table shows.

Table showing the flow of water in grams per minute through 2 feet of wire gauze in a brass tube.

Pressure of water.	Tempera-ture.	Observed flow at temperature of—		Computed flow at temperature of—	
		Experiment.	15° C.	Experiment.	15° C.
Cm.	°*C.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*
90.94	54	487.5	224.7	487.5	299.2
201.8	55	909.9	400.4	1,088.9	663.8
311.5	55	1,251.1	576.5	1,684.1	1,025.0
411.5	56	1,460.3	672.8	2,138.4	1,354.0
494.4	56	1,689.7	778.8	2,667.5	1,626.0
603.8	56	2,006.7	924.9	3,485.3	1,987.0
723.3	56	2,186.0	1,007.3	3,665.0	2,380.0
916.5	56	2,476.8	1,141.5	4,968.3	3,015.0

The data of these two tables show an extremely wide departure from a flow directly proportional to the pressure. Indeed, in the case of the 2-foot tube there is a departure of 19.67 per cent in passing from a head of 90.94 cm. to 201.8 cm., while under a head of 916.5 cm. the observed flow is less than one-half that which is computed.

In fig. 20 these observations have been plotted, using the pressures as abscissas and the flow as ordinates. In the lower portion of the cut the flows under the lower pressures are plotted, and conjectural ones are interpolated to meet the observations made under higher pressures, while in the upper portion the full curves are plotted on a more reduced scale. The straight solid lines are drawn at the slope which indicates a flow proportional to the pressure, and they express clearly the wide departures from the law which sets in at relatively very low pressures.

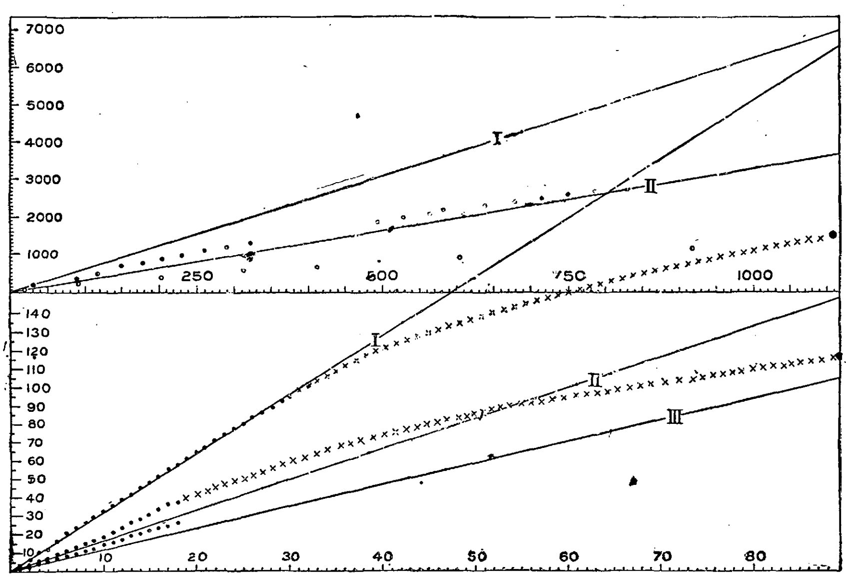


FIG. 20.—Curves of flow of water through wire gauze. Lines I, II, III show increase of flow, computed from Poiseuille's law, for sections 1, 2, and 3 feet long. Circles and crosses show observed flow. Abscissas indicate pressure in centimeters and ordinates flow in grams.

The wire gauze was chosen for these trials as something which presented passageways for the water sufficiently different from capillary tubes on the one hand and which yet insured some of the characteristics of the lines of flow which must exist in a mass of sand, at the same time precluding any rearrangement of parts either with the movement of water or with changes in temperature.

FLOW OF FLUIDS THROUGH DISKS OF PERFORATED BRASS.

The next piece of apparatus used is represented in fig. 21, and is made in such a manner that the flow takes place through a definite number of circular openings, all of the same size, and held rigidly in one position, which can not be changed.

Circular disks 1.5 inches in diameter were cut from perforated sheet brass, having openings 0.451 mm. in diameter, and so placed that 534 perforations occupied a circle 1 inch in diameter. One hundred of these circular disks were brought together so as to form a cylinder, the disks being separated by brass washers, each 1.5 inches in diameter, having a circular opening 1 inch in diameter and cut from sheet brass having a thickness a little less than the diameter of the openings in the perforated brass. The center washer of the pile had a section cut from it so as to leave an opening through which the pressure might be taken out. In this condition the 100 perforated disks and the 101 washers were brought together in a vice and pressed firmly together, while the edges of the disks and washers were soldered together so as to form a cylinder having 534 lines of perforations and 53,400 holes through which fluids could be passed; but as no effort was made to place the holes in lines the lines of flow would not be perfectly straight and parallel.

The figure represents the apparatus set up with five of the sections described, placed together end to end, each provided with a pressure gage, as shown. When used in this way the fluid may be considered as flowing along 534 somewhat parallel though not straight lines, each stream being obliged to enter and emerge from 500 short capillary tubes, each having a length less than the diameter.

The first series of measurements of flow was made with kerosene instead of water in order to avoid the possibility of electrolytic action, which might possibly clog the holes, and the two end sections only were used. To avoid disturbances which the end influence might be supposed to make in the readings of the pressure, the overflow was so adjusted as to produce a difference of pressure between the centers of the two sections used of 1, 2, 3, and 4 cm. of kerosene. This arrangement made the measuring of the pressure take place just 50 disks back from either end and measured the loss of head between 100 disks. The flow was measured under four pressures, and three 10-minute readings were taken in each case, giving the results stated below:

Pressure.	Time.	Temperature.	Observed flow.	Computed flow.
Cm.	*Minutes.*	°*C.*	*Grams.*	*Grams.*
1	10	19.5	196.2	196.2
2	10	19.6	392.5	392.4
3	10	19.4	589.6	588.6
4	10	19.2	784.7	784.8

The flows follow quite closely an increase proportional to the pressure.

After these measurements of flow were made the full battery of pieces was set up, as represented in fig. 21, and the flow was measured under pressures of 4, 8, 12, 16, 20, and 24 cm., and at the same time the pressures at the several internal gages, A, B, C, D, E, F, and the external one, K, were also read and the results are given in the following table:

Table showing relation of pressure to flow of kerosene through disks of perforated brass.

Temperature.	Time.	Pressure.							Flow.		Percentage departure.
		A	B	C	D	E	F	K	Observed.	Computed.	
°C.	*Min.*	*Cm.*	*Cm.*	*Cm.*	*Cm.*	*Cm.*	*Cm.*	*Cm.*	*Grams.*	*Grams.*	
17	10	0.4	0.9	1.5	2.1	2.7	3.3	4	121.4	121.4	....
17	10	.8	1.8	3.0	4.3	5.5	6.9	8	236.9	242.8	2.430
17	10	1.3	2.9	4.7	6.9	8.7	10.4	12	355.2	364.2	2.471
17	10	1.7	3.8	6.3	9.3	11.5	14.1	16	473.1	485.6	2.574
17	10	2.2	5.0	8.0	11.6	14.3	17.5	20	585.3	607.0	3.575
17	10	2.6	5.8	9.8	14.3	17.8	21.0	24	699.3	728.4	3.995

In this case the table shows that the flow does not increase so rapidly as the pressure does, the departure being nearly 4 per cent at a pressure of 24 cm., while at 8 cm. the departure from the law is 2.43 per cent.

As the flow was so rapid through this apparatus, and as there was so much danger of clogging from chemical action if water were used,

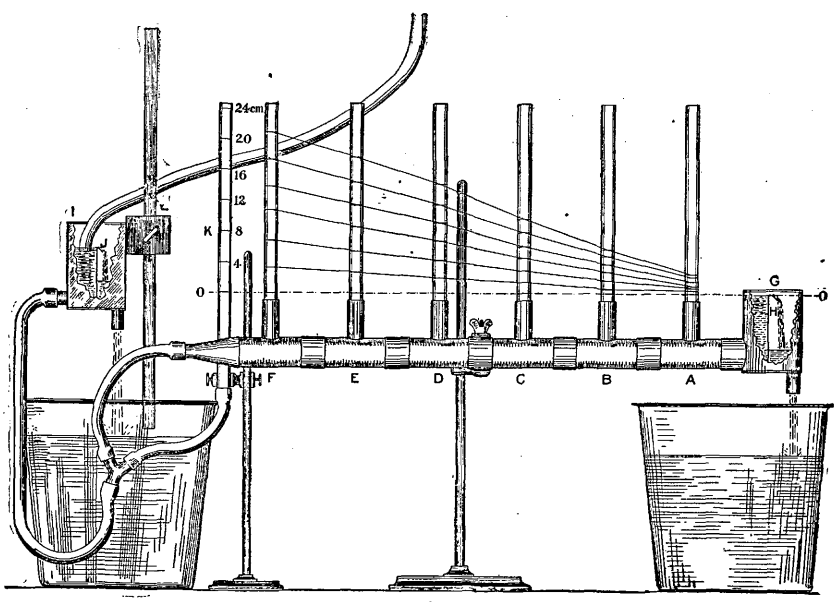


FIG. 21.—Apparatus of perforated brass disks. A, B, C, D, E, F, sections with internal pressure gages; G, H, discharge; I, J, supply; K, external pressure gage.

there appeared to be little prospect of getting decisive results with it and it was abandoned.

One of the sections, however, was mounted in the manner described in another place and the flow of water through it was measured under pressures ranging from 1 foot of water up to more than 50 feet; these measurements are given in the next table.

Table showing the relation of pressure to flow of water through 100 disks of perforated brass.

Temperature.	Pressure of water.	Flow per minute.		Temperature.	Pressure of water.	Flow per minute.	
		Observed.	Computed.			Observed.	Computed.
°C.	Feet.	Pounds.	Pounds.	°C.	Feet.	Pounds.	Pounds.
11.0	1.0	1.69	1.69	9.75	11.0	9.42	18.59
10.5	2.0	3.295	3.38	9.6	12.0	9.79	20.28
10.5	3.0	3.725	5.07	9.6	13.0	10.27	21.97
10.1	5.0	5.550	8.45	9.6	14.0	10.70	23.66
10.0	6.0	6.420	10.14	9.6	15.0	10.98	25.35
9.9	7.0	7.145	11.74	9.5	20.59	13.75	34.80
10.0	8.0	7.800	13.52	10.6	33.96	17.99	57.39
9.9	9.0	8.23	15.22	10.9	44.26	20.48	74.80
10.1	10.0	8.55	16.90	9.7	52.70	22.03	89.06

Here it will be seen that the flow, after a pressure of 2 feet has been exceeded, falls far short of increasing in proportion to the pressure.

Air flowed through this same section under a constant pressure of 1 cm. and a temperature of 13° C. at the mean rate of 4,285.7 c. c. per minute as a mean of five trials.

FLOW OF FLUIDS THROUGH MADISON SANDSTONE.

In November, 1897, we had a piece of very friable Madison sandstone shaped into a cylinder 4.2 cm. in diameter and 4.7 cm. long, and this was cemented into a piece of gas pipe provided with reducers and hose couplings so that it could be connected with the hose bib faucets on the several floors of the laboratory. Sulphur was used to seal the stone in the pipe, it being melted and poured around the specimen, thus making a water-tight joint between the metal and the stone. Two series of trials were made with this specimen, which are recorded in the table below. Well water stored in a tank was used for these trials, and the apparatus was connected directly to the faucets on the several floors of the laboratory in order to vary the pressure in these preliminary trials.

Table showing relation of pressure to flow of water through Madison sandstone No. 1.

First series.					Second series.				
Number of trial.	Time.	Temperature.	Pressure of water.	Flow.	Number of trial.	Time.	Temperature.	Pressure of water.	Flow.
	Min.	°*C.*	*Feet.*	*C. c.*		*Min.*	°*C.*	*Feet.*	*C. c.*
1	10	24.1	32.333	3,550	1	10	23.6	55.75	4,860
2	10	24.1	32.333	3,300	2	10	23.0	55.75	4,820
3	10	24.1	32.333	3,190	3	10	27.1	47.25	4,110
4	10	24.1	32.333	3,108	4	10	24.8	47.25	3,930
13	10	24.1	32.333	2,675	5	10	20.8	36.33	2,570
5	10	22	19.083	1,380	6	10	20.0	36.33	2,550
6	10	22	19.083	1,410	7	10	18.25	23.083	1,410
7	10	19	4.833	260	8	10	16.0	23.083	1,350
8	10	19	4.833	250	9	10	13.5	8.833	400
9	10	23	43.25	4,100	10	10	25.5	55.75	4,520
10	10	23	43.25	3,910	11	10	25.5	55.75	4,320
11	10	15	51.75	4,440					
12	10	15	51.75	4,400					

From this table it will be observed that the flow, besides varying with the pressure, also tends to decrease the longer the water is allowed to flow, and the proof of the decrease is found in the fact that a return to the original pressure shows a smaller discharge; but the surprising feature of this table is that it shows, in spite of the tendency of the flow to decrease with time, a marked tendency to increase faster than the pressure. This fact is more clearly brought out in the table next given, where the several flows under the same pressures have been averaged and computed to a flow at a temperature of 15°, and the flow called for by Poiseuille's law is also computed from that which would have taken place under the lowest pressure in each series had the temperature been 15°.

Table showing the relation of mean flow to pressure through Madison sandstone No. 1.

Mean and computed flow, first trial.					Mean and computed flow, second trial.				
Time.	Temperature.	Pressure.	Observed flow.	Computed flow.	Time.	Temperature.	Pressure.	Observed flow.	Computed flow.
Min.	° *C.*	*Cm.*	*Grams.*	*Grams.*	*Min.*	° *C.*	*Cm.*	*Grams.*	*Grams.*
10	15	130.7	227.7	227.7	10	15	703.5	1,298.0	1,061.0
10	15	581.6	1,153.0	898.9	10	15	1,107.0	2,203.0	1,670.0
10	15	985.4	2,486.0	1,523.0	10	15	1,440.0	3,023.0	2,173
10	15	1,318	3,230	2,038.0	10	15	1,699	3,875.0	2,563
10	15	1,577	4,420	2,438	10	15	1,699	3,379	2,563
10	15	269.2	406.1	406.1					

The amount of departure of the flow computed from that which took place under the lowest pressure in each of the two series is shown by the departure of the two curves from the two straight lines I and II in fig. 22, where, did the Poiseuilleian law hold, all observed flows should when plotted fall upon the two straight lines. It will be seen that the flow increases faster than the pressure in spite of the fact that there had been a progressive decline in the amount of discharge under like pressures.

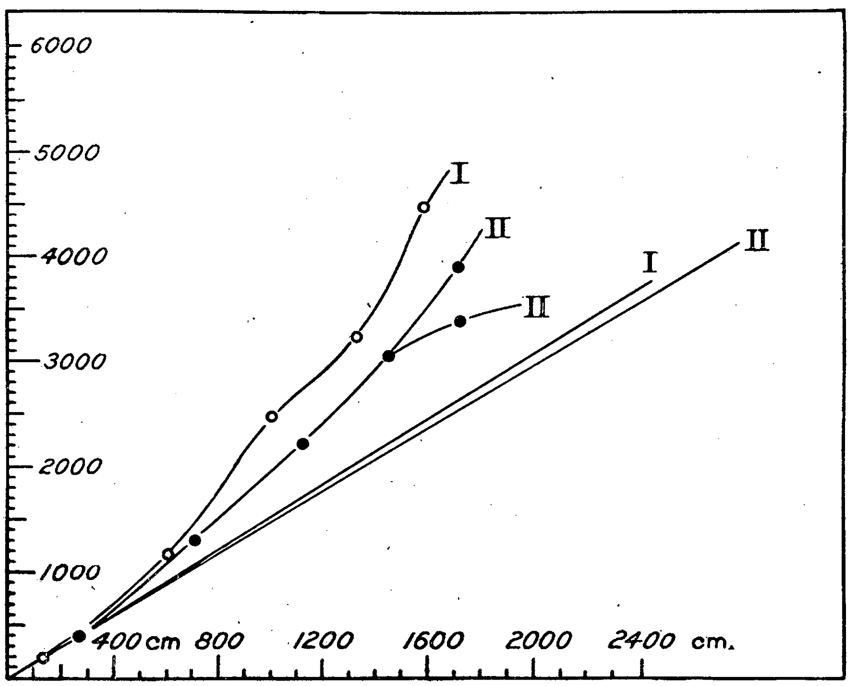


FIG. 22.—Curves of flow of water through Madison sandstones No. 1. Straight lines I, II, Poiseuilleian lines; dark and light circles, connected by broken lines I, II, observed flow. Abscissas indicate pressure in centimeters and ordinates flow in grams.

FLOW OF WATER AND OIL THROUGH ROCK, AS DETERMINED BY NEWELL.

After the results just cited were reported to Mr. F. H. Newell, he kindly forwarded for examination a Thesis on the Geology of Bradford Oil Rocks; some Experiments Pertaining to their Structure and Capacity to Furnish Petroleum, which he prepared in 1885. As this thesis contains the earliest experimental data with which the writer is acquainted bearing upon the relation of the flow of fluids through rock to pressure, some of these will be here cited, Mr. Newell having kindly consented to permit their free use.

The apparatus which Newell finally adopted for obtaining his experimental data is represented by figs. 23 and 24 and the "preliminary tests" which he made with these pieces give the results which have the most important bearing upon the present discussion.

The results first presented were obtained with the apparatus shown in fig. 23, in which he used two pieces of stone from Amherst, Ohio, "probably from the Berea grit."

The Amherst stone is a light yellow sandstone, quite free working, though showing well-marked lines of stratification. It is very porous and pervious, and was used because not only near at hand, but cut easily and was pervious enough to be used in thick pieces up to 1½ inches without difficulty.

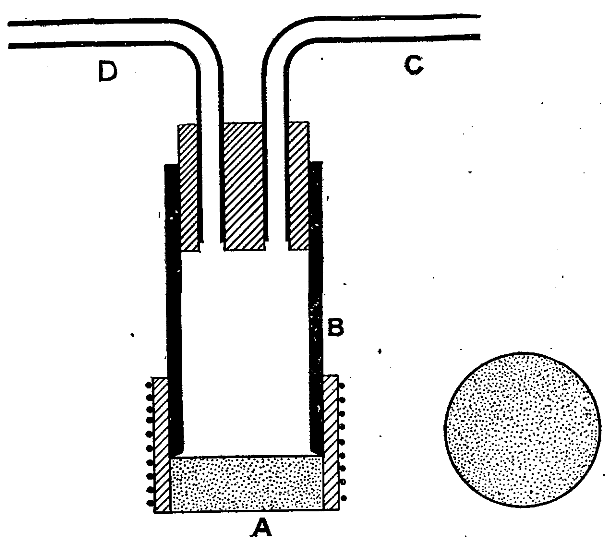


FIG. 23.—First apparatus used by Newell in studying the flow of water and oil through rock. A, A, sample of stone; B, glass tube; C, supply; D, pressure gage.

The grains are very uniform in size. It contains considerable clay and has very numerous spots of iron rust arranged in bands parallel to stratification.

The specimens were ground down to 0.5 inch and then cut into disks equaling the outside diameter of the short glass cylindrical tubes. Specimen A5 was cut with flat faces at right angles to plane of stratification; A6 parallel to stratification.

There is no statement in the paper giving the exact diameters of these specimens, but the drawing indicates that they were 1.5 inches. In making the tests distilled water was used, which was caught in beakers, and the amount flowing through was determined by weighing. The following table contains the data obtained from ten trials under five pressures with each of the two specimens:

Table showing the relation of pressure to flow of water through Amherst sandstone, by Newell.

Time.	Pressure.		Flow along bedding plane A5.					Flow across bedding plane A6.				
	Mercury.	Water.	Observed flow.	Total observed flow.	Computed flow.	Departure.		Observed flow.	Total observed flow.	Computed flow.	Departure.	
Min.	*In.*	*Cm.*	*C. c.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*	*C. c.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*
30	2	......	1.72	......	......	......	......	0.45	1.06	......	......	......
30	2	69	1.56	3.28	3.28	0.00	0.00	.61	......	1.06	0.00	0.00
30	4	......	3.48	......	......	......	......	1.13	......	......	......	......
30	4	138	3.31	6.79	6.56	.23	3.51	1.13	2.26	2.12	.14	6.60
30	8	......	7.68	......	......	......	......	2.62	......	......	......	......
30	8	276	6.51	14.19	13.12	1.07	8.16	2.49	5.11	4.24	.87	20.52
30	16	......	15.08	......	......	......	......	5.79	......	......	......	......
30	16	552	11.92	27.00	26.24	.76	2.70	4.76	10.55	8.48	2.07	24.41
30	32	......	34.24	......	......	......	......	11.14	......	......	......	......
30	32	1,104	32.90	67.14	52.48	14.66	27.93	10.74	21.88	16.96	4.92	29.01

It will be observed that the rate of flow through the stone was much faster in the section where the movement took place along the planes of stratification, and this is as would be expected if there was any difference in the structure corresponding to the bedding planes, for if some layers were finer grained than others, or if certain layers were more completely silted up than others, these would be the chief factors in determining the rate of flow through the whole specimen in the case where the flow is across the bedding planes, because no more water could pass the more open layers than was able to pass those of the closest texture, but where the flow was taking place along the bedding planes each particular stratum could carry water in proportion to the coarseness of its texture, uninfluenced by any other.

These observations, therefore, bring out one important principle, in that they show that, as a general rule, the rate of flow of water through rock will be relatively more rapid along horizontal or slightly inclined bedding planes than across them.

This principle is particularly important in its bearing upon the digging of wells of all kinds, for it emphasizes the importance of penetrating as deeply as possible the water-bearing strata, not only to utilize a greater head, but to take advantage of the fact that water may approach the well faster under the same head when it can move along bedding planes.

It is very clear from the table, in spite of the gradual retardation of flow which occurred with both specimens as the trials were repeated, that the flow increased faster than the pressure, the percentage departure in general increasing in both cases with the pressure. It will be seen that at a pressure of 1,104 cm. of water the percentage departure

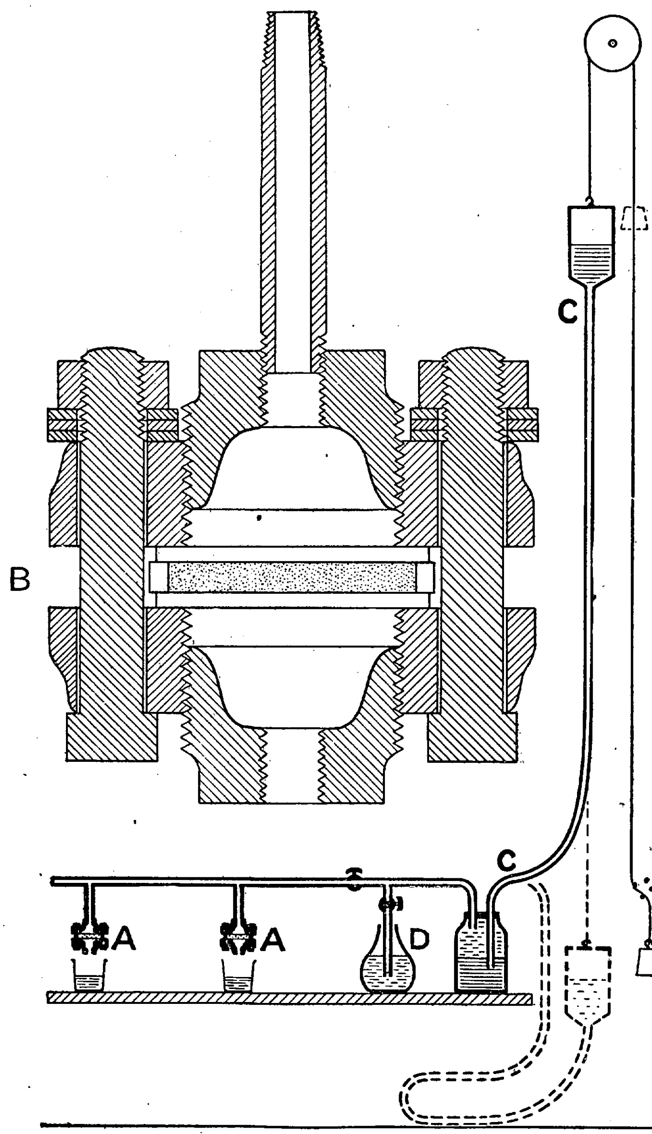


FIG. 24.—Second apparatus used by Newell in studying the flow of water and oil through rock. A, A, mounting for holding sample; B, same as A, natural size; C, mercury flask and bottle for varying pressure; D, flask for refilling C.

was nearly 28 per cent where the flow was along the bedding plane and 29 per cent when it was across the stratification.

In fig. 25 these departures are clearly shown by the straight and curved lines there plotted.

The next series of experiments made by Newell were with kerosene, the apparatus represented and described in fig. 24 being used. The rocks through which the flow took place were specimens A3 and A4 of Amherst stone, 0.5 inch thick. Specimen A3 was cut with its sur-

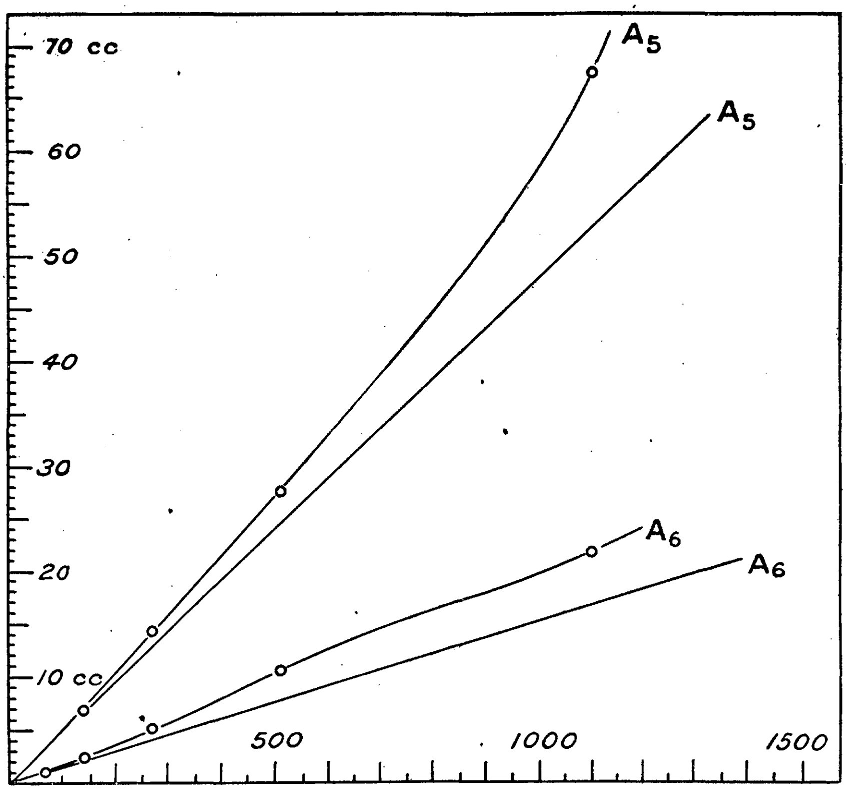


FIG. 25.—Flow of water through Amherst sandstone, A5 and A6. Straight lines show theoretical flow; circles, observed flow. Abscissas indicate pressure in centimeters, ordinates flow in cubic centimeters.

faces at right angles to the stratification, while A4 was cut with surfaces parallel to the stratification. Both specimens were 2 inches in diameter.

The pore space of A3 was determined to be 19.34 per cent and that of A4 18.98 per cent. The oil used was kerosene, having a specific gravity of 0.836. Newell states that tests made before those recorded in the following table showed that A3 was more permeable than A4, but that it must have become more easily clogged.

Table showing the relation of pressure to flow of kerosene through Amherst sandstone.

Time.	Pressure.		Flow along bedding plane A3.				Flow across bedding plane A4.			
	Mercury.	Water.	Observed flow.	Computed flow.	Departure.		Observed flow.	Computed flow.	Departure.	
Min.	*Inches.*	*Cm.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*
	3	98.3	13.9	13.9	0.00	....	13.4	13.4	0.00	....
2	6	197.0	26.9	27.8	− .9	3.237	26.4	26.8	− .4	1.493
	9	295.5	40.2	41.7	− 1.5	3.597	41.4	40.2	+ 1.2	2.985
2	12	394.0	52.0	55.6	− 3.6	6.475	56.0	53.6	+ 2.4	4.478
	15	492.5	64.2	69.5	− 5.3	7.626	75.0	67.0	+ 8.0	11.94
2	18	591.0	71.2	83.4	−12.2	14.63	81.4	80.4	+ 1.0	12.44
	18	591.0	71.2	69.6	+ 1.6	2.299	81.4	68.4	+13.0	19.01
2	15	492.5	58.4	58.0	+ .4	.690	65.0	57.0	+ 8.0	14.04
	12	394.0	45.4	46.4	− 1.0	2.155	50.0	45.6	+ 4.4	9.649
2	9	295.5	33.9	34.8	− .9	2.586	36.2	34.2	+ 2.0	5.848
	6	197.0	23.0	23.2	− .2	.862	24.0	22.8	+ 1.2	5.263
2	3	98.5	11.6	11.6	− 0.00	0.00	11.4	11.4	0.00	0.00

It is evident from this table that when the kerosene was flowing through the rock across the bedding planes the rate increased more

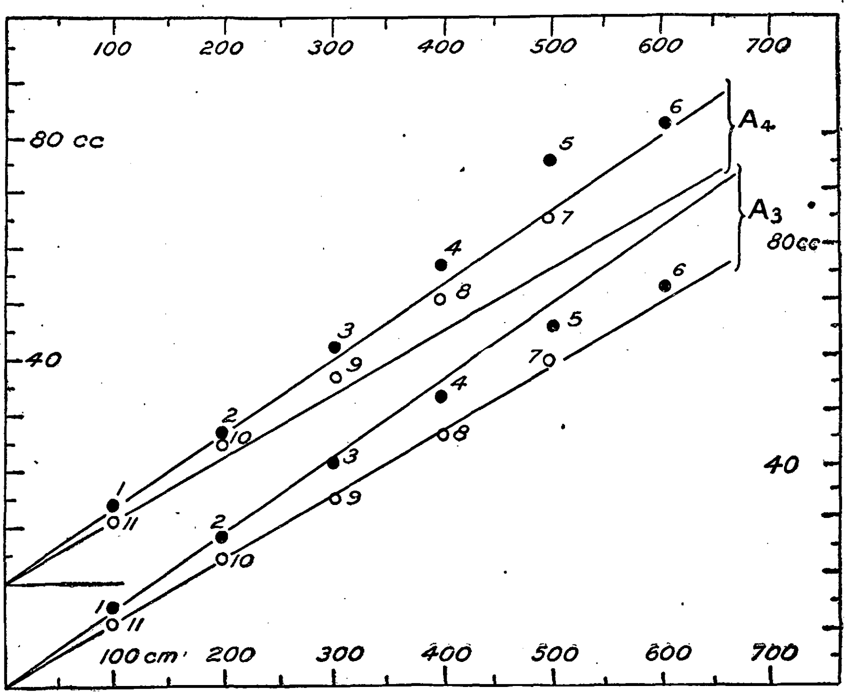


FIG. 26.—Flow of kerosene through Amherst sandstone, A3 and A4. Upper straight lines show theoretical flow, first half of experiment; lower straight lines for second half. Circles and dots show observed flow; numbers show order of experiment. Abscissas indicate pressure, ordinates measured from the scale on the right the flow in the case of A3, and from the scale on the left the flow in the case of A4.

rapidly than the pressure, and sufficiently so as not to be overcome by the clogging of the stone, which was in progress. On the other hand, where the lines of flow were parallel with the bedding planes the flow increased less rapidly than the pressure, and this was even true when the theoretical flows were computed from the last low-pressure observation, as shown in the lower half of column headed "Computed flow." The flows are plotted in fig. 26.

Another set of tests were made with these same specimens, in which Newell used "crude pipe-line oil" having a specific gravity of 0.848, and his results are given in the next table.

Table showing the relation of pressure to flow of crude pipe-line oil through Amherst sandstone.

Time.	Pressure.		Flow along bedding plane A3.				Flow across bedding plane A4.			
	Mercury.	Water.	Observed flow.	Computed flow.	Departure.		Observed flow.	Computed flow.	Departure.	
Min.	*Inches.*	*Cm.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*
1	6	197.0	2.23	2.23	0.00	0.00	4.50	4.50	0.00	0.00
1	9	295.5	3.13	3.345	— .215	6.427	6.13	6.75	— .62	9.185
1	12	394.0	4.10	4.460	— .360	8.072	8.07	9.00	— .93	10.33
1	15	492.5	5.10	5.575	— .475	8.52	9.60	11.25	—1.65	14.67
1	18	591.0	6.70	6.69	+ .010	1.495	11.37	13.50	—2.13	15.78
1	21	689.5	7.50	7.805	— .305	3.908	14.20	15.75	—1.55	9.841
1	24	788.0	8.30	8.92	+ .62	6.951	14.50	18.00	+3.50	19.44
1	24	788.0	8.30	4.00	+4.30	10.75	14.50	10.92	+3.58	32.77
1	21	689.5	6.60	3.50	+3.10	88.57	12.60	9.555	+3.045	31.86
1	18	591.0	4.70	3.00	+1.70	56.67	9.90	8.19	+1.71	20.88
1	15	492.5	3.10	2.50	+ .60	24.00	7.80	6.825	+ .975	14.28
1	12	394.0	2.25	2.00	+ .250	12.50	5.75	5.46	+ .29	5.311
1	9	295.5	1.50	1.50	.00	.00	4.20	4.095	+ .105	2.565
1	6	197.0	1.00	1.00	.00	.00	2.73	2.73	0.00	0.00

In this set of trials the results are not decisive, because the rate of clogging is so rapid as to cover any tendency of the flow to increase more rapidly than the pressure. It is true, however, that were it admissible to average the two observations which were taken under the same pressure, in most cases the flow would appear to increase more rapidly than the pressure. The flows are plotted in fig. 27.

After having made these tests with oil Newell again returned to water, using a piece ("K") of red Triassic sandstone from the Connecticut valley, which is largely used as a building stone. "The specimen was comparatively fine grained, quite uniform in size of particles, and showed no stratification."

The stone was 0.3 inch thick, 2 inches in diameter, and had a pore space of 13.10 per cent.

The other piece used ("B") "was a yellow friable sandstone from Bradford, Pa., coming from one of the sandstone layers in the conglomerate below the Olean. It contained some clay and grains were of irregular size, well rounded." The thickness of the specimen was 0.54 inch; it was 2 inches in diameter and had a pore space of 15.34 per cent.

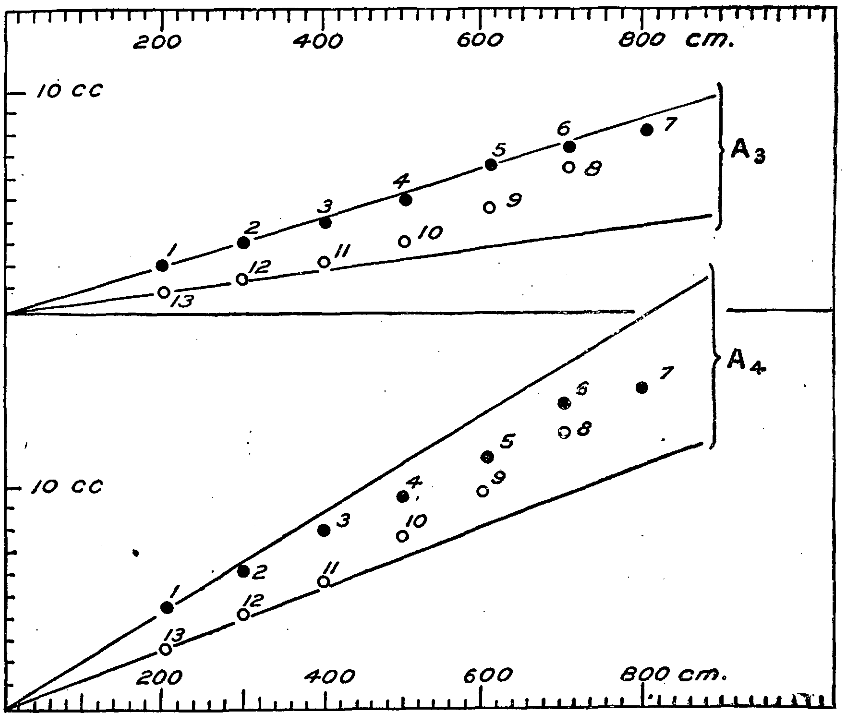


FIG. 27.—Flow of crude pipe-line oil through Amherst sandstone, A3 and A4. Upper straight lines show theoretical flow, first half of experiment; lower straight lines for second half. Circles and dots show observed flow; numbers show order of experiment. Abscissas indicate pressure and ordinates flow.

Newell made a long series of tests with these two stones, frequently reversing them to investigate the cause of clogging, and we select from his table the results of a number of tests under the several pressures used, as stated in the column "Number of trials." These we have averaged and have reduced them to a common period of thirty minutes.

Table showing the relation of pressure to flow of water through sandstone.

Number of trial.	Time.	Pressure.		Triassic sandstone "K."				Bradford sandstone "B."			
		Mercury.	Water.	Observed flow.	Computed flow.	Departure.		Observed flow.	Computed flow.	Departure.	
	Min.	*Inches.*	*Cm.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*
5	30	6	197	10.1	10.1	0.0	0.0	2.45	2.45	0.0	....
4	30	12	394	35.625	20.2	15.425	76.19	5.863	4.90	.963	19.65
2	30	18	591	73.4	30.3	40.1	132.3	13.4	7.35	6.05	82.31
13	30	24	788	67.915	40.4	27.515	68.12	24.18	9.80	14.38	146.7

In these cases there is a marked tendency for the flow to increase faster than the pressure, as shown in fig. 28.

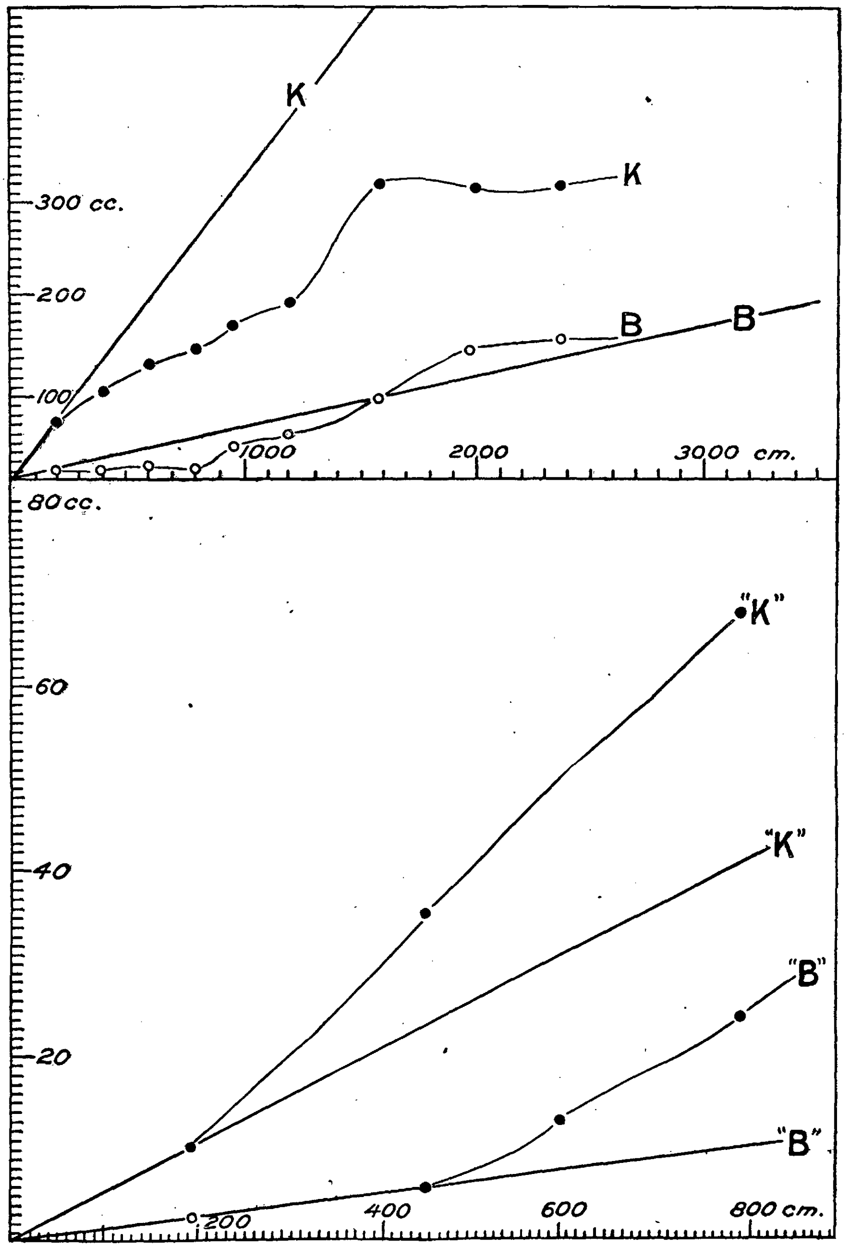


FIG. 28.—Diagram showing flow of water through red Triassic sandstone, "B," and Bradford sandstone, "K." Straight lines show theoretical flow; dots and circles, observed flow. The upper section shows results after grinding down. Abscissas indicate pressure and ordinates flow.

The two specimens were then ground down so as to give new and clean faces for the water to enter, and distilled water was used. "K" was ground down to a thickness of 0.25 inch and "B" to 0.5 inch. These are his results computed to thirty minutes from the first nineteen trials, when the pressures were increased step by step. The measurements under the low pressure were made first and the stones were frequently reversed, so that the flow took place first in one and then in the opposite direction.

Table showing the relation of flow to pressure in sandstone after both faces had been ground down.

Number of trials.	Time.	Pressure—		Specimen K.				Specimen B.			
						Departure.				Departure.	
		Of mercury.	Of water.	Observed flow.	Computed flow.	Cubic centimeters.	Per cent.	Observed flow.	Computed flow.	Cubic centimeters.	Per cent.
	Min.	Inches.	Cm.	C. c.	C. c.			C. c.	C. c.		
2	30	6	197	65.0	65.0	00	00	11.0	11.0	00	....
2	30	12	394	98.0	130.0	— 32	24.62	13.5	22.0	8.5	38.64
2	30	18	591	127.25	195.0	— 67.75	34.64	17.25	33.0	15.75	47.73
3	30	24	788	146.5	260.0	—113.5	43.65	19.25	44.0	24.75	56.25
2	30	30	935	169.3	325.0	—155.7	47.91	38.5	55.0	16.5	30.00
2	30	36	1,182	192.25	390.0	—197.75	50.72	52.75	66.0	13.25	20.08
2	30	48	1,576	322.8	520.0	—197.2	37.92	94.5	88.0	6.5	7.386
2	30	60	1,970	316.5	650.0	—333.5	51.31	141.75	110.0	31.75	28.86
2	30	72	2,364	321.75	780.0	—458.25	58.76	153.0	132.0	21.0	15.91

In this case the flows have been quite irregular, and the relations of flow to pressure are also quite different from what they were before the surfaces were ground down. It will be noticed that the grinding of specimen K resulted in increasing the flow through it much more than could be expected from the making of the specimen thinner, and it may be that the departure from the law of capillary flow in this case may be partly explained by the higher velocity with which the water was forced to traverse the stone.

In the case of specimen B there was an increase of flow following the grinding from 2.4 c. c. per thirty minutes to 11 c. c. in the same time, and while this higher rate was maintained the flow did not increase as rapidly as the pressure did; but when the rate of flow fell back to what it had formerly been the discharge again began to increase faster than the pressure, as it did in the first series of trials. Fig. 28 shows these results in graphic form.

Finally, Newell made a series of measurements of flow through a piece "of. fine, rather hard Italian marble 2 inches in diameter and 0.25 inch thick." The pore space of this stone was found to be only 0.62 per cent. For the first six trials, given in the table below, the hydrant pressure with city water was used, but for the last three distilled water with a constant pressure was again resorted to.

Table showing the relation of pressure to flow of water through Italian marble.

Number of trials.	Time.	Pressure.		Hydrant water.		Distilled water.	
		Mercury.	Water.	Observed flow.	Computed flow.	Observed flow.	Computed flow.
	Minutes.	*Inches.*	*Cm.*	*C. c.*	*C. c.*	*C. c.*	*C. c.*
1	30	60	1,970	1.29	1.29	1.50	1.50
1	30	72	2,364	1.68	1.648	2.13	2.10
1	30	84	2,758	1.995	1.806	....	....
1	30	60	1,970	1.52	1.52	1.26	....
1	30	72	2,364	1.80	1.824	....	....
1	30	84	2,758	2.01	2.128	....	....

In these trials the figures show that with the hydrant water the first set of trials gave a flow increasing faster than the pressure, and the second set of trials gave a flow slightly decreasing with the pressure, while with the distilled water the flow increased a little faster than the pressure. If we make a general average of the three sets of trials, computed to a thirty-minute flow, we shall have the following results, shown also in fig. 29:

Table showing the percentage departure of observed from computed flow of water through Italian marble.

Pressure.	Time.	Mean observed flow.	Mean computed flow.	Departure.
Cm.	*Minutes.*	*C. c.*	*C. c.*	*Per cent.*
1,970	30	1.3925	1,3925	0.00
2,364	30	1.87	1.671	11.64
2,758	30	2.0025	1.9495	2.718

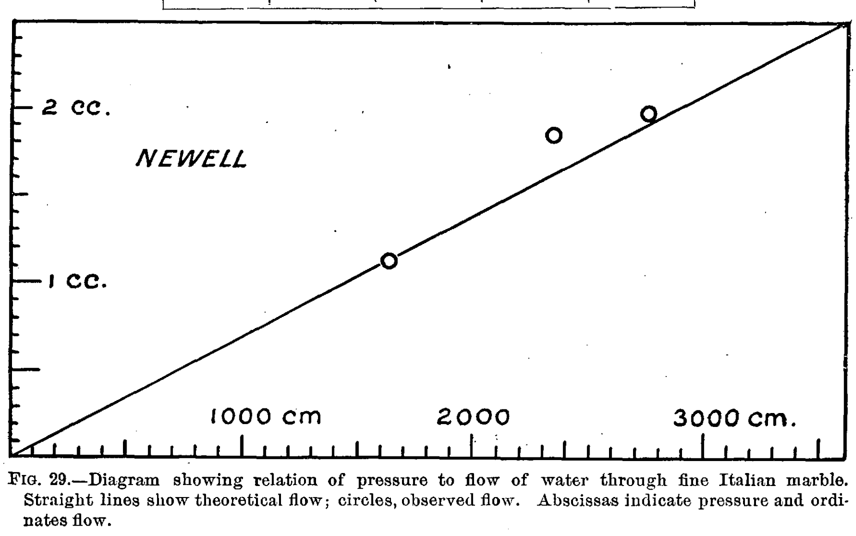


FIG. 29.—Diagram showing relation of pressure to flow of water through fine Italian marble. Straight lines show theoretical flow; circles, observed flow. Abscissas indicate pressure and ordinates flow.

It appears, therefore, from the data here presented from Newell's paper, that in the majority of cases the flow has increased somewhat more rapidly than the pressure. Indeed, of the 154 trials included in the tables constructed from his data 104 show a flow increasing faster than the pressure, while 50 show the reverse relation, and 24 of these 50 cases occur in the table of flows for specimens K and B after they had been ground down and placed under higher pressure heads—conditions which are known to establish similar relations of flow to pressure in capillary tubes which are relatively short, or where the pressures are high in proportion to diameter or length of tube through which the flow is taking place.

FLOW OF WATER THROUGH OTHER SANDSTONES.

In the present study of the relation of pressure to flow of water through sandstone longer sections have been used than those giving Newell's data, and, this being true, where other conditions are the same the percentage effect of clogging would be relatively smaller so far as clogging is a change which occurs near the surface of the specimen under examination. The apparatus used in this work consisted of a brass cylinder 2 inches inside diameter, in which was cemented the specimen through which the flow was to be measured (see fig. 30). Sulphur was at first used as a cementing material; but it was soon found that changes in temperature resulted in checking the sulphur to such an extent as to permit a slight flow through it, and sealing wax was substituted.

The method of cementing a cylinder of stone in place was as follows: One end of the brass cylinder was first closed by means of a brass disk covered with a lining of paper, both being held in place by coupling on another section, thus clamping the two rigidly between the shoulders of the two sections of brass tube. The lower end of the section of stone was then covered with a disk of close, thick felt and placed so as to rest upon the center of the brass disk referred to. A similar disk of felt was then placed upon the top of the stone and covered with a brass washer. The disks of felt were then pressed firmly upon the stone by means of a lever press, and after the brass cylinder had been heated melted sealing wax was poured into the cylinder around the stone. The object of the disks of felt was to prevent the cementing material from coming in contact with the ends of the stone, and they were removed when the sealing wax was cool.

Brass tubing was used instead of iron, because it was found that iron quickly rusted and caused a deposit upon the face of the stone which clogged the pores and interfered with the results. The flow of water through the several samples was measured during considerable intervals of time, without in any way altering the conditions, use being made of clear well water stored in a lead-lined tank, coated on the inside with a black acid and waterproof paint.

In order to guard further against sediment in the water, which might come from rusting at the ends or side of the water pipe, there was inserted a filter 6 inches in diameter and 14 inches long, which was filled with the best cotton batting cut into disks closely fitting the

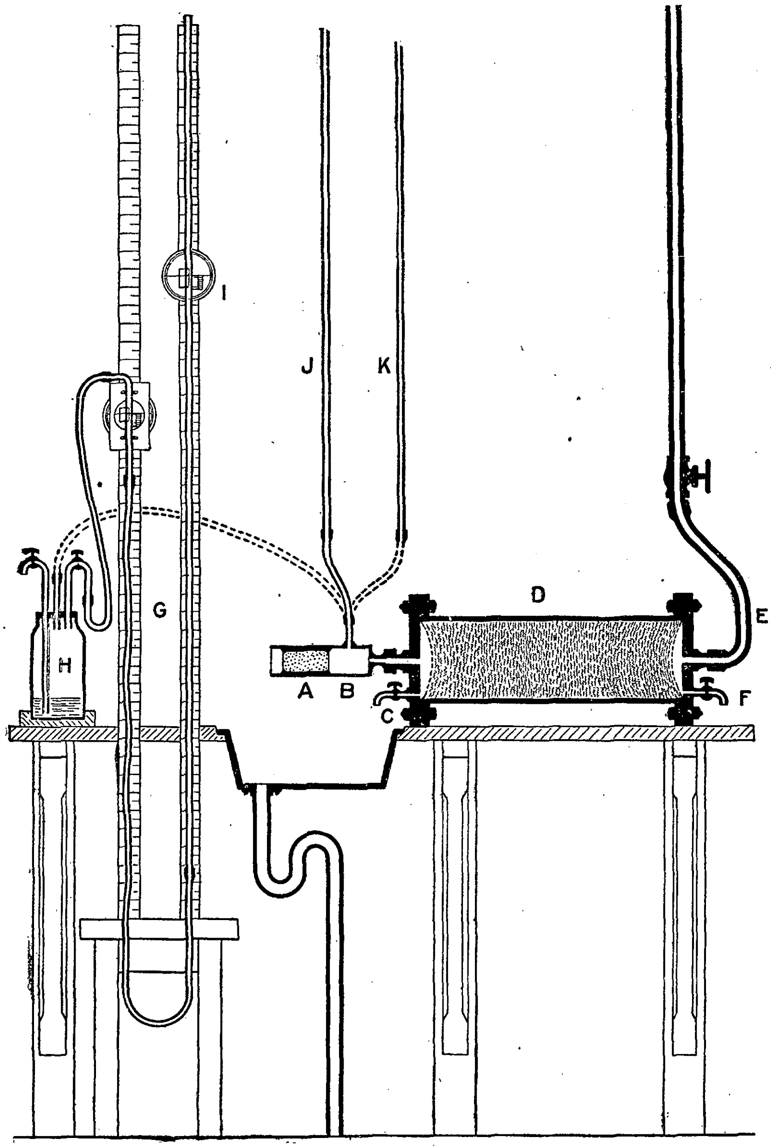


FIG. 30.—Apparatus used to measure the flow of water through rock. A, sample and holder; B, water chamber; D, filter; E, supply pipe; G, H, mercury gage; I, reservoir; J, K, water gages.

tube. These disks were thoroughly wet before being put in place and 4 pounds of dry cotton were required to make the filter.

The inside of the filter wall and the faces of the flanges were thoroughly protected with acid and waterproof paint before the cotton was introduced. All fittings used were of brass, and the specimen under examination in its jacket was connected directly to the filter, as represented in fig. 30, D.

Most of the pressures were measured with a mercury gage, represented in the figure at G, H, where the readings were made by means of verniers to thousandths of a foot, the vernier disks being provided with mirrors to insure the proper position of the eye in reading the pressures.

In some of the work the two check-gages shown in the figure, J, K, were used, which gave a direct vertical column of water from the pressure gage. The temperature of the water was measured in the collecting beaker as it was discharged.

The first sample experimented upon in the brass percolator tube was a piece of Dunnville sandstone, No. 2, from the Potsdam horizon in Dunn County, Wisconsin. This rock is used for building purposes to some extent and works easily. It contains many mica grains and some clay. The sample had a length of 5.1 cm., a diameter of 4.02 cm., and a volume measured by displacement under mercury of 65 c. c. Its pore space was 29.40 per cent as computed from its dry weight, 120 grams, and its specific gravity was 2.6162, determined by crushing the sample after the experiments and finding the specific gravity of the sand after boiling in water to expel all air. The effective size of the sand grains was 0.03635 mm., as determined after crushing, but as indicated by measurements of the stone itself it was 0.04912 mm. The grains of the crushed stone are shown in natural size in Pl. VII.

When the sample was first connected with the filter the flow was 3,230.4 grams during the first 150 minutes, but at the end of 23 hours and 55 minutes continuous run it had increased to 4,856 grams under a pressure of 2.549 feet of mercury at a temperature of 19.2° C., and at the expiration of this time the pressures were varied and the results given in the table below were obtained. The method used to secure different pressures was to partly close the stopcock leading to the filter and then to open the small cock (C, fig. 30) the amount required to give the pressure desired.

Table showing the relation of flow to pressure in Dunnville sandstone, No. 2.

Order of experiment.	Temperature.	Pressure—		Flow of water—			Departure.	Time of flow.
		Of mercury.	Of water.	At observed temperature.	At 15° C.	Computed.		
	° *C.*	*Feet.*	*Cm.*	*Grams.*	*Grams.*	*Grams.*	*Per cent.*	*Min.*
1	19.2	2.549	1,055.0	485.6	438.8	284.5	54.2	15
4	11.5	1.6992	697.0	231.0	255.3	187.9	35.8	15
3	14.6	1.3818	566.9	182.4	182.4	152.9	19.2	15
2	16.1	.7226	296.4	71.0	69.13	79.93	—1.3	15
5	13.3	.276	113.2	29.0	30.53	30.53	0.0	15

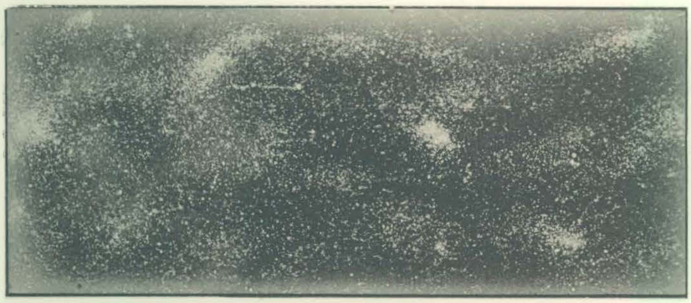
It is here seen that in all cases except one the observed flow when computed to a temperature of 15° C. increases much faster than the pressure.

With another sample of the Dunnville stone (No. 1), having a length of 4.02 inches and a diameter of 1.59 inches, or 4.02 cm., a longer series of measurements of flow was made, but not until water had been allowed to run through the specimen on several occasions for considerable lengths of time.

In the first set of trials referred to, the flow increased from 164.4 grams at the beginning to 192.7 grams at the close, after six hours. In a second set of trials the flow started at 159.8 grams and closed at 206.2 grams. At still another it started at 193 grams and closed at 236.8 grams; all under a pressure of about 2.557 feet of mercury. These statements give a fair idea of the persistency of the flow under like conditions and prove that the water reaching the specimen was so clear as not to materially clog the stone. Before the data in the following table were taken there had probably been the equivalent of forty-eight hours' continuous flow through the specimen.

Table showing the relation of pressure to flow in Dunnville sandstone No. 1.

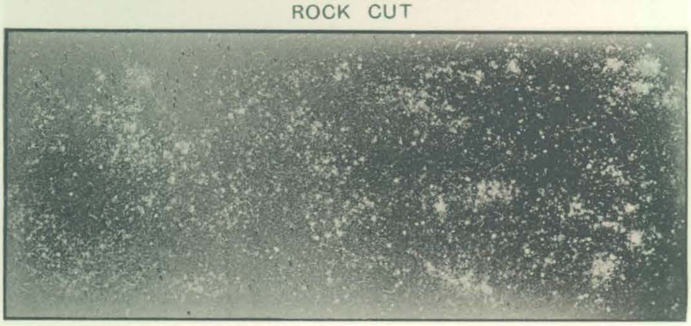
Order of trial.	Temperature of water.	Pressure of mercury.	Time of flow.	Observed flow.	Flow.		Departure from law of Poiseuille.	
					Computed to 15° C.	Computed from low pressure.	Grams.	Per cent.
	°C.	Feet.	Min.	Grams.	Grams.	Grams.		
6	18.9	2.492	15	176.7	159.6	117.0	42.6	36.4
33	16.1	2.457	15	186.7	186.0	115.3	70.7	61.3
34	16.0	2.457	15	211.6	210.8	115.3	95.5	82.8
35	16.0	2.457	15	215.2	214.4	115.3	99.1	85.9
7	18.9	2.3885	15	179.6	162.3	112.1	50.2	44.7
10	18.2	2.298	15	176.8	164.4	107.8	56.6	52.5
11	17.5	2.198	15	159.6	150.5	103.2	47.3	45.8
14	18.1	2.121	15	159.5	148.3	99.55	48.75	48.9
15	17.8	2.014	15	153.2	142.4	94.53	47.87	50.6
18	18.0	1.921	15	142.7	132.7	90.16	42.54	47.1
22	17.0	1.727	15	121.0	115.7	81.06	34.64	42.7
23	16.8	1.633	15	117.3	112.2	76.64	35.56	46.3
26	16.6	1.549	15	107.6	103.8	72.70	31.1	42.7
27	16.7	1.459	15	98.2	94.75	68.48	26.27	38.3
30	16.3	1.378	15	94.1	90.80	51.37	39.43	36.7
31	16.2	1.281	15	87.2	86.88	60.12	26.66	44.3
32	16.2	1.191	15	80.3	80.01	55.90	24.11	43.1
29	16.4	1.109	15	73.1	70.53	52.05	17.48	33.5
28	16.5	1.020	15	67.3	64.94	47.87	17.07	35.6



DUNNVILLE

MADISON QUARRY

ROCK CUT



SUPERIOR SANDSTONE

GRAINS OF CRUSHED SANDSTONE. NATURAL SIZE

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Table showing the relation of pressure to flow in Dunnville sandstone No. 1—Continued.

Order of trial.	Temperature of water.	Pressure of mercury.	Time of flow.	Observed flow.	Flow.		Departure from law of Poiseuille.	
					Computed to 15° C.	Computed from low pressure.	Grams.	Per cent.
	°C.	*Feet.*	*Min.*	*Grams.*	*Grams.*	*Grams.*		
25	16.7	.945	15	59.2	57.12	44.35	12.77	28.7
4	16.7	.8415	15	51.2	49.40	39.50	9.90	25.0
21	17.2	.773	15	45.8	43.79	36.28	7.51	20.7
20	17.3	.6965	15	43.5	41.02	32.69	8.33	25.4
17	17.9	.6235	15	36.1	33.57	29.26	4.31	14.7
16	17.9	.532	15	32.2	29.94	24.97	4.97	19.9
13	18.0	.471	15	26.0	24.12	22.11	2.01	9.0
12	17.7	.3755	15	22.0	20.75	17.62	3.13	17.7
9	18.4	.313	15	13.8	12.65	14.69	—2.04	—13.8
8	18.6	.2035	15	9.4	8.617	9.551	— .934	— 9.7

In this case the table shows a large increase of flow with increased pressure, and no exceptions apart from those at the lowest pressure, and which are in part due to the fact that in selecting a standard for computing the flows from the pressures the mean of the last four flows and their pressures were taken in order to have a smaller probable error in this quantity.

Work was next done with a set of two cylinders cut from the Madison horizon of the Potsdam sandstone No. 2, having a length of 7.78 cm., or 3.06 inches, and a diameter of 3.83 cm., or 1.52 inches, with a volume of 87 c. c. as measured under mercury.

Sample No. 3 had a length of 4.08 cm., or 1.71 inches, and a diameter of 3.66 cm., or 1.44 inches, with a volume measured under mercury of 42 c. c. Both cylinders were cut with their faces parallel to the bedding plane.

Like the first sample of Madison stone experimented with, the rock is of a very loose, friable nature; its grains easily fret off under the fingers, and it can not be used for structural purposes of any sort. It is a quite pure quartz sand, with well-rounded grains, only slightly stained with iron oxide, and the crushed grains are shown in Pl. VII, over "Madison quarry."

In conducting these trials the flow has been measured by systematically changing the pressure, first from high to low and then from low to high, usually by steps as close to 0.01 foot of mercury as could be readily secured with the gage, and these results, arranged in tabular form, apppear in the following tables:

Table showing the relation of pressure to flow of water through Madison sandstone No. 2.

Order of trial.	Time.	Temperature.	Pressure of mercury.	Observed flow.	Computed flow.	Percentage departure.
	Minutes.	°*C.*	*Feet.*	*Grams.*	*Grams.*	
11	10	13.5	1.8365	705.0	....	....
12	10	13.5	.306	80.5	117.4	31.4
13	10	14.0	1.731	645.9	....	....
14	10	14.0	.386	98.3	143.8	37.1
15	10	14.3	1.645	586.6	....	....
16	10	14.3	.457	115.1	163.0	29.3
17	10	14.4	1.548	536.1	....	....
18	10	15.0	.532	136.9	183.4	25.3
19	10	15.1	1.453	486.0	....	....
20	10	15.2	.605	156.6	202.4	22.6
21	10	14.2	1.362	443.9	....	....
22	10	14.2	.681	183.6	221.9	17.2
23	10	14.1	1.270	396.8	....	....
24	10	14.0	.757	202.6	236.5	14.3
25	10	13.8	1.184	359.5	....	....
26	10	13.7	.838	231.2	254.5	9.1
27	10	13.6	1.0925	324.7	....	....
28	10	13.5	.9185	256.0	272.9	6.1

Table showing the relation of flow to pressure in Madison sandstone No. 3.

Order of trial.	Time.	Temperature.	Pressure of mercury.	Observed flow.	Computed flow.	Percentage departure.
	Minutes.	° *C.*	*Feet.*	*Grams.*	*Grams.*	
3	10	14.0	2.157	1,642.6	....	....
4	10	14.0	.119	49.0	90.59	45.9
5	10	14.0	1.964	1,581.2	....	....
6	10	14.0	.192	99.6	122.76	27.1
7	10	14.3	1.866	1,439.6	....	....
8	10	14.3	.253	121.1	195.24	37.9
9	10	15.2	1.767	1,318.4	....	....
10	10	15.4	.342	132.2	255.10	48.1
11	10	16.0	1.661	1,176.6	....	....
12	10	15.4	.403	186.3	285.44	34.7
13	10	15.4	1.575	1,077.6	....	....
14	10	15.4	.479	220.2	329.73	33.2
15	10	15.5	1.476	964.0	....	....
16	10	15.4	.553	248.0	361.16	31.3
17	10	14.2	1.394	897.6	....	....
18	10	14.5	.680	300.5	437.85	31.3

Table showing the relation of flow to pressure in Madison sandstone No. 3—Continued.

Order of trial.	Time.	Temperature.	Pressure of mercury.	Observed flow.	Computed flow.	Percentage departure.
	Minutes.	° *C.*	*Feet.*	*Grams.*	*Grams.*	
19	10	14.4	1.298	820.4	....	....
20	10	14.3	.710	322.2	447.73	28.0
21	10	14.2	1.203	728.0	....	....
22	10	14.3	.789	393.2	477.42	17.6
23	10	14.3	1.121	645.6	....	....
24	10	14.2	.870	462.0	500.51	16.1
25	10	14.0	1.043	577.4	....	....
26	10	14.0	.955	515.8	528.21	2.3

In these tables we have computed each lower flow from the higher flow which immediately preceded it, in order to reduce the disturbing element which results from the progressive changes to as small a value as possible. As the probable errors of observation necessarily appear in larger percentages where the quantities measured are small, it has seemed best to use the flow under the highest pressure as the basis for the values in the column of computed flows; but this, of course, makes the computed flows larger than the observed flows, instead of smaller, as would be the case were the plan before used still followed.

In these cases there is no exception to the flow increasing faster than the pressure, and the percentage departures are large, ranging from 31.4 to 6.1 in the first to 48.1 to 2.3 in the second.

The results obtained with the second specimen of Madison sandstone are given in the preceding table. At the close of the series given in this table the higher pressures used in the first part of the table were resumed in order to note what progressive change may have taken place, and it was found that the mean flow of trials 3 and 5 compared with trials 27 and 28 gave 1,611.9 grams for the former and 1,611.0 for the latter, with the temperature in the former trials of 14° C. and in the latter of 17.2°, while the mean pressure for the earlier trials was 2.061 feet and in the latter 2.11 feet of mercury.

It appears, therefore, that there must have been a small decrease of flow during the experiment, which would tend to make the percentage departures appear a little larger than they really are; but here again there can be no doubt that the flow has increased faster than the pressure.

After these two trials had been made with the separate sections of the Madison sandstone, they were then coupled together and the flow was measured through the two pieces at the same time, thus giving practically a third sample having a length equal to the sum of the two, 11.86 cm. or 4.77 inches, and the results obtained are given in the table which follows:

Table showing the relation of flow to pressure in the two Madison sandstones, Nos. 2 and 3, coupled together.

Order of trial.	Time.	Tempera-ture.	Pressure of mercury.	Observed flow.	Computed flow.	Percentage departure.
	Minutes.	° *C.*	*Feet.*	*Grams.*	*Grams.*	
29	10	18.5	2.425	661.4	....	....
30	10	....	.058	6.6	15.82	58.3
31	10	17.9	2.344	618.6	....	....
32	10	....	.192	33.8	50.67	33.2
33	10	17.8	2.2585	572.6	....	....
34	10	....	.269	53.5	67.14	20.3
35	10	16.4	2.179	527.4	....	....
36	10	....	.346	67.6	83.73	19.2
37	10	16.3	2.083	497.0	....	....
38	10	....	.420	82.2	100.21	17.9
39	10	15.9	1.989	463.8	....	....
40	10	....	.481	95.6	112.07	14.6
41	10	15.2	2.446	597.8	....	....
42	10	15.1	2.446	606.6	....	....
43	10	15.0	2.446	615.6	....	....
44	10	15.0	2.446	619.2	....	....

In this case, as in the others, the flow increases faster than the pressure, and in a manner equally as marked. The last four measurements of flow taken under pressure of 2.446 feet give a mean flow of 609.8 grams, while the flow in trial 29, corrected to the temperature and pressure of the last four trials, is 611.5 grams, showing that the flow has remained nearly constant.

If now we use the flows under the highest pressures in the last three tables as a basis for computing the flows under all of the other pressures we shall have the results appearing in the table which follows. In this table the flows have been reduced to a temperature of 15° C.

Table showing the relation of flow to pressure in cylinders of Madison sandstones where the computed flows are all derived from the highest pressure.

Time of flow.	Madison sandstone No. 2.			Madison sandstone No. 3.			Madison sandstone Nos. 2–3.		
	Pressure, mercury.	Observed flow at 15° C.	Computed flow at 15° C.	Pressure, mercury.	Observed flow at 15° C.	Computed flow at 15° C.	Pressure, mercury.	Observed flow at 15° C.	Computed flow at 15° C.
Min.	*Feet.*	*Grams.*	*Grams.*	*Feet.*	*Grams.*	*Grams.*	*Feet.*	*Grams.*	*Grams.*
10	1.8365	732.8	732.8	2.157	1,686.0	1,686.0	2.425	606.3	606.3
10	1.731	662.9	690.67	1.964	1,623.0	1,535.26	2.344	575.1	586.00
10	1.645	594.3	656.36	1.866	1,459.0	1,458.65	2.2585	532.4	564.63
10	1.548	543.2	617.65	1.767	1,318.4	1,382.26	2.179	508.9	544.75
10	1.453	486.0	579.75	1.666	1,173.0	1,302.31	2.083	479.6	520.75
10	1.362	455.6	543.44	1.575	1,076.0	1,231.18	1.989	462.1	497.25
10	1.270	407.2	506.73	1.476	962.3	1,153.79	.481	95.25	120.25
10	1.184	369.0	472.42	1.394	921.2	1,089.69	.420	81.90	105.00
10	1.0925	335.3	435.91	1.298	831.2	1,014.65	.346	65.23	86.50
10	.9185	264.4	366.48	1.203	747.2	940.39	.269	49.75	67.25
10	.838	240.3	334.36	1.121	654.1	876.29	.192	31.43	48.00
10	.757	207.9	302.04	1.043	592.6	815.31	.058	6.05	14.50
10	.681	188.4	271.72	.955	529.4	746.52	....	....	....
10	.605	156.6	241.39	.870	474.2	680.08	....	....	....
10	.532	136.9	212.27	.789	398.4	616.76	....	....	....
10	.457	116.6	182.34	.710	326.4	555.01	....	....	....
10	.386	100.9	154.01	.680	304.5	531.56	....	....	....
10	.306	83.67	122.09	.553	247.6	432.28	....	....	....
10	....	....	....	.479	219.8	374.43	....	....	....
10	....	....	....	.403	186.0	315.03	....	....	....
10	....	....	....	.342	132.0	267.34	....	....	....
10	....	....	....	.253	122.7	198.77	....	....	....
10	....	....	....	.192	102.2	150.09	....	....	....
10	....	....	....	.119	50.29	93.02	....	....	....

With this method of presenting the data, there is also shown a very persistent and strong increase of flow over what would be required by the Poiseuilleian law as the pressure is increased. The results of this table are plotted in fig. 31.

In order to make sure that there could be nothing in the reading of the pressures which brought about this seeming contradiction of the law, and in order that the pressures might be read more closely, there was substituted for the mercury gage represented in fig. 30 a water gage, also shown in the same figure. This gage consisted of a straight glass tube rising directly above the cylinder carrying the section of stone through which the water was flowing, and the pressures were read by means of a target rod, reading by vernier to a thousandth of a foot. The target was provided with a mirror to secure the correct position of the eye in taking the readings.

In these trials, as in those just recorded, the flows were measured under first a high and then a low pressure in order to eliminate, as far as possible, the effect of any progressive changes which might occur, and the results are recorded in the next table:

Table showing the relation of flow to pressure in cylinder of Madison sandstone No. 2 where pressures are measured with water gage.

Order of trial.	Time.	Temperature.	Pressure of water.	Observed flow.	Computed flow.	Percentage departure.
	Minutes.	° *C.*	*Feet.*	*Grams.*	*Grams.*	
1	10	15.2	4.0	68.6	68.6	0.00
3	10	16.1	3.9	66.9	66.9	0.00
5	10	16.3	3.8	63.4	65.17	2.72
7	10	16.4	3.7	60.5	63.45	4.65
9	10	16.4	3.6	54.7	61.74	11.40
10	10	16.4	1.1	13.3	18.86	29.49
8	10	16.4	1.0	13.3	17.15	22.45
6	10	16.3	.9	12.5	15.43	18.99
4	10	16.1	.8	11.5	13.72	16.18
2	10	15.2	.7	10.0	12.00	16.67

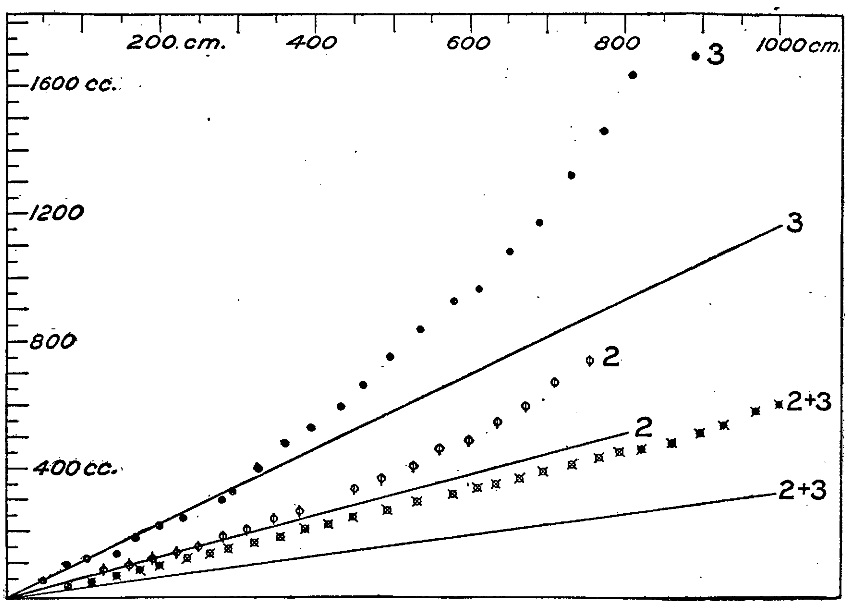


FIG. 31.—Diagram showing relation of flow to pressure through Madison sandstone Nos. 2 and 3. Straight lines 2, 3, and 2+3 show theoretical flow for samples 2 and 3 separate and 2+3 coupled together; circles and dots show observed flow. Abscissas indicate pressure and ordinates flow.

It is thus seen that even with these comparatively low pressures, differing one from another by as little as one-tenth of a foot of water, there still remains the same increase of flow more rapid than the pressure.

Both pieces of stone were again coupled together and the flows measured through them, the water gage being used to determine the pressures, and these results were secured:

Table showing the relation of flow to pressure in cylinders of Madison sandstone Nos. 2 and 3 coupled together where pressures are measured with water gage.

Time.	Pressure.	Observed flow.
Minutes.	*Feet.*	*Grams.*
10	4.0	34
10	4.0	31
10	.7	4.8
10	.7	4.8

Here the computed flow for the low pressure derived from the mean flow for the high pressure is 15.9 per cent higher than the observed flow under the low pressure.

Another set of four cylinders were cut from a very white and fine-grained block of the Madison sandstone taken from the bottom of "Rock cut" on the Chicago and Northwestern Railway, south of the city. These cylinders were cut with their faces at right angles to the bedding plane, and the stone was so soft that it was impossible to work them into the desired shape and size until they were first thoroughly dried.

Cylinder No. 6, through which the flows recorded in the following table were measured, had a length of 7.61 cm., or 3 inches, and a diameter of 3.28 cm., or 1.28 inches, with a volume determined by immersion in mercury of 60 c. c.

As in the other cases presented, water was allowed to flow through this specimen continuously for more than twelve hours in order to bring it into a condition of steady flow before the series of observations here recorded was made, and during this time the flow had increased from 30.3 grams in ten minutes, under a pressure of 2.445 feet of mercury, to 49.9 grams under a pressure of 2.432 feet.

It should be stated that in making the changes from one pressure to another the flow was not stopped either during this series of measurements or any of those already recorded.

Table showing the relation of flow to pressure in Madison sandstone No. 6.

Order of trials.	Time.	Tempera-ture.	Pressure of mercury.	Observed flow.	Computed flow.	Percentage departure.
	Minutes.	° C.	*Feet.*	*Grams.*	*Grams.*	
2	10	21.2	2.387	48.1	48.20	0.21
4	10	20.9	2.305	45.9	46.55	1.40
6	10	20.3	2.234	44.1	45.11	2.24
8	10	20.3	2.149	42.5	43.39	2.05
10	10	19.8	2.066	40.2	41.72	3.64
12	10	19.9	1.984	38.8	40.06	3.15
14	10	19.9	1.906	36.8	38.49	4.39
16	10	19.9	1.829	35.0	36.93	5.23
18	10	19.9	1.764	33.4	35.26	5.28
20	10	20.6	1.670	31.5	33.72	6.58
22	10	20.5	1.592	29.1	32.15	9.49
24	10	20.1	1.505	26.7	30.39	12.14
26	10	20.2	.556	6.8	11.23	39.45
27	10	19.8	2.382	48.2	48.10	—.21
25	10	20.3	1.435	25.3	28.78	12.09
23	10	20.2	1.375	24.0	27.77	13.58
21	10	20.4	1.296	22.5	26.17	14.02
19	10	20.6	1.223	20.9	24.70	15.38
17	10	20.0	1.156	19.7	23.34	15.60
15	10	19.9	1.080	17.9	21.81	17.93
13	10	19.9	1.007	15.9	20.33	21.79
11	10	19.8	.930	14.4	18.78	23.32
9	10	20.1	.848	12.3	17.12	28.15
7	10	20.1	.774	9.6	15.63	38.58
5	10	20.5	.699	8.8	14.11	37.63
3	10	20.9	.6155	6.9	12.43	44.49
1	10	21.2	.518	4.9	10.46	53.15

In this case there is a large percentage departure from the law, the flow increasing in a quite regular manner from less than 1 per cent to more than 50 per cent. In calculating the values in the column of this table headed "Computed flow" the data of trials No. 2 and No. 27 were used, the mean of the two being taken. The very close agreement between these two measured flows shows that there had been but little if any progressive change during the experiment.

Attention has already been called to the possibility that air retained in the stone might exert an influence leading to an increase of flow with an increase of pressure, and the results of observations on tubes filled with wire gauze where boiled water, yet quite warm, was used in order to avoid the possibility of air being carried into the apparatus and allowed to accumulate there, have been already given.

The morning following the day when the water was boiled tests were again made on the No. 6 Madison stone with the boiled water. The flow began at a rate of 15 grams in ten minutes under a pressure of 2.499 feet of mercury and a temperature of 19.8° C., but declined to 9.3° after twenty-five hours, and then increased gradually until a rate of 28 grams was reached, at which point it remained constant during a continuous run of ten hours. The measurements given below were taken about ten hours apart, the flow having been continuous during more than twenty-four hours.

Flow of boiled water through Madison sandstone No. 6 during ten minutes.

Pressure of mercury.	Temperature.	Observed flow.	Computed flow.	Percentage departure.
Feet.	°C.	*Grams.*	*Grams.*	
2.499	21.3	27.9	27.95	....
2.499	21.3	28.0	....	....
.401	21.3	2.3	....	....
.401	21.3	2.3	4.485	48.72
AFTER TEN HOURS' CONTINUOUS RUN.				
2.471	17.5	27.9	27.9	....
.466	17.5	3.3	5.262	37.29

There appears from these results no indication that the use of boiled water materially alters the relation of flow to pressure, for the percentage departure is nearly as large as it was when ordinary filtered well water was used.

Taking the observations which were made by Newell in 1885 in connection with those of the writer here presented, this conclusion is clearly sustained:

The flow of water through sandstone does not conform to the law of Poiseuille between pressure gradients of 2.3 to 1 and 85 to 1, but increases faster than the pressure.

It should be observed here that these gradients are within the range of nearly all pumped wells where the water is lowered during pumping from 0.9 foot to more than 30 feet.

FLOW OF WATER THROUGH SAND.

In this investigation a very large number of measurements of the flow of water through sands of different sizes of grain and under different pressures have been made, and it is the purpose to discuss the bearing of these data upon the subject here under consideration.

In studying the relation of flow of water to pressure through sands three different forms of apparatus have been used, and these will now be described, in connection with the data secured, in the reverse order from which they were used.

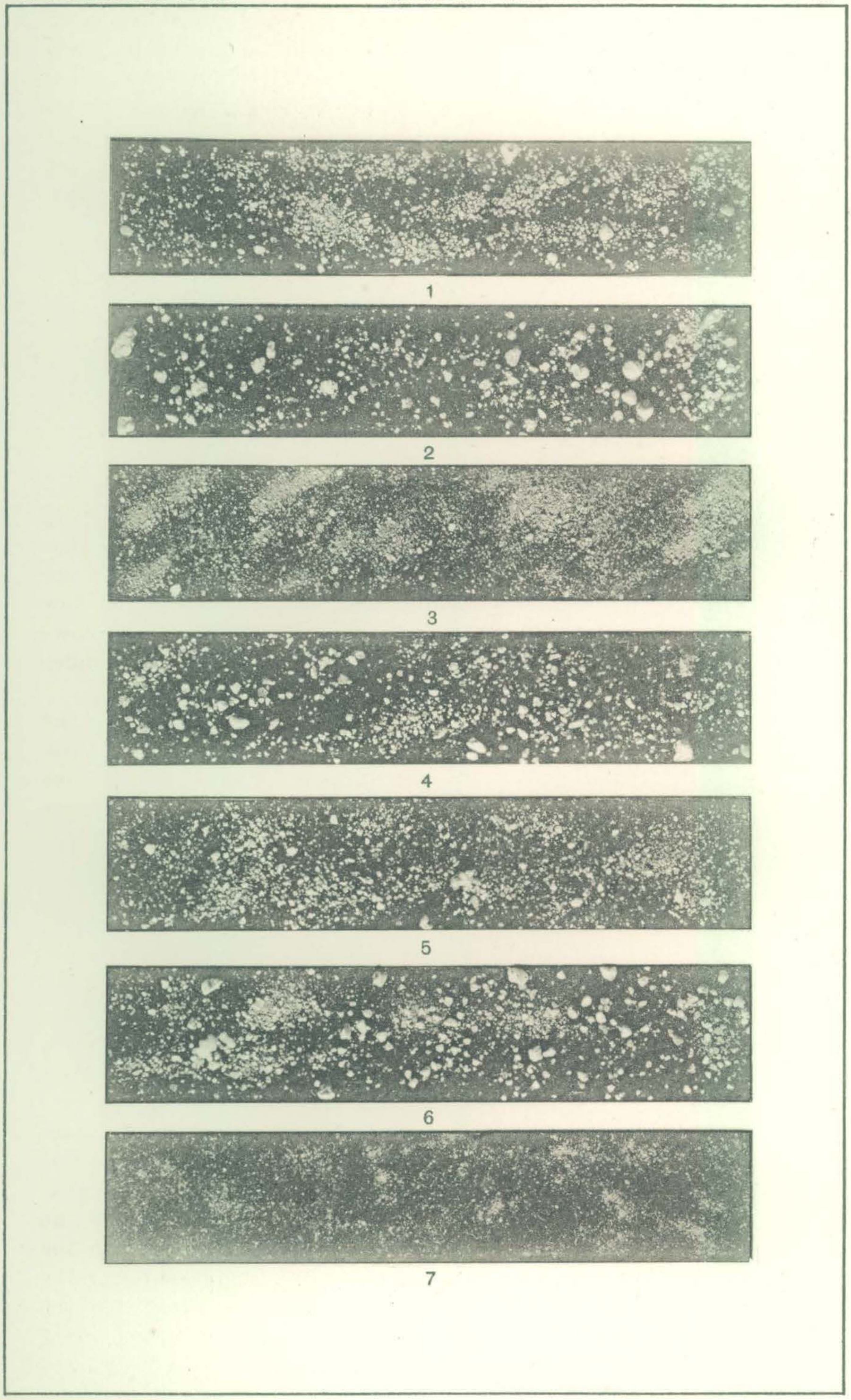
The last apparatus used was a brass tube, in which could be placed a column of sand 5.95 feet long and 0.955 inch in diameter, provided with caps having a bottom of brass wire gauze of different degrees of coarseness to correspond with the size of the grains of sand under experiment. This apparatus, when filled with sand, was placed in a horizontal position and connected with the filter represented in fig. 30, the pressure being measured in the head of the filter next to the apparatus by connecting with the stopcock C.

The sand was filled into the tube dry and thoroughly jarred until it settled no more; then the screen-covered end was placed under water and the air was exhausted from the sand by means of an air pump until the sand became filled with water. In this condition the apparatus was connected with the filter, care being taken to prevent any air from entering the apparatus. As the screen-covered cap prevented the escape of the sand while it permitted the exit of the water, it was possible to use any desired pressure in measuring the flow.

The first sands used in this apparatus were a set of 7 samples taken from the Los Angeles River Valley, California, described in detail in another part of this paper and shown in Pl. VIII. It will be seen that they are mixed sands having grains of quite variable size, which are at the same time not much rounded. The water was allowed to flow through the sample for some time, and then a set of usually two flows under the same high pressure, alternating with a set of two flows under nearly the same low pressure, were taken.

The data obtained, corrected for temperature, are presented in the table which follows; but as there was always observed a marked progressive decline in the flow, due to rearrangement of grains, the figures given are obtained by comparing the flows under two high pressures with the flow under the low pressure, which was taken between the two high-pressure flows, and then the two low-pressure flows which occurred on either side of a high-pressure flow were averaged as a standard with which to compare the single high-pressure flow.

The samples were investigated in the order in which they are numbered, and it was discovered, when the finest-grained sample was put into the apparatus, that on account of the length of the column of sand and the slow rate at which the water moved through it the time necessary to adjust the pressures in changing from one to another was not sufficiently long to enable the effects of the preceding pressure to have vanished from the apparatus before the measurement of the flow under the new conditions was begun. This became evident when it was observed that in changing from a pressure of more than 2 feet of mercury to one of only 0.5 foot the flow frequently was larger under the low pressure than it was under the high pressure—that is, when the water had been flowing long enough under a high pressure for the movement to have extended through the whole column, then, when the low pressure was quickly established and the receptacle for collecting the water was set in place, the water would continue to be discharged



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under the high pressure already in the tube, as the water must necessarily flow out of the apparatus both ways until the pressure was equalized, and would then fall off until, at the free end, it became lower than the new pressure established.

It is quite certain that the results for sample No. 3 are in error on account of this lagging of the pressure, which was discovered too late to enable any allowance to be made for it. It is evident that the effect would be to make the flows under the high pressures too low and those under the low pressure too high, and hence tend to reverse the relations of flow to pressure, just as they appear to be reversed in one of the trials of No. 3.

It has not been practicable to repeat these observations as yet, but it is fortunate that whatever error may have crept in on this account could tend only to reduce the departure from the generally accepted law, making it appear less than it actually is.

Table showing the relation of flow of water to pressure through mixed sands.

Number of sample.	Time of flow.	Temperature.	Pressure, mercury.		Observed flow under—		Computed flow for low pressure.	Percentage departure.
			High.	Low.	High pressure.	Low pressure.		
	Min.	*° C.*	*Feet.*	*Feet.*	*Grams.*	*Grams.*	*Grams.*	
1	10	20.3	2.7095	.5625	72.1	13.0	14.97	13.16
			2.7095	.579	66.7	10.5	14.25	26.31
2	10	15.6	2.702	.579	91.0	10.57	19.50	45.79
			2.702	.550	82.35	10.0	16.76	40.33
3	10	15.6	2.694	.606	25.35	5.4	5.702	5.296
			2.694	.5873	23.9	5.4	5.21	—3.647
4	10	16.2	2.677	.687	602.7	145.5	154.7	5.948
			2.677	.6728	552.2	122.1	138.0	11.53
5	10	16.2	2.696	.5825	80.26	13.6	17.34	21.57
			2.696	.5633	77.8	12.66	16.26	22.15
6	10	19.3	2.693	.5876	130.2	24.33	28.41	14.36
			2.693	.6083	120.4	23.18	27.20	14.78
7	10	19	2.678	.596	3.575	.5	.7956	37.15

An inspection of this table shows that in every case where the lower flow is computed from the higher, assuming that the flow increases as rapidly as the pressure, we get a flow which is larger than that observed by amounts varying from 5 per cent to 45 per cent. It is true there is one exception to this statement in the 14 cases presented, but it is quite certain that this is apparent rather than real, for the reasons just stated.

The second apparatus used is represented in fig. 52, which consisted of a galvanized-iron cylinder of 6 inches inside diameter filled with a sand sorted to one size, in the center of which was placed a drive-well point 18 inches long and 1¾ inches in diameter. Water was admitted to the sand at both ends of the cylinder, and after flowing through the sand escaped into the point and out of the apparatus. The pressure was measured at the upper end of the cylinder only, the mercury gage represented in fig. 30 being used. There were three of these pieces of apparatus filled with sands of three degrees of coarseness, adapted to the screen on the well points, which were Gould's No. 90, No. 80, and No. 50. The effective diameter of the sand grains was 0.09531 mm. for the No. 90, 0.1717 mm. for the No. 80, and 0.2941 mm. for the No. 50.

The apparatus was not designed to investigate the particular question under consideration here, but a portion of the data are brought into requisition now because they show how the flow is related to the pressure.

Two series of data obtained from well point No. 90 will be here presented, the first being derived from an experiment where ordinary filtered well water was used, and the second from one where that water had been boiled and was yet warm.

On account of the tendency of the flow in these sands to become progressively slower as the experiment was prolonged, it became necessary here, as in other cases, to use alternately high and low pressures. In using the data to get the computed flow under the lower pressures from those under the higher pressures the average of the two high-pressure flows and the pressures standing next to a single low-pressure flow between them have been taken for making one calculation; then the second calculation is gotten by taking the mean of the two low-pressure flows which stand on either side of the single high pressure between them. In this way the values in the column headed "Computed low-pressure flow" were obtained.

Table showing the relation of pressure to flow through sands of drive-well point No. 90.

Time of flow.	Temperature.	Pressure of mercury.	Observed flow.	Combined flows under— High pressure.	Combined flows under— Low pressure.	Computed low-pressure flow.	Percentage departure.
Minute.	° *C.*	*Feet.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	
1	21.4	0.2315	1.050	....	....	....	....
1	19.8	2.347	12.420	12.42	1.273	1.415	10.04
1	18.7	.297	1.496	11.83	1.496	1.512	1.058
1	16.8	2.300	11.240	11.24	1.584	1.634	3.06
1	16.8	.3715	1.672	10.71	1.672	1.773	5.696
1	16.3	2.188	10.180	10.18	1.824	1.900	4.001
1	16.4	.445	1.976	9.935	1.976	2.263	12.68
1	16.0	2.097	9.690	9.69	1.514	1.539	1.625
1	16.2	.221	1.052	10.35	1.052	1.024	— 2.675
1	16.1	2.372	11.000	11.00	.944	1.009	6.444
1	16.4	.214	.836	11.56	.836	1.042	19.76
1	16.3	2.374	12.120	....	....	....	....

Here it will be seen that in every case but one the flows have increased more rapidly than the pressures, by amounts ranging from 1.6 per cent to 19.76 per cent of the computed low-pressure flows.

When hot boiled water was used instead of cold water, the results obtained were as shown in the next table.

Table showing the relation of pressure to flow of warm boiled water through sand of well point No. 90.

Time of flow.	Temperature.	Pressure of mercury.	Observed flow.	Combined flows under—		Computed low-pressure flows.	Percentage departure.
				High pressure.	Low pressure.		
Minute.	° *C.*	*Feet.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	
1	59	2.246	45.20	45.20	37.92	32.45	—16.84
1	59	1.614	37.92	....	....	....	....
1	59	1.614	37.24	37.24	22.40	27.16	17.53
1	58	1.177	22.40	....	....	....	....
1	58	1.177	22.26	22.26	18.26	15.51	—17.73
1	56	.820	18.26	....	....	....	....
1	56	.820	18.08	18.08	9.92	11.42	13.13
1	56	.518	9.92	....	....	....	....
1	56	.2325	1.928	9.92	1.928	4.453	56.71
1	56	2.246	22.40	22.40	1.928	2.319	16.86

In this set of trials there are two exceptions, in six comparisons, to the general rule of flow increasing faster than the pressure.

In the case of the No. 50 drive-well point the series of observations permitted of but two comparisons, and these both give a flow increasing faster than the pressure, the results being as below:

Table showing the relation of pressure to flow through sands of drive-well point No. 50.

Temperature.	Time.	High pressure, mercury.	Low pressure, mercury.	High-pressure flow.	Low-pressure flow.	Computed low-pressure flow.	Percentage departure.
° *C.*	*Minute.*	*Feet.*	*Feet.*	*Pounds.*	*Pounds.*	*Pounds.*	
57	1	1.513	0.2875	49.74	8.70	9.452	7.956
57	1	1.513	.2848	48.24	8.825	9.080	2.808

For some reason which has not been discovered, all measurements of flow through the sand of drive-well point No. 80 were quite irregular, and the rate of flow declined very rapidly as the experiment progressed.

The results of the measurements of flow of warm boiled water through this point are given in the table below:

Table showing the relation of pressure to flow of warm boiled water through sand of drive-well point No. 80.

Time of flow.	Temperature.	Pressure of mercury.	Observed flow.	Combined flows under—		Computed low pressure.	Percentage departure.
				High pressure.	Low pressure.		
Minute.	° *C.*	*Feet.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	
1	56	1.816	39.79	....	....	....	—6.888
1	56	.245	5.71	39.60	5.71	5.342	— .979
1	57	1.821	39.40	39.40	5.745	5.095	3.051
1	57	.226	4.58	38.92	4.58	4.724	— .564
1	57	1.903	38.44	38.44	4.455	4.430	—2.85
1	57	.2125	4.33	37.74	4.33	4.210	....
1	57	1.905	37.04	....	....	....	....

In these flows, with one exception, the rate decreased faster than the pressure rather than increased, as was the case with the other two well points.

The first piece of apparatus used to study the flow of water through sands was adapted to investigate the movements under only relatively low pressures, and is represented in fig. 41.

This apparatus proved very satisfactory for what it was intended, except where the flow was very small. In such cases the water would tend to round up at the top of the soil tube before overflowing and then discharge in a body, which was liable to make successive measurements alternately too high or too low. Besides this the heaping up of the water tended to reduce the effective pressure by that amount, while the establishment of the true zero of the pressure gage to a small fraction of a millimeter was made more difficult and uncertain.

The pressures with this apparatus were all measured with a water gage, and could be read to one-tenth of a millimeter by direct observations made possible by the inclined attitude of the gage, which was usually so placed as to rise 1 in 10, as represented in the figure.

The experiments were conducted in the constant temperature room, where the maximum change during a day was seldom equal to 1° C., and care was also taken to leave the apparatus with its contents in the room at least twelve hours before beginning measurements.

The sand was filled into the apparatus in an air-dry condition in small amounts at a time, each filling being gently tamped with a broad, flat disk. To expel the air, boiling water was run through the sand from the bottom upward under a low pressure continually during one-half an hour. The gas was then shut off from the water and the flow maintained until the temperature had fallen to nearly that of the room, when the apparatus was taken to the constant temperature room to remain twelve or more hours before work was begun with it.

The sand used for the observations given in the following table was composed of medium-sized grains of variable size, but well rounded and thoroughly washed in running water until it came away clear when the sand was being stirred.

As it is important to know what variations of flow may occur under the conditions of such a piece of apparatus, nearly the full series of observations made with this sand are given:

Table showing the relation of low pressures to flow of distilled water through sand. Time, ten minutes.

Pressure in centimeter of water.	First trial.			Second trial.			Third trial.			Fourth trial.		
	Temperature.	Observed flow.	Flow divided by pressure.	Temperature.	Observed flow.	Flow divided by pressure.	Temperature.	Observed flow.	Flow divided by pressure.	Temperature.	Observed flow.	Flow divided by pressure.
	°C.	Grams.		°C.	Grams.		°C.	Grams.		°C.	Grams.	
1	12.8	79.4	79.4	......	......	......	......	......	......	13.6	77.9	77.90
2	12.85	153.8	76.9	13.4	150.0	75.0	13.7	158.2	79.1	13.65	157.1	78.55
3	12.9	235.1	78.3	......	......	......	13.7	236.0	78.66	13.70	232.5	77.50
4	12.9	303.8	75.9	13.5	306.8	76.70	13.7	313.2	78.30	13.70	308.7	77.17
5	13.0	378.4	75.7	......	......	......	13.7	393.8	78.76	13.70	389.1	77.82
6	13.0	457.4	76.2	13.5	465.4	77.56	13.7	474.5	79.08	13.75	466.8	77.80
7	13.05	524.3	74.9	......	......	......	13.7	554.0	79.14	13.80	547.8	78.25
8	13.1	611.1	76.4	13.5	624.7	78.09	13.7	634.0	79.25	13.83	627.9	78.49
9	13.2	690.7	76.7	......	......	......	13.75	712.6	79.18	13.90	709.7	78.85
10	13.2	769.4	76.9	13.4	781.7	78.17	13.75	791.1	79.11	13.90	786.8	78.68
11	13.15	848.4	77.1	......	......	......	13.75	872.4	79.31	13.90	868.7	78.97
12	13.1	929.1	77.4	13.45	942.7	78.56	13.8	952.4	79.37	13.90	949.8	79.15
13	13.1	1,008.9	77.6	......	......	......	......	......	......	13.90	1,032.1	79.39
14	13.15	1,091.5	77.9	13.4	1,102.8	78.61	......	......	......	13.90	1,112.8	79.48
15	13.3	1,173.8	78.2	......	......	......	......	......	......	14.0	1,192.0	79.47
16	13.3	1,253.6	78.3	13.4	1,258.7	78.67	......	......	......	14.0	1,272.4	79.52
17	13.5	1,333.7	78.4	......	......	......	......	......	......	14.0	1,354.2	79.66
18	13.5	1,410.2	78.3	13.45	1,418.6	78.81	......	......	......	14.0	1,435.8	79.77
19	......	......	......	13.45	1,498.1	78.84	......	......	......	14.05	1,515.8	79.78
20	......	......	......	13.45	1,577.0	78.85	......	......	......	14.05	1,595.4	79.77
21	......	......	......	13.4	1,658.6	78.98	......	......	......	14.05	1,676.5	79.83
22	......	......	......	13.5	1,737.3	78.97	......	......	......	14.10	1,760.2	80.01
23	......	......	......	13.5	1,817.7	79.03	......	......	......	14.1	1,839.7	79.99
24	......	......	......	13.5	1,901.4	79.20	......	......	......	14.1	1,925.2	80.22
25	......	......	......	13.55	1,980.7	79.23	......	......	......	14.1	2,004.8	80.19
26	......	......	......	13.65	2,062.7	79.33	......	......	......	14.1	2,088.7	80.34
27	......	......	......	13.65	2,145.4	79.46	......	......	......	14.1	2,172.9	80.48
28	......	......	......	13.75	2,233.3	79.76	......	......	......	14.15	2,255.6	80.56
29	......	......	......	13.70	2,311.9	79.72	......	......	......	14.2	2,343.9	80.82
30	......	......	......	13.7	2,395.0	79.83	......	......	......	14.2	2,424.8	80.83

Before the observations recorded in the preceding table were begun a preliminary set covering a full day had been made to familiarize the operator with the apparatus and the method of work. It should be further stated that the flow of water through the sand was continuous from the beginning to the end of a set of observations except as work was stopped for dinner or for the day, and that the percolator always stood full of water, so that there was no possibility that any air other than such as was absorbed in the water could get into the sand.

When these trials had been completed, another set was made, alternating from high to lower pressures, in order that the effect of progressive changes might be eliminated, and the table below contains the data derived from these:

Table showing the relation of low pressure to flow of distilled water through sand; fifth trial.

Time of flow.	Temperature.	Pressure of water.	Observed flow.	Flow divided by pressure.	Number of trial.
Minutes.	°*C.*	*Cm.*	*Grams.*		
10	14.0	2	155.1	77.55	1
10	14.0	30	2,398.3	79.94	2
10	14.05	15	1,195.0	79.66	3
10	14.15	2	157.3	78.65	4
10	14.20	30	2,421.7	80.72	5
10	14.20	15	1,201.2	80.08	6
10	14.20	2	158.9	79.45	7
10	14.25	30	2,423.7	80.79	8
10	14.25	15	1,189.2	79.95	9
10	14.30	2	158.4	79.20	10
10	14.30	30	2,425.6	80.85	11
10	14.30	15	1,203.0	80.20	12
10	14.30	2	159.3	79.65	13

The preliminary trial with this sand was made March 26, 1897, the first trial March 27; the second and third trials on the 29th; the fourth on the 30th, and the fifth on the 31st. At this point the apparatus was allowed to stand in the constant-temperature room undisturbed in any way until April 10, when a sixth trial was made, in which it was the purpose to extend the series to as high a pressure as was possible with the apparatus. The gage was given a less steep slope, such that for every 10 cm. of the scale there was an actual increase of head of 3 cm., and the pressures were varied by successive steps of 1.5 cm. up to 37.5 cm. In attempting to adjust the pressure to 39 cm. sand was forced over, thus bringing the series to a close. The results are given in the next table:

Table showing the relation of low pressures to the flow of distilled water through sand; sixth trial.

Time of flow.	Temper-ature.	Pressure of water.	Observed flow.	Flow divided by pressure.
Minutes.	°C.	*Centimeters.*	*Grams.*	
10	15.4	1.5	122.7	81.80
10	15.4	3.0	244.0	81.33
10	15.4	4.5	366.1	81.36
10	15.4	6.0	487.4	81.23
10	15.35	7.5	610.8	81.44
10	15.4	9.0	737.1	81.90
10	15.45	10.5	858.3	81.74
10	15.4	12.0	980.6	81.70
10	15.4	13.5	1,100.0	81.48
10	15.4	15.0	1,224.9	81.66
10	15.4	16.5	1,346.8	81.56
10	15.45	18.0	1,470.1	81.66
10	15.5	19.5	1,592.2	81.65
10	15.55	21.0	1,711.3	81.49
10	15.5	22.5	1,832.5	81.44
10	15.5	24.0	1,954.3	81.43
10	15.5	25.5	2,079.4	81.54
10	15.5	27.0	2,202.2	81.56
(*a*)	(*a*)	(*a*)	(*a*)	(*a*)
10	14.8	27.0	2,132.3	78.96
10	15.0	27.0	2,136.4	79.11
10	15.0	28.5	2,246.9	78.84
10	15.0	30.0	2,361.3	78.71
10	15.0	31.5	2,472.1	78.47
10	15.0	33.0	2,585.6	78.35
10	15.0	34.5	2,689.4	77.95
10	15.0	36.0	2.816.6	78.24
10	15.0	37.5	2,984.0	79.57

a Thirty-six hours' time intervened here, but otherwise no known cause for change of rate except the change of temperature which table shows.

If the data of the fifth trial are combined in such a manner as to eliminate the effect of the progressive change which is apparent, it will be possible to see whether the flow is increasing faster than the pressure, as it was found to do under the higher pressure to which the Los Angeles sands were subjected. To do this three comparisons are made, first, the 30 pressure with the 2 pressure; second, the 15 pressure with the 2 pressure; and, third, the 30 pressure with the 15 pressure.

In making the comparison, two high pressures on opposite sides of a low pressure or two low pressures on opposite sides of a high pressure are averaged and the results appear in the next table.

Table showing the relation of low pressures to the flow of water through sands.

Trials compared.	Observed flow.	Computed flow.	Difference.	Percentage departure.
Pressures of 30 cm. compared with 2 cm.				
1 and 4 with 2	156.2	159.88	3.68	2.30
2 and 5 with 4	157.3	160.66	3.37	2.10
4 and 7 with 5	158.1	161.44	3.34	2.07
5 and 8 with 7	158.9	161.51	2.61	1.62
7 and 10 with 8	158.65	161.58	2.93	1.81
8 and 11 with 10	158.4	161.64	3.24	2.01
10 and 13 with 11	158.85	161.70	2.85	1.76
Pressures of 15 cm. compared with 2 cm.				
3 and 6 with 4	157.3	159.71	2.40	1.50
4 and 7 with 6	158.1	160.16	2.06	1.29
6 and 9 with 7	158.9	160.03	1.13	.71
7 and 10 with 9	158.65	159.9	1.25	.78
9 and 12 with 10	158.4	160.15	1.75	1.09
10 and 13 with 12	158.85	160.4	1.55	.97
Pressures of 30 cm. compared with 15 cm.				
2 and 5 with 3	1,195.0	1,205.0	10	.83
3 and 6 with 5	1,198.1	1,210.85	12.75	1.05
5 and 8 with 6	1,201.2	1,211.35	10.15	.84
6 and 9 with 8	1,200.25	1,211.85	11.60	.95
8 and 11 with 9	1,199.3	1,212.32	13.02	.96
9 and 12 with 11	1,201.15	1,212.8	11.65	1.07

There is here no exception to the rule of flow increasing faster than pressure, and we are forced to conclude that under the conditions of these experiments the flow of water through sands under low pressures is not proportional to the pressure.

Three independent sets of experiments have now been presented in which quite different forms of apparatus were used under widely different pressures and with widely different sands, both as to size of grain and character of grain, and yet there is an essential agreement among them all in showing that the flow of water through these sands increases faster than the pressure.

In the apparatus of the last experiments we have a column of sand 12 inches or 30.4816 cm. long, and we find that with a pressure gradient of 30 cm. to 15 cm., or of 2 to 1, there is an observed departure from Poiseuille's law amounting to 1.5 per cent. In the apparatus used with the Los Angeles sands we had a length of column of 181.356 cm., or 5.95 feet, and when the pressure gradient rose at the rate of nearly 1 to 1, as compared with a rise of 6 to 1, the flow increased faster than the pressure by amounts ranging from 5 to 26 and even 37 per cent.

FLOW OF AIR AND WATER THROUGH SANDS, SANDSTONES AND OTHER POROUS MEDIA.

As the work of Graham and O. E. Meyer relating to the flow of air and gases through capillary tubes is held to have demonstrated that the laws of Poiseuille also hold for air, the inference appears legitimate that if the laws of capillary flow hold for water through soil they should also hold for air, and since the experiments made in connection with this inquiry have failed to show a complete agreement with the law in a study of the flow of water, it was deemed desirable to measure the flow of air through some of the same media under different pressures, to see whether the flow of air through soils does or does not conform to the Meyer-Poiseuille law.

Accordingly, a large number of measurements of the flow of air through sand, sandstone, shot, and other media have been made, some of the results of which will now be presented.

FLOW OF AIR THROUGH POROUS MEDIA UNDER LOW PRESSURE.

The results first presented are those obtained by measuring the flow of air through a column of sand 16.7 cm. long and 3.812 cm. in diameter under 10, 20, 30, 40, and 50 mm. of constant water pressure. The effective diameter of the sand grains was .1551 mm. and the packing of the sand was such as to give a pore space of 36.45 per cent. In composition it was a nearly pure quartz sand, composed of well-rounded grains, which had been screened through a sieve of No. 60 mesh to obtain grains of nearly uniform size.

The apparatus used was that represented in fig. 34 (p. 179), modified by substituting for the weight which produces the pressure a crank and small axle, about which a cord was wound and which was turned by hand slowly but with sufficient rapidity to hold the pressure constantly at the desired amount. As the pressure gage was so inclined as to magnify the readings tenfold it was easy to maintain the pressure so nearly constant that the variations did not exceed 0.1 mm. of water, and the measurements were made in the constant-temperature room, so that the temperature changes were less than 0.5° C. in the four series of measurements which were taken and which are given in the next table.

Table showing relation of low pressure to flow of air through No. 60 sand.

Pressure of water.	Temperature.	Time.	Flow in seconds of dial.				Mean flow.		Computed flow.	Difference.	Percentage departure.
			Trial 1.	Trial 2.	Trial 3.	Trial 4.	In seconds of dial.	In cubic centimeters.			
Mm.	° *C.*	*Min.*							*C. c.*	*C. c.*	
10	17.5	4	1,135	1,130	1,188	1,162	1,153.75	97.195	97.195	0.0	0.0
20	17.5	4	2,300	2,371	2,370	2,342	2,345.75	197.63	194.39	3.24	1.67
30	17.5	4	3,530	3,582	3,588	3,520	3,552.5	299.32	291.59	7.73	2.65
40	17.5	4	4,790	4,795	4,822	4,820	4,806.75	404.95	388.78	16.17	4.16
50	17.5	4	5,940	6,016	6,063	5,975	5,998.5	505.37	485.98	19.39	3.99

There are two corrections which might be applied to these results; the first is necessitated by the rise of water in the large flask of the pressure gage as the water flows back out of the pressure tube when the pressure is applied, but as the area of the section of the flask is 1,225 times that of the gage tube, the maximum correction required for the 50-mm. pressure affects only the third decimal place, and may therefore be neglected. The other correction is that required to reduce the volume of air in the bell where it is measured under a reduced pressure to the volume it would have under the outside atmospheric pressure at which it entered the sand; but as we are here concerned only with comparative results rather than with absolute amounts of flow under different pressures, and as this correction would not alter the percentage relations, it may also be omitted.

The results given in the table may therefore be taken just as they stand, and they show that under these low pressures the flow of air through this sample of sand increases more rapidly than the pressure increases, as we have found true for water.

The Los Angeles sand No. 7 was also used in these trials and gave the results shown in the next table:

Table showing relation of low pressure to flow of air through Los Angeles sand No. 7.

Pressure of water.	Temperature.	Time.	Flow.		Computed flow.	Difference.	Percentage departure.
			In seconds of dial.	In cubic centimeters.			
Mm.	° *C.*	*Min.*			*C. c.*	*C. c.*	
10	17.1	10	138.5	11.667	11.667	--------	--------
20	17.1	10	277	23.33	23.33	0.0	0.0
30	17.1	10	421	35.47	35.00	.47	1.34
40	17.1	10	558	47.01	46.67	.34	.73

In this case there is a close agreement with the law, but the departure, what there is, is in the direction of flow increasing faster than the pressure.

In the next trial a brass tube was used, 5.95 feet or 181.356 cm. long, having a cross-section of 4.621 square cm. filled with sand No. 2 (Pl. XIV, *B*) having an effective diameter of .7146 mm. and a pore space of 36.26 per cent.

This tube was provided with two saw cuts just 4 feet apart and nearly 1 foot from each end, over which were soldered brass tubes to which pressure gages could be attached, the object being to take out the pressures far enough back in the sand to be free from any end influence which might be assumed to exist. The gages attached to these openings were arranged as represented in fig. 40, to magnify the readings by inclining the tubes. There were three sets of trials made with the results given below:

Relation of pressure to flow of air through No. 2 sand.

Pressure of water.	Temperature.	Time.	Flow in seconds of dial.			Mean flow.		Computed flow.	Difference.	Percentage departure.
			Trial 1.	Trial 2.	Trial 3.	In seconds of dial.	In cubic centimeters.			
Mm.	°*C.*	*Min.*							*C. c.*	*C. c.*
10	18.3	2	398	385	388	390.3⅓	32.85	....	....	....
20	18.3	2	829	853	819	383.6	70.18	65.70	4.48	6.82
30	18.3	2	1,238	1,205	1,180	1,207.6	101.7	98.55	3.15	3.20
40	18.3	2	1,620	1,628	1,625	1,624.3	136.7	131.4	5.3	4.03
50	18.3	2	2,042	2,020	2,055	2,039	171.6	164.2	7.35	4.47

Here again there is a persistent and at the same time marked increase of flow faster than the pressure.

These departures from the law can not be explained by any error, either in the gage or in the gage readings, because it was tested throughout its entire range by means of another vertical water gage, one observer setting the pressure on the inclined gage at some point and making a record of it, while a second observer recorded the pressures observed by him on the vertical gage. These trials were made repeatedly in all parts of the scale, and they were found to agree as closely as it was possible to read the vertical scale with a hand lens. Neither can it be due to any systematic error in the apparatus, for measurements agreed, whether the series were run from high to low or from low to high pressures, and no matter what part of the aspirator bell was under water at the time.

If the flows are divided by the loss of pressure between the two internal gages, we shall have the results stated below:

Mean flow divided by pressure.

	10 millimeters.	20 millimeters.	30 millimeters.	40 millimeters.	50 millimeters.
1	64.19	69.66	72.40	66.78	67.62
2	63.11	70.50	69.65	68.12	67.33
3	63.61	67.13	69.01	68.28	68.50
	63.63⅔	69.096	70.35	67.72	67.816
		63.636	63.636	63.636	63.636
Difference	....	5.46	6.71	4.08	4.18

If these differences are compared with the percentage differences in the last table, it will be seen that there is an essential agreement between them, as should be expected if the end influences had no appreciable effect upon the flow.

The next trials were made with extra-fine dust shot in the same apparatus. The shot was perfectly clean, with grains spherical and nearly uniform in diameter, this being very close to 1 mm., with a pore space of 37.89 per cent.

In this case the flows were measured for pressures, varying by successive steps of 1 mm. up to 10 mm., then for 20, 30, 40, and 50 mm., and the results are given below. The time of observation was 10 minutes, but results are computed to 1 minute. Temperature 18.6° C.

Table showing the relations of pressure to flow of air through dust shot.

Time.	Pressure.	Obsevred flow.	Computed flow.	Difference.	Departure.	Pressure.	Observed flow.	Computed flow.	Difference.	Departure.
Min.	*Mm.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*	*Mm.*	*C. c.*	*C. c.*	*C. c.*	*Per ct.*
1	1	5.40	....	0.0	0.0	8	45.10	43.20	1.9	4.398
1	2	11.985	10.80	1.185	10.97	9	51.03	48.60	2.43	5.00
1	3	16.705	16.2	.505	3.117	10	56.58	54.00	2.58	4.778
1	4	22.87	21.60	1.27	5.88	20	113.93	108.00	5.93	10.61
1	5	28.48	27.00	1.48	5.48	30	177.97	162.00	15.97	9.858
1	6	34.365	32.40	1.965	6.065	40	232.81	216.00	16.81	7.782
1	7	41.99	37.80	4.19	11.08	50	293.055	270.00	23.055	8.539

In this case there is a long series of low pressures where there are 14 steps in which there is no exception to the rule of the flow increasing faster than the pressure.

Trials of flow of air through several of the pieces of sandstone were also made under varying low pressures, and these are next presented. To measure these flows the same aspirator and gage were used as have been used in the trials just described, a fitting being provided (represented in fig. 32) which made it possible to couple each section of the stone to the aspirator, thus enabling them to be used for air or for water without remounting or in any manner altering the specimen.

The samples used for this work were the Madison sandstones Nos. 2 and 3, coupled together; the Dunnville sandstone No. 1; the Madison sandstones Nos. 4 and 6, and the Lake Superior sandstone No. 1. Chips cut from samples Nos. 4 and 6 were also crushed and the sand was used in the long aspirator tube described in connection with the tests made with No. 60 sand, for comparison with the stone in the natural condition.

The results of the observations are put into two condensed tables which follow. Where the flows have been reduced to cubic centimeters

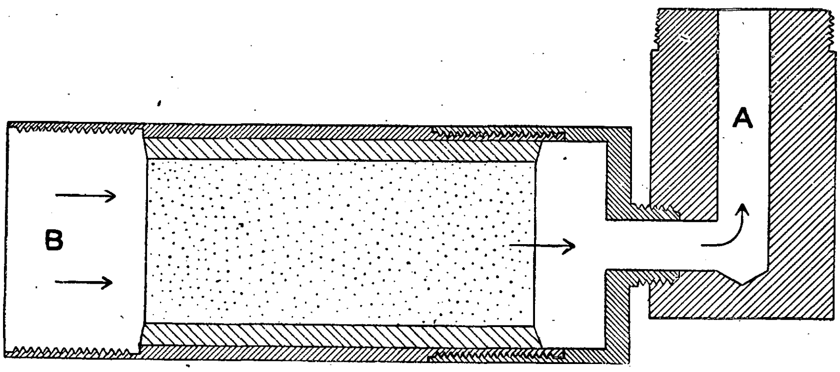


FIG. 32.—Apparatus for measuring flow of air through rock under low pressure; used with apparatus in fig. 40. A, connecting piece; B, sample and mounting cylinder.

per minute, the time of each observation varied from ten to thirty minutes, according to the rate of flow through the specimen, and in all of the sandstones the results are the mean of three trials, except those of the Dunnville, which are single observations in one series. The observations on the crushed sandstone were repeated three times in each of two separate series of experiments, so that these values are a mean of six determinations. As an illustration of the amount of variation which occurred in duplicating measurements of flow, there is given below one of the series of measurements for a sandstone and for the sand also.

Table showing the relation of pressure to flow of air through pieces of sandstone.

[Time, 1 minute.]

Pressure of water.	Madison sandstone, Nos. 2 and 3 coupled. At 16.3° C.			Dunnville sandstone, No. 1. At 16.2° C.			Lake Superior sandstone, No. 1. At 16.4° C.		
	Mean observed flow.	Mean computed flow.	Mean percentage departure.	Mean observed flow.	Mean computed flow.	Mean percentage departure.	Mean observed flow.	Mean computed flow.	Mean percentage departure.
Mm.	*C. c.*	*C. c.*		*C. c.*	*C. c.*		*C. c.*	*C. c.*	
10	6.782	....	....	1.9766	....	....	4.2017	....	....
20	14.413	13.564	4.97	4,055	3.953	2.88	8.605	8.403	2.41
30	21.977	20.346	10.09	5.895	5.930	—.587	13.630	12.605	.81
40	29.42	27.128	8.45	8.107	7.906	2.54	18.180	16.807	8.17

Table showing the relation of pressure to flow of air in sandstone and in the sand derived from the crushed rock.

[Time, 1 minute.]

Pressure of water.	Madison sandstone, No. 4. At 16.2° C.			Madison sandstone, No. 6. At 16.7° C.			Sand from crushed Madison sandstone. Nos. 5 and 6. At 16.5° C.		
	Mean observed flow.	Mean computed flow.	Mean percentage departure.	Mean observed flow.	Mean computed flow.	Mean percentage departure.	Mean observed flow.	Mean computed flow.	Mean percentage departure.
Mm.	*C. c.*	*C. c.*		*C. c.*	*C. c.*		*C. c.*	*C. c.*	
10	1.7733	....	....	1.2207	....	....	4.5718	....	....
20	3.815	3.547	7.56	2.745	2.441	12.44	8.851	9.144	—3.20
30	5.547	5.220	6.26	3.767	3.662	2.86	13.623	13.716	— .67
40	7.773	7.093	9.59	5.170	4.882	5.89	17.707	18.287	—3.18

It will be seen from these two tables that, with the sandstones, in the 15 comparisons of flow with pressure there is but one exception to the rule of flow increasing faster than the pressure, the percentage departures ranging from slightly more than five-tenths of 1 per cent to 12 per cent.

It will be seen, however, that in the case of the sand derived from the crushed rock none of the flows have increased so rapidly as the pressure. This reversal is what should be expected after the air has attained a certain velocity, and what we have persistently found true when much higher pressures were used to produce the flow of air through these same samples, as will be reported in advance.

But the case of another sand with well-rounded grains has already been cited, where with much higher velocities than those here produced under the same pressures the flow did increase faster than the pressure.

The relative velocity of air through these two sands will be better appreciated if they are brought together for comparison, as below.

Table showing the comparative flow of air through sand and crushed sandstone.

Pressure.	Flow through sand.	Flow through crushed sandstone.
Mm.	*C. c.*	*C. c.*
10	24.30	4.57
20	49.41	8.85
30	74.83	13.62
40	101.24	17.71

The two sets of observations appear to be contradictory and to throw doubt upon the accuracy of the data. The measurements, however, were repeated too many times in both cases, and the agreement between repeated measurements was too close to admit of such an explanation of the difficulty.

The table which follows shows what agreement was obtained between successive trials in the case of the crushed sandstone:

Table showing the relation of pressure to flow of air through crushed sandstone.

Time.	Pressure of water.	Flow—		Time.	Pressure of water.	Flow—	
		In seconds of dial.	In cubic centimeters.			In seconds of dial.	In cubic centimeters.
Min.	*Mm.*			*Min.*	*Mm.*		
10	10	560	47.15	10	30	1,625	136.8
10	10	539	45.39	10	30	1,633	137.5
10	10	541	45.55	10	30	1,645	138.5
10	20	1,046	88.08	10	40	2,078	175.0
10	20	1,032	86.90	10	40	2,092	176.2
10	20	1,041	87.66	10	40	2,118	178.2

The next table shows the agreement between repeated trials in the case of one of the sandstones.

Table showing the relation of pressure to flow of air in Lake Superior sandstone No. 1.

Time.	Pressure of water.	Flow—		Time.	Pressure of water.	Flow—	
		In seconds of dial.	In cubic centimeters.			In seconds of dial.	In cubic centimeters.
Min.	*Mm.*			*Min.*	*Mm.*		
10	10	498	41.93	10	30	1,605	135.1
10	10	498	41.93	10	30	1,622	136.6
10	10	501	42.19	10	30	1,630	137.2
10	20	1,023	86.14	10	40	2,190	184.4
10	20	1,018	95.72	10	40	2,145	180.6
10	20	1,025	86.31	10	40	2,142	180.4

It ought, perhaps, to be expected that a sand made up of angular grains would offer greater resistance to the flow of air through it than one of rounded grains would, and hence that a velocity at which this reversal of the relation of flow to pressure which has been observed takes place should be much less for a medium made up of angular fragments.

FLOW OF AIR THROUGH CAPILLARY TUBES OF TRIANGULAR SECTION.

In order to test the influence of the shape of the cross section of a capillary tube on the flow of air through it we filled a tube having a diameter of 11.658 mm. with 119 knitting needles, crowding them in as closely as it was possible to do. The diameter of these needles was

1.0668 mm. and their length was 22.54 cm. These needles, placed together in the manner described, would form three-sided capillary tubes where three of the needles came into contact, but having sides convex inward, as represented in fig. 56 of Professor Slichter's paper (p. 308 of this volume). If they did not come into complete contact then the tube would have a form, when shown in section, more like his fig. 57. The area of the section of the triangular tube would be 0.0443 mm., thus making an area given by a circular tube having a diameter of 0.2374 mm.

This piece of apparatus was mounted so as to be used with the aspirator for the very low pressures, and the following results were secured:

Table showing the relations of pressure to flow of air through capillary tubes of triangular section.

Time.	Pressure of water.	Observed flow.	Computed flow.	Percentage departure.	Time.	Pressure of water.	Observed flow.	Computed flow.	Percentage departure.
Min.	*Mm.*	*C. c.*	*C. c.*		*Min.*	*Mm.*	*C. c.*	*C. c.*	
2	1	39.4754	....	....	2	10	402.7	394.75	2.01
2	2	80.34	78.95	1.76	2	20	786.2	789.5	—.42
2	3	119.6	118.42	.997	2	30	1,189.8	1,184.2	.47
2	4	157.8	157.90	—.06	2	40	1,604.6	1,579.0	1.62
2	5	198.0	197.38	.31	2	50	1,992.9	1,973.8	.97

The results in this table are the mean of ten series of observations for the first five pressures and five series for the five higher pressures. It will be noticed that while the observations show a close agreement with the Poiseuille-Meyer law as regards pressure, there is nevertheless a decided indication that under these conditions the flow increases faster than the pressure, there being only two reversals in the series of ten pressures.

A fine capillary tube about 6 inches long was next drawn out, one end being left attached to the tube from which it was drawn, and the following results were obtained with that, the figures given indicating observed and computed flows per ten minutes in seconds of dial:

Table showing the relation of pressure to flow of air through glass capillary tube.

Pressure in millimeters.	Observed flow.	Computed flow.
10	570	570
20	1,165	1,140
30	1,770	1,710
40	2,315	2,280
50	2,850	2,850

These measurements show the same variation, but fall into exact agreement with the law at a pressure of 50 mm. of water.

When a somewhat larger tube than this was used, the following results were obtained per ten minutes in seconds of dial:

Table showing the relation of pressure to flow of air through glass capillary tubes.

Pressure in millimeters.	Observed flow.	Computed flow.	Percentage departure.
10	2,470	2,470	....
20	4,858	4,940	1.66
30	7,277	8,410	1.58
40	9,816	9,880	.65
50	12,260	12,350	.73

In this case there is not a large departure from the law, but it is in the opposite direction; the flow under the two highest pressures being, however, almost in exact accord with the law.

The chief value of these two sets of observations is found in the fact that they show that the apparatus we have been using is capable of giving results under the conditions of simple capillary tubes, which agree with those found by Meyer and other investigators.

FLOW OF WATER THROUGH CAPILLARY TUBES UNDER HIGH PRESSURE.

In order to test the apparatus for measuring the flow of water through sand and stones, two pieces of thermometer tubing which had been used for high-grade thermometers were selected. No. I had a length of 5.7 cm., and a diameter of 0.01912 cm. Tube No. II had a length of 44.8 cm., and a diameter of 0.02078 cm., the diameters in both cases being determined by filling with mercury and weighing.

These tubes were used on the same apparatus for filtering the water which was used for the stones and sand, and both the mercury and water manometers were used for measuring the pressure which was taken out at the head of the filter next to the tube.

EXPERIMENT I.—TUBE NO. I.

Table showing the relation of pressure to flow of water through glass thermometer tube.

Time.	Temperature.	Pressure of mercury.	Flow.	Computed flow.
Minutes.	°C.	*Feet.*	*Grams.*	*Grams.*
10	17.7	2.4575	10.1	....
10	17.7	2.4575	9.9	....
10	17.7	2.4575	10.0	....
Mean	....	....	10.0	....
10	17.7	.494	1.9	....
10	17.7	.494	2.0	....
10	17.7	.494	2.1	....
10	17.7	.494	1.9	....
Mean	....	....	1.975	2.01

In this case the flow has increased faster than the pressure, but the amount is only 1.74 per cent.

EXPERIMENT II.—TUBE NO. I.

In this case the recently boiled water which has been referred to before was used, and below are the results obtained:

Table showing the relation of pressure to flow of boiled water through glass thermometer tube.

Time.	Temperature.	Pressure of mercury.	Observed flow.	Computed flow.	Percentage departure.
Minutes.	°C.	*Feet.*	*Grams.*	*Grams.*	
10	20.7	2.4623	10.3		
10	20.7	2.4623	10.5		
10	20.7	2.4623	10.2		
Mean			10.275		
10	20.8	1.81816	7.3		
10	20.8	1.81816	7.3		
10	20.8	1.81816	7.3		
Mean			7.3	7.586	3.77
10	20.9	1.157	4.6		
10	20.9	1.157	4.6		
10	20.9	1.157	4.6		
Mean			4.6	4.83	4.672
10	21.0	.786	3.1		
10	21.0	.786	3.1		
10	21.0	.786	3.1		
Mean			3.1	3.27	5.199
20	21.1	.4713	3.45		
20	21.2	.4713	3.45		
20	21.2	.4713	3.45		
Mean			3.45	3.932	12.26

In this case, as in the last one, there is a flow increasing faster than the pressure by per cents, increasing from 3.77 to 12.26.

EXPERIMENT I.—TUBE NO. II.

These measurements were made on the day following those of the last series, a water manometer being used instead of one of mercury. This, for the high pressures, consisted of a straight quarter-inch galvanized pipe extending directly up through the several floors of the laboratory to the attic from the end of the filter next to the tube, as shown in fig. 30 (p. 136), but ending above in a glass tube. The low pressure was measured in the same manner in a straight glass tube.

Table showing the relation of pressure to flow of water through thermometer tube.

Time.	Temperature.	Pressure of water.	Observed flow.	Computed flow.	Percentage departure.
Minutes.	° *C.*	*Feet.*	*Grams.*	*Grams.*	
20	23.3	5.30	1.15	....	....
20	23.9	5.30	1.25	....	....
20	23.6	5.30	1.15	....	....
20	23.5	5.30	1.30	....	....
80	....	....	4.85	6.132	20.90
10	23.8	32.521	4.30	....	....
10	23.9	32.521	4.40	....	....
10	23.9	32.521	4.70	....	....
10	....	32.521	4.80	....	....
10	....	32.521	4.90	....	....
20	23.85	32.521	9.70	....	....
10	23.85	32.521	4.85	....	....
80	....	....	37.65	....	....

In this case also there is a very marked increase of flow faster than the pressure, amounting to more than 20 per cent.

EXPERIMENT II.—TUBE NO. II.

The measurements thus far reported have all been made by allowing the water to fall from the end of the capillary tube into an open beaker in which it was weighed on a Springer torsion balance sensitive to 0.1 gram. It should be said also that the tubes were placed in a horizontal position. In this condition there would be some loss of water by evaporation, and as the percentage loss from the low-pressure flows would be greater than those from the high pressures, the discharges in this series were made to take place into a large test tube closed with a cork, through which the capillary tube extended, and provided with a small vent. Water enough was left in the tube to immerse the capillary tube so that the discharge could take place under water and thus avoid the formation of drops. The flask and capillary tube were weighed together on a chemical balance before and after each observation, and care was taken to shut off both the supply pipe and pressure gage at the instant of closing the experiment. In beginning an experiment the water was allowed to flow through a side opening to avoid pressure on the capillary tube until the moment of starting had arrived.

The following are the results secured in these trials:

Table showing the relation of pressure to flow of water through thermometer tube.

Time.	Temperature.	Pressure of water.	Observed flow.	Computed flow.	Percentage departure.
Minutes.	° *C.*	*Feet.*	*Grams.*	*Grams.*	
10	22.2	5.577	.8770	....	....
10	22.2	5.577	.8530	....	....
20	....	....	1.7300	1.7583	1.61
10	22.2	36.153	5.7115	....	....
10	22.2	36.153	5.6873	....	....
20	....	....	11.3988	....	....

In this series too, although the differences are much smaller than in the last series, they are in the direction of a flow increasing faster than the pressure, and yet, so far as is known, everything has been done which should be done to bring them together.

FLOW OF AIR UNDER HIGH BUT VARIABLE PRESSURE THROUGH POROUS MEDIA AND CAPILLARY TUBES.

Since the flow of water under high pressures through porous media has not been found to be directly proportional to the pressure, and since the flow of air under constant low pressures has been found to increase faster than the pressure, even in capillary tubes, it is important to know what is true regarding the flow of air under higher pressures.

It was not practicable to adopt the method used for the flow of air under low pressures for the higher pressures, and hence resort was had to the method used by Meyer, Hoffman, and others of permitting the flow to take place under constantly varying pressures.

The apparatus here used is represented in fig. 33 and consisted of a galvanized-iron cylinder holding nominally 40 gallons, provided with a

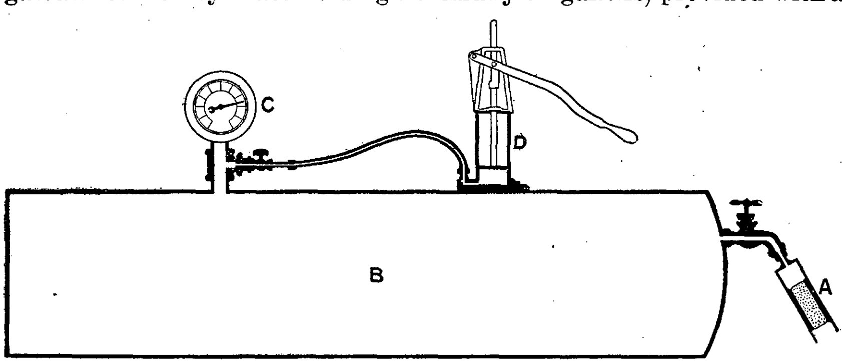


FIG. 33.—Apparatus for measuring flow of air through rock and soil under high pressure. A, sample; B, air reservoir; C, pressure gage; D, compression pump.

Bourdon pressure gage which was calibrated by comparison with a mercurial manometer at the even pound marks from 15 pounds down to 2 pounds.

By means of a compression pump the reservoir was charged until a pressure somewhat above that at which the observations were to begin was reached and then allowed to rest until it had come into a temperature equilibrium with the surroundings. The specimen through which the flow was to be measured was then connected with the reservoir and the cock A was opened, and the time was recorded at which the gauge index reached the even pound marks from 15 down to 2 pounds.

Measurements were made of the flow of air through tubes filled with wire gauze, dust shot, several sands, several of the sandstones, and the two capillary tubes used in the last section, and the results are given in the tables which follow.

To show whether or not the flow of the air through these media was proportional to the pressure, the suggestion of Professor Slichter was followed in using the formula employed by Meyer, Hoffman, and others—

$$\frac{\text{Log}\left(\frac{p+p_2}{p-p_2} \cdot \frac{P-p_2}{P+p_2}\right)}{p_2 t} = C,$$

where C should be constant if the Poiseuille-Meyer law holds true.

P is the pressure in the reservoir at the beginning of the experiment; p is the pressure in the reservoir at the close of the experiment; p_2 is the constant pressure at the free end and t is the time.

All measurements of pressure are given in feet of mercury and the atmospheric pressure is expressed in the same terms.

In giving the values of C in the tables p_2 has been omitted from the expression $p_2 t$ and the results have been multiplied by 100,000 to avoid the printing of long decimal fractions in the tables. The equation as used in the table stands thus:

$$\frac{\text{Log}\left(\frac{p+p_2}{p-p_2} \cdot \frac{P-p_2}{P+p_2}\right)}{t} \times 100{,}000 = C,$$

and this should be understood as representing the values in the columns headed C in the tables.

The experiments were all conducted in the main laboratory and were subject to the ordinary diurnal changes of temperature which occurred during the time of the observations, and as it was impracticable to record the temperature of the apparatus through which the air was passing at the time, this has been omitted.

The values assigned to the pound marks on the dial of the Bourdon gage, from which the pressures were read, are the mean of five separate determinations. As these readings will serve to show what allowance should be made in considering the determinations of pressure for the several experiments which are recorded, they are given in the following table:

Table showing results obtained in calibrating the pressure gage on the air reservoir.

Pounds.	1.	2.	3.	4.	5.	Mean.	Logarithm.
15	2.4685	2.4685	2.4695	2.4700	2.4690	2.4691	0.392509
14	2.3125	2.3130	2.3120	2.3125	2.3120	2.3124	.364061
13	2.1545	2.1575	2.1595	2.1530	2.1550	2.1559	.333629
12	1.9555	1.9605	1.9625	1.9627	1.9640	1.96104	.292487
11	1.7715	1.7740	1.7755	1.7720	1.7740	1.7734	.248807
10	1.5830	1.5850	1.5870	1.5870	1.5815	1.5847	.199947
9	1.4300	1.4360	1.4310	1.4340	1.4320	1.4326	.156125
8	1.2770	1.2710	1.2615	1.2645	1.2635	1.2675	.102949
7	1.1020	1.1040	1.1050	1.1065	1.1110	1.1057	.043637
6	.9255	.9285	.9310	.9315	.9250	.9283	$\bar{1}$.967688
5	.7895	.7920	.7855	.788	.7875	.7885	$\bar{1}$.896802
4	.6105	.6100	.6105	.611	.6105	.6105	$\bar{1}$.785686
3	.4370	.4430	.4400	.440	.4395	.4399	$\bar{1}$.643354
2	.2555	.2550	.2565	.2585	.2475	.2546	$\bar{1}$.405858

In order to reduce to a minimum the errors in reading the gage which are due to the friction of the needle, it was the custom to jar the gage gently but continuously at the time when the finger was passing the index mark.

In the tables which follow, the first column contains the nominal pressures at which the times were recorded, and the second column contains the real pressures of the air in the reservoir. The values in the columns headed "Time" represent the time in seconds required for the pressure to fall from one point to another. The values in the columns headed C should all be equal if the flow of air were proportional to the pressure.

Table showing the relation of pressure to flow of air through porous media.

Pressure.	Pressure of mercury.	Wire gauze.				Dust shot.			
		Length, 1 foot.		Length, 2 feet.		Length, 2.975 feet.		Length, 5.95 feet.	
		Time.	p_2=2.4558. C.	Time.	p_2=2.464. C.	Time.	p_2=2.4375. C.	Time.	p_2=2.4458. C.
Pounds.	*Feet.*	*Secs.*		*Secs.*		*Secs.*		*Secs.*	
15	2.4691	......	....	......	....	......	....	......	....
14	2.3124	3	639.87	5	384.30	7	273.50	12	159.75
13	2.1559	4	521.45	6	347.98	7	297.25	14	148.79
12	1.961	4	725.50	7	414.97	10	289.56	16	178.04
11	1.7734	5	634.48	7	453.60	11	287.80	19	169.40
10	1.5847	5	724.50	9	403.57	13	278.70	20	180.94
9	1.4326	5	649.80	9	372.50	11	304.02	20	167.34
8	1.2675	5	833.64	8	521.40	11	378.30	19	219.20
7	1.1057	7	683.20	10	478.58	15	318.40	23	207.77
6	.9283	9	701.10	13	485.10	13	370.27	30	210.19
5	.7885	9	670.50	13	465.02	19	317.66	29	207.97
4	.6105	11	884.90	17	562.80	21	463.09	38	256.02
3	.4399	14	919.66	23	559.30	30	428.59	52	247.50
2	.2546	20	1,110.67	30	711.50	42	528.83	73	304.20

Table showing the relation of pressure to flow of air through sand.

Pressure.	Pressure of mercury.	No. 20 sand. Length, 2.975 feet. Time.	No. 20 sand. Length, 2.975 feet. p_2=2.484. C.	No. 20 sand. Length, 5.95 feet. Time.	No. 20 sand. Length, 5.95 feet. p_2=2.484. C.	No. 80 sand. Length, 5.95 feet. Time.	No. 80 sand. Length, 5.95 feet. p_2=2.4775. C.	No. 100 sand. Length, 5.95 feet. Time.	No. 100 sand. Length, 5.95 feet. p_2=2.4775. C.
Pounds.	*Feet.*	*Secs.*		*Secs.*		*Secs.*		*Secs.*	
15	2.4691	......	....	......	....	......	....	......	....
14	2.3124	29	66.43	45	42.81	52	36.91	63	30.47
13	2.1559	36	58.14	47	44.53	60	35.01	73	28.78
12	1.961	43	67.71	62	46.96	69	42.12	86	33.80
11	1.7734	50	65.64	67	48.99	79	40.14	92	34.47
10	1.5847	54	67.40	74	49.81	81	45.13	121	30.21
9	1.4326	52	64.59	69	48.68	76	43.56	85	38.95
8	1.2675	52	80.35	70	59.69	80	52.26	90	46.46
7	1.1057	64	74.89	88	54.47	94	50.91	116	41.26
6	.9283	82	77.01	100	63.15	111	56.76	141	44.68
5	.7885	81	74.72	119	50.86	113	53.54	141	42.91
4	.6105	102	95.56	128	76.31	134	72.72	170	57.32
3	.4399	140	92.01	180	71.56	183	70.37	228	56.44
2	.2546	210	105.87	261	85.20	264	84.22	325	68.41

Pressure.	Pressure of mercury.	No. 60 sand. Length, 5.95 feet. Time.	p_2=2.4775. C.	Time.	p_2=2.4775. C.	Time.	p_2=2.4775. C.	Mean. Time.	Mean. p_2=2.4775. C.
Pounds.	*Feet.*	*Secs.*		*Secs.*		*Secs.*		*Secs.*	
15	2.4691	......	....	......	....	......	....	....	....
14	2.3124	47	40.84	52	36.91	48	39.99	49	39.247
13	2.1559	60	35.01	59	35.61	64	32.83	61	34.843
12	1.961	74	39.28	77	37.75	73	39.82	74.6	38.950
11	1.7734	79	40.14	76	41.72	77	41.18	77.3	41.013
10	1.5847	87	42.01	89	41.07	84	43.51	86.7	42.197
9	1.4326	78	42.45	?105	31.53	81	40.88	79.5	41.665
8	1.2675	89	46.98	89	46.98	87	48.06	88.3	47.340
7	1.1057	99	48.34	100	47.86	100	47.86	99.7	48.020
6	.9283	122	51.64	121	52.07	122	51.64	121.7	51.783
5	.7885	124	48.79	121	50.00	122	49.59	122.3	49.460
4	.6105	156	62.46	156	62.46	152	64.11	154.7	63.010
3	.4399	202	63.75	209	61.61	204	63.12	205	62.827
2	.2546	283	78.56	276	80.56	279	79.69	279.3	79.603

From these tables it is very evident that in no case has the Poiseuille-Meyer law been confirmed, the flow in every case being very much slower than is called for. Had the law been fulfilled, all values in the columns headed C would have been equal, or nearly so; but as it is, the flow has been too slow by large amounts. When comparison is made between the constants for the highest pressures and those for the lowest pressures, it will be found in each case that the flows under the high pressures have been too slow by the following percentage amounts:

Table showing percentages of slowness of flow of air through different materials as compared with requirements of Poiseuille-Meyer law.

Material.	Thickness.	Highest-pressure flow too slow by—
	Feet.	*Per cent.*
Wire gauze	2	85.15
Do	1	72.57
Dust shot	5.95	90.43
Do	2.975	93.35
No. 20 sand	5.95	99.25
Do	2.975	59.37
No. 60 sand	5.95	102.80
No. 80 sand	5.95	128.2
No. 100 sand	5.95	124.5

The pores formed by the elements which make up the different media through which we have measured the flows constitute long capillary tubes, which have a somewhat triangular section similar to those formed by the knitting needles which have been considered. The pores, however, are not straight and are not of uniform diameter in all sections, as Professor Slichter shows in his paper, page 314. He has concluded that the mean effective area of the section of the pore for spherical grains of the same diameter, when they have the closest packing possible, is about 0.1475 time the square of the radius of the grain.

Assuming that this estimate is correct, we may state the dimensions of the capillary pores through which the measured flows given in the table have taken place. The effective sizes of the grains have been determined by a method which will be described later, and using these values and that stated above we get the results given in the next table, in which has also been given the diameter of a circular tube having the same area of cross section.

Table showing dimensions of pores in the wire gauze, shot, and sands of the foregoing tables.

Medium.	Length of tube.	Effective diameter of grain.	Effective area of pore.	Diameter of circular pore of equal area.
	Cm.	*Mm.*	*Sq. mm.*	*Mm.*
Wire gauze:				
1	30.48	....	....	....
2	60.96	....	0.1316	0.4093
Dust shot:				
1	90.678	....	....	....
2	181.356	1	.0369	.2260
No. 20 sand:				
1	90.678	.4745	.00831	.1028
2	181.356	.4745	.00831	.1028
No. 60 sand	181.356	.1551	.000887	.0336
No. 80 sand	181.356	.1143	.000482	.0248
No. 100 sand	181.356	.0826	.000252	.0179
Meyer's Tube No. II	155.3	....	.1114	.3766

In this table has been placed the dimensions of Meyer's capillary Tube No. II, which is one of those used by him in demonstrating that the law of Poiseuille holds for air. Below is given a set of his observations with this tube to show how different the flow has been.

Table showing departures from constant logarithmic differences in observations of Meyer with Tube No. II.

Experiment.	Pressures of mercury.	Departures of flow from first logarithmic constant.								Per cent of departure.	
										Smallest.	Largest.
	Millimeters.										
1	1,346.7 to 344.9	0.0362	+3	−2	−9	− 5	− 7	−6	−9	0.5525	2.486
2	1,326.7 to 392.8	.0373	−3	−4	−5	− 6	− 5	−5	....	.804	1.609
3	631.7 to 152.0	.0528	−1	0	+5	+10	+13	....	....	0	2.462
4	662.4 to 386.6	.0205	+8	+2	+4	+ 5	+ 6	....	....	.976	3.903
5	700.4 to 195.2	.0195	+1	+3	+2	+ 1	+ 2	....	....	.513	1.538
7	619.0 to 131.0	.0552	−2	−6	−8	.....	.....	....	....	.362	1.449

The pressures used when expressed in millimeters of mercury ranged from 752.5 to 77.6, while Meyer's pressures ranged from 1,346.7 to 131 mm., as given in the following table, yet the largest percentage departure from the law, as shown by his logarithmic differences, is 3.903. But the length of his tube was 155.3 cm., while the sand columns, when the tube was full, had a length of 181.3 cm., which is longer than his. Further than this, the diameter of his tube was 0.3766 mm., which is longer than those of the coarsest, or No. 20, sand, or 0.1028 mm., supposing the grains to be of uniform diameter and to possess the closest packing possible. It is true, however, that these grains are neither spherical nor uniform in diameter; neither did they possess the closest possible packing, and hence it follows that the actual pores through which the flow occurred in this sand may have been larger than the dimension given in the table, namely, 0.1028 mm.

But be this as it may, there can be no doubt that the effective diameters of the pores in sands Nos. 60, 80, and 100 are smaller than that of Meyer's tube. It would appear, therefore, that did the Poiseuille-Meyer law hold for sands under like pressures a closer agreement than has been observed should have been found.

FLOW OF AIR THROUGH SANDSTONES.

Next will be given a series of similar observations on the flow of air through sandstones, where the same apparatus was used. These specimens of stone had been rendered water free by drying in the oven before they were mounted in the cylinders, but remained exposed to the air after mounting, so they may have contained varying amounts of hygroscopic moisture.

Table showing the relation of pressure to flow of air through Madison sandstone.

Pressure.	Pressure of mercury.	Sandstone No. 2. Length, 1.71 inches (4.343 cm.).		Sandstone No. 3. Length, 3.06 inches (7.772 cm.).		Sandstones Nos. 2 and 3. Length, 4.77 inches (12.115 cm.).	
		Time.	$p_2=2.47$. C.	Time.	$p_2=2.47$. C.	Time.	$p_2=2.47$. C.
Pounds.	*Feet.*	*Seconds.*		*Seconds.*		*Seconds.*	
15	2.4691	....	....	....	....	....	....
14	2.3124	21	91.31	38	50.46	60	31.96
13	2.1559	25	83.95	47	44.66	70	29.98
12	1.1961	40	72.60	57	50.95	83	34.99
11	1.7734	32	99.02	64	49.51	92	34.44
10	1.5847	44	84.94	70	52.18	111	32.90
9	1.4326	41	81.91	70	47.98	101	33.25
8	1.2675	47	88.90	79	52.89	121	34.53
7	1.1057	57	83.91	96	49.82	146	32.76
6	.9283	70	89.96	116	54.29	178	35.38
5	.7885	77	78.54	130	46.52	195	31.01
4	.6105	98	99.40	172	56.63	271	35.94
3	.4399	138	93.29	258	49.90	388	33.18
2	.2546	205	108.40	374	59.44	630	35.29

Table showing the relation of pressure to flow of air through Dunnville sandstone.

Pressure.	Pressure of mercury.	Sandstone No. 3. Length, 1.62 inches (4.115 centimeters).		Sandstone No. 1. Length, 4.02 inches (10.211 centimeters).		Sandstone Nos. 1 and 3. Length, 5.64 inches (14.324 centimeters).	
		Time.	p_2=2.47. C.	Time.	p_2=2.47. C.	Time.	p_2=2.47. C.
Pounds.	*Feet.*	*Seconds.*		*Seconds.*		*Seconds.*	
15	2.4691	-------	---------	--------	---------	--------	---------
14	2.3124	84	22.83	193	9.936	305	6.287
13	2.1559	95	22.09	220	9.540	335	6.265
12	1.961	122	23.81	270	10.76	425	6.833
11	1.7734	129	24.56	310	10.22	470	6.741
10	1.5847	161	22.69	352	10.38	544	6.714
9	1.4326	153	21.95	330	10.18	541	6.208
8	1.2675	173	24.15	391	8.590	580	7.204
7	1.1057	209	22.88	467	10.24	732	6.534
6	.9283	259	24.31	575	10.95	863	7.297
5	.7885	301	20.09	648	9.333	1,080	5.600
4	.6105	385	25.30	930	10.47	1,405	6.949
3	.4399	550	23.41	1,193	10.79	1,940	6.636
2	.2546	923	24.08	2,004	11.09	3,027	7.344

In these cases it is plain that here also the flow has not conformed with the law, the amount passing through in a given time under the different pressures being less than would be computed.

If the percentage departures are computed in the same manner as with the sands the following results are obtained:

Percentage departure from Poiseuille-Meyer law in Madison and Dunnville sandstones.

Sandstone.	Length of sample.	Highest-pressure flow too slow by—
	Centimeters.	*Per cent.*
Madison	4.343	10.44
Do	7.772	17.80
Do	12.115	10.42
Dunnville	4.115	5.475
Do	10.211	13.1
Do	14.32	16.8

Here are shown departures ranging from 5 to 16 per cent, and while these are very much smaller than those observed in the coarser sands, they are still too large and too persistent throughout the six series to be explained by errors of observation.

One of the samples of Dunnville stone was crushed in a mortar and separated into its constituent grains. The sand was filled into the aspirator tube and the rate of flow of air through this measured to determine the effective size of the individual grains. The size found was 0.03635 millimeter, and using the equation,

$$\text{Area of pore} = .1475 \times R^2,$$

we get an area of cross section of the effective pore in this case amounting to 0.00004875 square millimeter, and from this the diameter of the pore is found to be .007878 millimeter. This is a small capillary tube and one whose diameter is contained in the combined length of the two pieces which were used together for the results given in the table 17,307 times. Meyer concludes from his experiments that with capillary tubes for air the proper ratio of length to diameter, in order that the law may hold, is about 1 to 6,000. As Professor Slichter's studies would make the lengths of these pores about 1.06 times the length of the stone measured straight, it is plain that the ratio of length of pore to diameter of pore is not such as would be expected to cause a departure from the law of Poiseuille.

It would therefore appear that if the law holds at all for these stones its range must be limited by far slower velocities than may obtain for straight capillary tubes with smooth walls. We have already shown that under pressures ranging from 1 mm. up to possibly 50 mm. the flow of air through these particular specimens did increase a little faster than the pressure. The inference might naturally be made from these two sets of measurements with the sands and the stones that, since the flow increases more rapidly than the pressures under those which are very low and does not increase so rapidly under pressures which are higher, there must be a range of pressures somewhere between these two limits where the rate of flow will be found to increase in accordance with the Poiseuille-Meyer law.

Still, if it is admitted that with a given capillary medium there are ranges of pressures under which the flow does increase faster than the pressure, and others where it is directly proportional to the pressures, while under still higher pressures the rate of increase becomes slower than the increase of pressure, it may also be assumed with as much apparent plausibility that we are here dealing with a set of phenomena which pass by insensible steps from one phase to the other and which can not be formulated by so rigid a law as that of Poiseuille.

FLOW OF AIR UNDER HIGH PRESSURE THROUGH CAPILLARY TUBE NO. II.

The two pieces of thermometer tubes through which the flow of water was measured under high pressures, as already described, were also used for air, they being placed upon the large reservoir used for the experiments on the flow of air through sands and sandstones, and the method of securing the results was the same as described for those.

The results which were secured with the longer of these tubes are given below.

Table showing the relation of pressure to flow of air through capillary Tube No. II.

Pressure of mercury.	Time.	Barometric pressure.	C.
Feet.		*Inches.*	
2.4691	June 6, 9.58.10 a. m	29.20	....
2.3124	June 6, 11.22.45 a. m	29.10	.3760
2.1559	June 6, 3.01.10 p. m	29.07	.3534
1.961	June 6, 6.07.20 p. m	29.02	.2585
1.2675	June 7, 10.13.25 a. m	29.01	.2463
1.1057	June 7, 5.32.20 p. m	28.93	.1808
.7885	June 8, 9.58.25 a. m	28.95	.2082
.4391	June 9, 3.38.00 p. m	29.02	.2113
.2546	June 10, 11.45.00 p. m	28.77	.1920

In this case there is a surprisingly large departure from the Poiseuille-Meyer law in the direction opposite that shown to hold with the sands and sandstones, but coinciding with the flow of water through the same tube, namely, the flow increasing faster than the pressure.

RESULTS OF OTHER INVESTIGATIONS RELATING TO THE FLOW OF WATER THROUGH SOILS.

Results of Darcy.—The investigations of Darcy[1] concerning the permeability of sand layers in water filters led him to the conclusion that the rate of flow through them was directly proportional to the pressure and inversely proportional to the thickness of the filter beds, and, further, that the amount of the outflow varied with the diameter of the sand grains.

Results of Hagen.—Hagen's[2] investigations, however, failed to establish any constant relation between the amount of discharge and the pressure under which it occurred. He was, however, led to agree with Darcy in that the flow was inversely proportional to the length or depth of the stratum penetrated.

[1] Les fontaines publiques de la ville de Dijon, par Henri Darcy, Paris, 1856.
[2] Handbuch der Wasserbaukunde, Berlin, 1869.

Results of Seelheim.—F. Seelheim[1] conducted a series of experiments relating to the flow of water through sands and clay, in which he used the apparatus represented in fig. 34. This consisted of a vessel for holding soils, whose form was varied, but was usually that shown in the engraving at A; a funnel, B, into which the discharge took place and in which the temperature was measured; a tube, C, whose length could be varied and in which the water pressure desired could be held constant by means of the siphon and Mariotte flask shown at D and E, F being a wadding filter.

The sands to be investigated were first subjected to thorough washing and digestion with concentrated hydrochloric acid, in order to remove calcium carbonates and soluble silicates. They were then washed, boiled with soda solution, and washed again. After being dried they were treated with fused potassium bisulphate to remove all clay, then washed, then boiled with potash lye, again washed, dried, and finally heated to remove all organic material.

The sands thus treated were then sorted by means of screens into four grades.

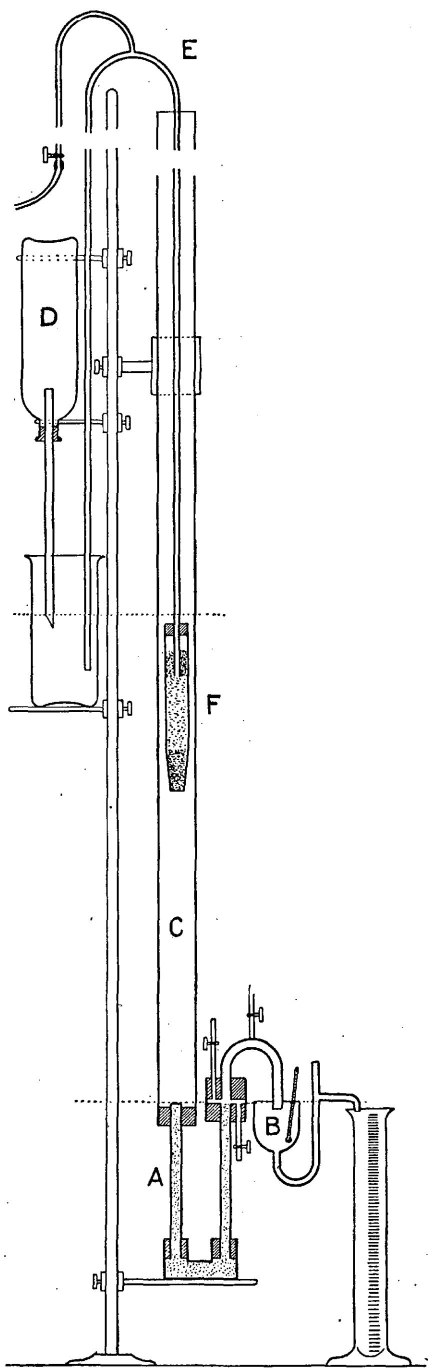


FIG. 34.—Seelheim's apparatus for measuring flow of of water through sands. A, U-formed tube; B, discharge funnel; C, pressure tube; D, Mariotte bottle; E, siphon; F, filter.

[1] Methoden zur Bestimmung der Durchlässigkeit des Bodens: Zeitschrift für analytische Chemie, Vol. XIX, p. 387.

The clay experimented with was treated in various ways to remove undesired materials until, when analyzed, it showed the following composition:

Analysis of clay used by Seelheim.

Constituent.	Per cent.
Silicic acid	45.54
Alumina	38.77
Water	15.69
	100.00

The sand was first boiled under water to remove air, and then introduced into the holder, A, already filled with water, which was jarred until no further settling occurred and until the holder was entirely full.

We shall now quote some of Seelheim's results so far as they bear upon the relation of flow to pressure.

Table showing relation of pressure to flow through sand in U-formed tube.

Pressure.	Time.	Temperature.	Mean flow.
Cm.	*Minutes.*	° *C.*	*C. c.*
150	15	8.0	41.0
100	15	7.9	27.5
50	15	8.0	13.7

In this series the flows are very nearly proportional to the pressure, the discharge under 100 cm. being 3.328 per cent higher than would be computed from the flow under the low pressure, while that under 150 cm. is 2.433 per cent too low.

In another experiment, in which chalk was used, where the ratio of chalk to water was as 3.5 grams to 1 gram, the following results were obtained by Seelheim:

Table showing relation of pressure to flow through chalk.

Pressure.	Time.	Temperature.	Mean flow.
Cm.	*Minutes.*	° *C.*	*C. c.*
150	60	12	0.38
100	60	12	.24

In this case the flow under the higher pressure is 5.55 per cent greater than would be computed from the law.

With clay, where the ratio of clay to water was 5 to 3.286, the results were:

Table showing relation of pressure to flow through clay.

Pressure.	Time.	Temperature.	Mean flow.
Cm.	*Minutes.*	° *C.*	*C. c.*
150	60	12	0.59
100	60	12	.39

In this case the flow increases faster than the pressure by only 0.855 per cent.

In his work with clay, having smaller amounts of water, Seelheim found it impervious under the lower pressures, but under higher pressures flows did take place, and the results below are given for a mixture of 5 parts of clay to 1.505 parts water.

Table showing relation of pressure to flow through clay.

Pressure.	Time.	Temperature.	Mean flow.
Centimeters.	*Minutes.*	°*C.*	*C. c*
456	240	12	0.35
1, 150	240	12	.87

In this case the flow under the higher pressure was 1.439 per cent faster than would be computed from the law.

In these four sets of trials there are four cases where the flow has increased faster than the pressure and one where the reverse was true. They stand as follows:

Percentage departure of flow from Poiseuille-Meyer law in foregoing experiments.

Material.	Pressure.	Percentage departure.
	Centimeters.	
Sand 1	50–150	—2. 433
Sand 2	50–100	+3. 328
Chalk......	100–150	+5. 555
Clay 1......	100–150	+ .855
Clay 2......	456–1, 150	+1. 439

Judging from the form of Seelheim's apparatus, evaporation must have taken place from the surface of the water in the funnel in which the temperatures were taken, and this and whatever evaporation may have occurred in the dropping and the measuring cylinder would diminish the percentage of flow under low pressures more than those under high pressures, and hence would tend to give results showing the relations which are found; that is, if evaporation did take place during the experiments and no corrections were applied for it, then an exact agreement with the law of Poiseuille shown by the figures would mean that the flow had not increased so rapidly as the pressure.

In his three sets of experiments to determine the relation of length of columns of sand to flow, his flows were not exactly what would be computed from the lengths of the columns through which the flow took place, as the results he obtained, which are given below, show.

Relation of flow to length of column.

Material.	Lengths.	Flows.	Time.	Percentage departure.
		C. c.	*Minutes.*	
Sand	2 to 1	8.3 to 16.8	30	+1.205
Clay	1.5 to 1	.46 to .71	60	+2.899
Chalk	1.5 to 1	.31 to .48	60	+3.226

This comparison is made here by using the flow through the long column as the standard, because reducing the length of the column is assumed by the law to be equivalent to increasing the pressure a like amount, and the percentage differences in the table show how much larger the observed flows were than would be computed from the law; but differences in this direction should be found if the flow did really increase faster than the pressure. Seelheim's results stand 7 to 1 in favor of flow increasing faster than the pressure.

Observations of Trautwine.—In Bulletin 45 of the Colorado Agricultural Experiment Station, Prof. L. S. Carpenter quotes some results obtained by John C. Trautwine, jr., chief of the bureau of water, Philadelphia, on the rate of seepage from the Queen Lane reservoir under different depths of water, from which it appears that the rate of flow increases faster than the pressure increases.

Carpenter gives the following table as showing the observed results:

Table showing the rate of seepage from Queen Lane reservoir, Philadelphia.

November, 1897 (before silting).		March, 1898 (after silting).	
Depth.	Loss per day.	Depth.	Loss per day.
Feet.	*Inch.*	*Feet.*	*Inch.*
15	0.29	20	0.15
20	.54	25	.24
		28	.32
		30	.46

It will be seen that these observations show seepage increasing very much more rapidly than the pressure.

Carpenter, referring to his own observations on the rate of seepage from canals, says that several cases "show that the loss increases with the depth of water in the canal, but the loss seems to be greater than shown from theoretical considerations."

In such cases as these account must of course be taken of the increase in the surface through which seepage may occur when the depth of the water in the canal or reservoir is increased, and the data from Trautwine simply show the total seepage, and hence the seepage ought to appear to increase with depth, provided the sides of the reservoir are not wholly impervious to water.

It might well happen, both in reservoirs and canals, that the new surface through which seepage could take place when the water level is raised might transmit the water relatively faster because of not being so thoroughly silted up, and if so, the seepage in such cases would appear to increase faster than the depth even when directly proportional to it.

We can not therefore accept these data as demonstrating that under the conditions of reservoirs and canals seepage increases faster than the pressure until correction has been made for the lateral seepage, which may become possible with the rise of the water.

Observations of Welitschkowsky.—The experiments of Welitschkowsky[1] and those of Wollny[2] were conducted with an apparatus represented in fig. 35, which consists, as Wollny used it, of a cylinder, A, 5 cm. in diameter, in which the medium to be investigated is placed. This is provided at the bottom with a fine wire screen to retain the sand and permit the escape of the water

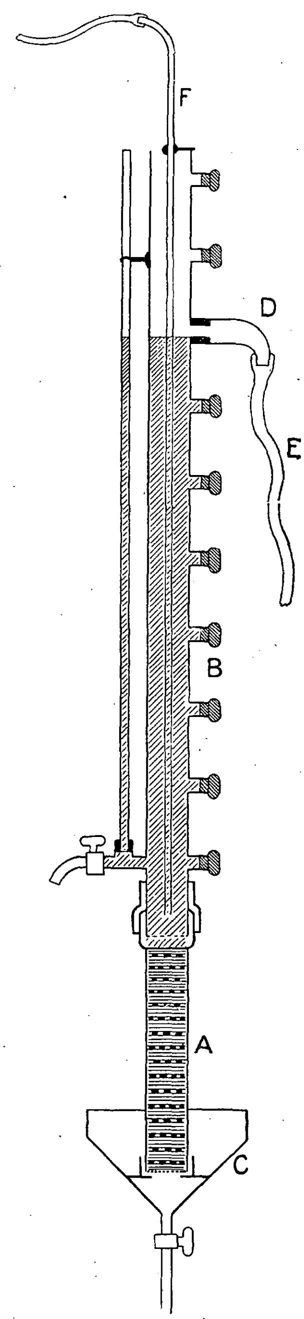


FIG. 35.—Apparatus used by Wollny for measuring flow of water through soil. A, soil tube; B, pressure tube; C, funnel; D, E, overflow; F, supply pipe.

[1] Archiv für Hygiene, Vol. II, 1884, pp. 499-512.

[2] Forschungen auf dem Gebiete der Agrikulturphysik, Vol. XIV, 1891, pp. 1-28.

into the funnel below. The pressure was varied by means of a tube which was provided with overflow tubes 10 cm. apart and which could be coupled to the soil tube in a water-tight manner by means of a wide rubber band.

Below is given one of the tables of results reached by Welitschkowsky, in which columns are introduced giving the flows computed from the flow under the lowest pressure, assuming that the law of Poiseuille holds true; but in computing these results the pressure is taken equal to the length of the sand column plus that of the column of water above the sand.

Table showing the relation of pressure to flow of water through sand made up of grains 0.33 mm. to 1 mm. in diameter.

[Flow of water in cubic centimeters per minute.]

Depth of water above the sand.	100 cm.		75 cm.		50 cm.		25 cm.	
	Observed.	Computed.	Observed.	Computed.	Observed.	Computed.	Observed.	Computed.
10 cm...	96	....	98	....	106	....	131	....
20 cm...	105	104.7	109	108.5	123	123.6	175	168.4
30 cm...	112	113.5	121	121.1	141	141.3	216	205.9
40 cm...	119	122.2	133	132.6	160	158.9	259	243.3
50 cm...	126	130.9	144	144.1	179	176.7	306	280.7
60 cm...	135	139.6	155	155.7	198	194.3	348	318.1
70 cm...	143	148.4	167	167.2	218	211.9	390	355.6
80 cm...	151	157.1	178	178.7	237	229.3	435	393.0
90 cm...	159	165.8	189	189.2	255	247.2	477	430.4
100 cm..	167	174.5	201	201.8	273	264.9	521	467.9

We have here a set of extremely interesting and instructive results. It is to be observed, in the first place, that the column of sand 25 cm. long gives a flow under each of the ten different pressures, increasing faster than the pressure by amounts ranging from 3.9 per cent under a pressure of 45 cm. of water to 11.3 per cent when the pressure becomes 125 cm. When the column has its length doubled, or made 50 cm. high, there is under the lowest pressures, 70 and 80 cm., a nearly complete agreement with the law; but as the pressure is increased the flow becomes faster than is required until, under a pressure of 150 cm., it exceeds the computed amount by 3 per cent. Then when this column was given a length of 75 cm. there became practically an almost complete agreement of observation with theory, the percentage departure in no case reaching as much as 0.5 of 1 per cent. It must be conceded, however, that this percentage departure is real rather than apparent, for were it due to the chance irregularities of errors of observation the departures would not be persistently in one direction, as they are with but two exceptions.

In the case of the sand column 100 cm. long the agreement with the law is very close under the lowest velocities, but as the velocity increases the departure changes phase and becomes larger and larger until one of 4.3 per cent is reached where the trials end. It is seen, therefore, that in this series of observations with one and the same sand, varied only in length of column and pressure under which the flow takes place,

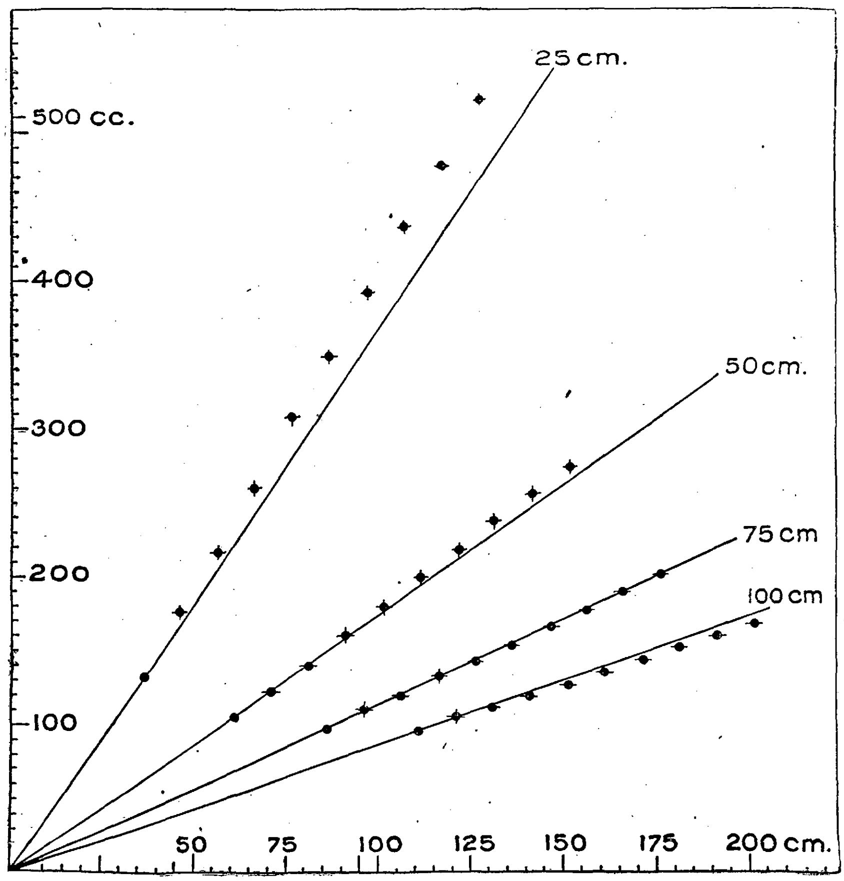


FIG. 36.—Diagram showing the relation of pressure to flow of water through sands, by Welitschkowsky. Straight lines show theoretical flow through sand columns of different specified depths; + dots, flow increasing faster than pressure; — dots, flow increasing slower than pressure. Abscissas indicate pressure and ordinates flow.

there is a passage from a rate of discharge increasing faster than the pressure increases through a flow almost exactly proportional to the pressure and then on to one where the flow increases less rapidly than the pressure. Taking the whole series together, there is a departure ranging from plus 11.3 per cent on one side to minus 4.3 per cent on the other, or a total of 15.6 per cent. The results of the table are shown graphically in fig. 36.

In a still finer sand, having a diameter less than 0.33 mm., the same investigator found the following relations of flow to pressure where the length of the column was 50 cm.:

Relation of flow to pressure in fine sand.

	Pressures in centimeters.									
	60.	70.	80.	90.	100.	110.	120.	130.	140.	150.
	C. c.	*C. c.*	*C. c.*	*C. c.*	*C. c.*	*C. c.*	*C. c.*	*C. c.*	*C. c.*	*C. c.*
Observed flow.	0.13	0.14	0.17	0.19	0.22	0.24	0.25	0.28	0.30	0.31
Computed flow	.13	.142	.173	.195	.217	.238	.260	.281	.302	.325

In this set the observed flows very nearly coincide with the computed flows.

Observations of Wollny.—Wollny followed Welitschkowsky, making a longer series of observations with essentially the same kind of apparatus, using finer materials and a greater variety of them, but it is very unfortunate for the purposes here that in tabulating his results small variations in flow have been set aside by interpolation and the flows under the pressures resulting from 10, 30, 50, 70, and 90 cm. of water above the sand have been computed from the others rather than observed.

It is further to be noted that Wollny appears to have considered only the column of water above the sample as effective in producing pressure instead of the height of the column of water plus that of the sand which must be taken with the form of apparatus used by him.

The table below shows the results of two series of Wollny's experiments with the data presented as he gives them, and the following table presents the same data in the form in which those of Welitschkowsky have been given; that is, as they must stand with the pressure equal to the length of the column of sand plus that of the water above the sand.

Table showing the relation of pressure to flow of water through sand as presented by Wollny.[1]

Number.	Size of grains.	Water pressure.	Discharge in 10 hours, in liters.		
			Soil 10 cm. thick.	Soil 20 cm. thick.	Soil 30 cm. thick.
	Millimeters.	*Centimeters.*			
IV ...	0.171 to	10	29.570	23.779	20.678
	0.250	20	45.380	32.192	26.111
		30	61.190	40.605	31.544
		40	77.000	49.018	36.977
		50	92.810	57.431	42.410
		60	108.620	65.844	47.843
		70	124.430	74.257	53.276
		80	140.240	82.670	58.709
		90	156.050	91.083	64.142
		100	171.860	99.496	69.575
VII ..	1 to 2	10	311.462	256.777	237.757
		20	444.799	361.402	331.299
		30	578.136	466.027	424.841
		40	711.473	570.652	218.383
		50	844.810	675.277	611.925
		60	978.147	779.902	705.467
		70	1,111.484	884.527	799.009
		80	1,244.821	989.152	892.551
		90	1,378.158	1,093.777	986.093
		100	1,511.495	1,198.402	1,079.639

[1] Forschungen auf dem Gebiete der Agrikulturphysik, Vol. XIV, pp. 13-14.

Since the values given under the pressures 10, 30, 50, 70, 90 have been computed rather than observed, they are omitted from the table which follows.

Table showing the relation of pressure to flow of water through sands.
(*From the last table.*)

[Flow during 10 hours, in cubic centimeters.]

Kind of sand.	Soil 10 centimeters thick.			
	Pressure.	Observed flow.	Computed flow.	Percentage departure.
	Centimeters.	*C. c.*	*C. c.*	
No. IV; size, 0.171 to 0.25 millimeters	30	45, 380	....	....
	50	77, 000	75, 633	+1. 84
	70	108, 620	105, 886	+2. 58
	90	140, 240	136, 139	+3. 01
	110	171, 860	166, 393	+3. 29
No. VII; size, 1 to 2 millimeters	30	444, 799	....	....
	50	711, 473	741, 332	—4. 03
	70	978, 147	1, 037, 864	—5. 75
	90	1, 244, 821	1, 334, 397	—6. 72
	110	1, 511, 495	1, 630, 930	—7. 32

Kind of sand.	Soil 20 centimeters thick.			
	Pressure.	Observed flow.	Computed flow.	Percentage departure.
	Centimeters.	*C. c.*	*C. c.*	
No. IV; size, 0.171 to 0.25 millimeters	40	32, 192	....	5
	60	49, 018	48, 288	+ 1. 51
	80	65, 844	64, 384	+ 2. 27
	100	82, 670	80, 480	+ 2. 72
	120	99, 496	96, 576	+ 3. 02
No. VII; size, 1 to 2 millimeters	40	361, 402	....	....
	60	570, 652	542, 103	+ 5. 27
	80	779, 902	722, 804	+ 7. 90
	100	989, 152	903, 505	+ 9. 48
	120	1, 198, 402	1, 084, 206	+10. 54

Kind of sand.	Soil 30 centimeters thick.			
	Pressure.	Observed flow.	Computed flow.	Percentage departure.
	Centimeters.	*C. c.*	*C. c.*	
No. IV; size, 0.171 to 0.25 millimeters	50	26, 111	....	....
	70	36, 977	36, 555	+ 1. 15
	90	47, 843	47, 000	+ 1. 79
	110	58, 709	57, 444	+ 2. 20
	130	69, 575	67, 889	+ 2. 48
No. VII; size, 1 to 2 millimeters	50	331, 299	....	....
	70	518, 383	463, 819	+11. 76
	90	705, 467	596, 338	+18. 30
	110	892, 551	728, 858	+22. 46
	130	1, 079, 639	861, 377	+25. 34

It will be seen that these results, when considered in their proper relation, show in one series an increase of flow faster than the increase of pressure, while in the other series the same thing is true, except for the shortest column, where the flow does not increase as rapidly as the pressure. The results of these tables are shown graphically in fig. 37.

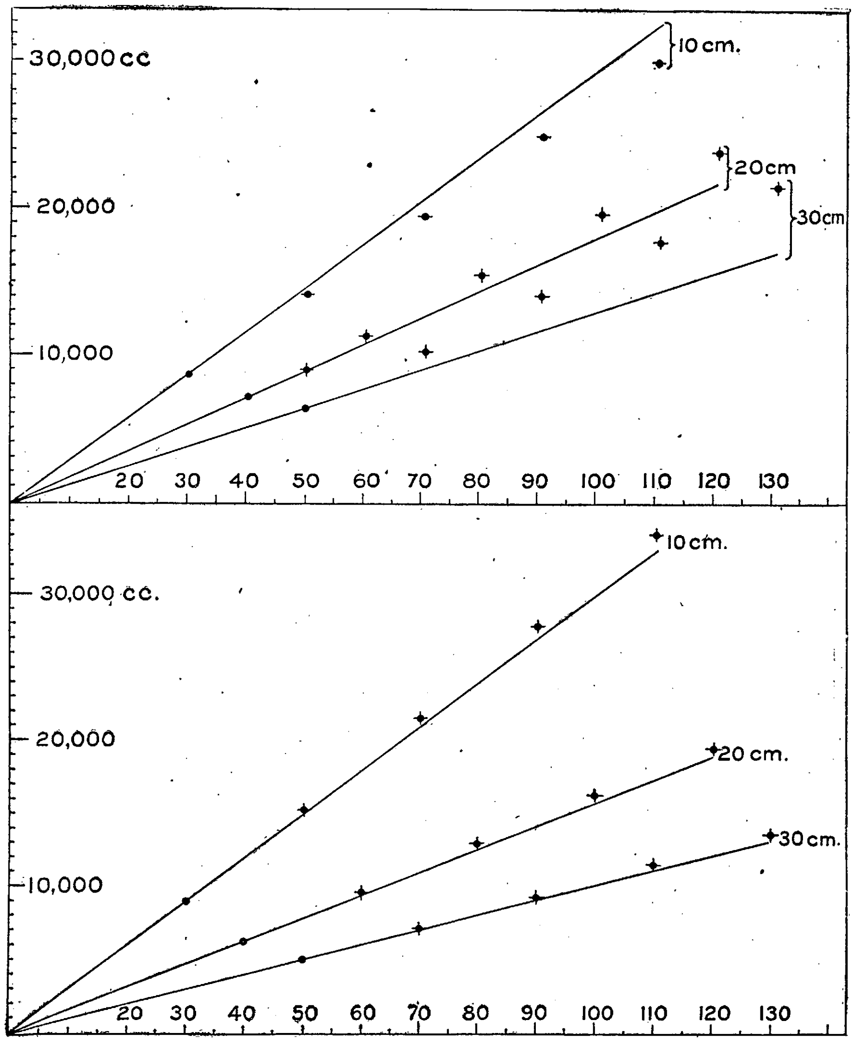


FIG. 37.—Diagram showing relation of pressure to flow of water through sands, by Wollny. Straight lines show theoretical flow through column lengths of 10, 20, and 30 centimeters; + dots, flow increasing faster than pressure; — dots, flow increasing slower than pressure. Abscissas indicate pressure in centimeters and ordinates flow in cubic centimeters.

In his three finest grades of quartz sand, Nos. I, II, and III, the flow increases less rapidly than the pressure, while with Nos. V and VI the reverse again is true. It should be noted that, as in the cases cited, the observations show a flow persistently, either increasing faster than the pressure or else not so rapidly as the pressure, for each particular sample and length of column.

RESULTS OF OTHER INVESTIGATIONS ON THE FLOW OF AIR THROUGH SOILS.

The observations made in this inquiry on the relation of pressure to flow of air through various porous media have already been presented. It is the purpose here to refer to some of the results of others in the same line.

Wollny[1] has presented the latest results bearing upon this subject, and in reviewing the matter preparatory to his own discussion he refers to the experiments of H. Fleck,[2] F. Renk,[3] G. Ammon,[4] and D. Welitschkowsky[5] on the permeability of soil for air as giving results which are in many respects discordant and contradictory.

Observations of Fleck.—While Fleck concludes that the quantity of air flowing through soil is inversely proportional to the pressure, Renk holds that this relation exists only within narrow limits, or only so long as the actual velocity of the air does not exceed 0.062 meter per second, and then only for the finer soils, unless the columns are long.

Observations of Welitschkowsky.—Welitschkowsky, working with a Munich pebbly soil having grains from 1 mm. to 2 mm. in diameter, secured the following relations of flow to pressure when the length of column was 49.6 cm. and the pore space 37.38:

Pressure of water.	Observed flow per minute.	Computed flow per minute.	Percentage departure.	Pressure of water.	Observed flow per minute.	Computed flow per minute.	Percentage departure.
Mm.	*Cubic cm.*	*Cubic cm.*		*Mm.*	*Cubic cm.*	*Cubic cm.*	
10	1,628	....	....	90	12,985	14,652	—11.38
20	3,118	3,356	— 7.09	100	14,202	16,280	—12.76
30	4,567	4,884	— 6.49	110	15,410	17,908	—13.95
40	5,996	6,512	— 7.92	120	16,826	19,639	—14.32
50	7,399	8,140	— 9.10	130	18,088	21,164	—14.54
60	8,802	9,768	— 9.889	140	19,647	22,792	—13.80
70	10,212	11,396	—10.39	150	20,803	24,420	—14.81
80	11,490	13,024	—11,77	160	22,061	26,048	—15.26

The material here used is coarser than the coarsest reported on by the writer, and the percentage departures from the Poiseuille-Meyer law are higher than shown by the low-pressure results, but not nearly so high as shown by the high-pressure results given in this paper.

Observations of Renk.—F. Renk,[6] working with medium gravel, fine gravel, coarse sand, medium sand, and fine sand, with diameters greater than 7 mm., smaller than 7 mm., smaller than 4 mm., smaller than 2 mm.,

[1] Forschungen auf dem Gebiete der Agrikultur-Physik, Vol. XVI, 1893, pp. 193–222.
[2] H. Fleck, Zeitschrift für Biologie, Vol. XVI, No. 1, 1880, pp. 42–54.
[3] F. Renk, Zeitschrift für Biologie, Vol. XV, 1879.
[4] G. Ammon, Forschungen auf dem Gebiete der Agrikulturphysik, Vol. III, 1880, pp. 209–241.
[5] D. Welitschkowsky, Archiv für Hygiene, Vol. II, 1883.
[6] Forschungen auf dem Gebiete der Agrikulturphysik, Vol. II, 1879, pp. 339–347.

smaller than 1 mm., and smaller than 0.33 mm. to 0.25 mm., respectively, and using lengths of column ranging from 25 cm. to 300 cm., having a diameter of 5 cm., obtained results some of which conformed to the Poiseuille-Meyer law, while others did not.

In the case of his coarse sand having a diameter of grain of less than 2 mm., his measured flows conformed to the law until a pressure gradient of 250 to 32, or nearly 8 to 1, was reached; with steeper gradients the flow increased less rapidly than the pressure. In his medium sand the flow was still proportional to pressure at the highest limit of his experiment, when the pressure gradient was 2,000 to 180, or very nearly 11 to 1. His largest percentage departure from the law with the coarse sand was 13.63, and occurred when the length of the column was 50 cm. and the pressure 150 mm., or with a pressure gradient of 10 to 3.

Observations of Ammon.—G. Ammon[1] worked with a siliceous sandy soil, 57.02 per cent of which passed a screen of 0.3 mm. diameter; a quartz sand 1 to 2 mm. in diameter; a pure calcareous sand, 87.723 per cent of which passed a screen of 0.3 mm. diameter; and a loam powder, 92.468 per cent of which passed a screen of 0.3 mm. diameter, using for his soil receptacle a brass tube 125 cm. long and 5 cm. in diameter, carrying a manometer near its upper end. His results on the influence of pressure are given in the table below:

Table showing the relation of pressure to flow of air through soil, by Ammon.

Kind of soil.	Pressure of water.	Observed flow per hour.	Computed flow per hour.	Percentage departure.
	Mm.	*Cubic cm.*	*Cubic cm.*	
Sandy soil	20	25,880	....	....
	40	48,040	51,760	— 7.744
	60	72,400	77,640	— 6.749
	80	95,320	103,520	— 7.923
Quartz sand	20	8,850	....	....
	40	17,710	17,700	+ 0.057
	60	26,460	26,550	— .339
	80	35,280	35,400	— .339
Calcareous sand	20	2,040	....	....
	40	3,900	4,080	— 4.142
	60	5,100	6,120	—16.67
	80	7,160	8,160	—12.25
Loam powder	20	1,210	....	....
	40	1,510	2,420	—37.60
	60	1,820	3,630	—49.86
	80	2,140	4,840	—55.79

[1] Forschungen auf dem Gebiete der Agrikultur-Physik, Vol. III, 1880, pp. 209-241.

In these cases we have comparatively low pressures and a length of soil column of 100 cm., and yet a very wide departure from the Poiseuille-Meyer law. In the sorted quartz sand only is there a fair approximation to it.

Observations of Wollny.—E. Wollny[1] has followed the foregoing experimenters with a long series of observations on the flow of air through sands and soils under different pressures. His apparatus consisted of a soil receptacle in the form of a vertical tube 125 cm. long and 5 cm. in diameter, provided with a water manometer near its upper end, and arranged with a water jacket under the control of two thermostats, for the purpose of maintaining a constant temperature when desired.

The air pressure was generated by a bellows, that passed the air first through a gas meter, which permitted the reading of the volume to 10 c. c. The desired pressure was secured by opening or closing the stopcocks leading to and from the gas meter.

One sand which he used was made up almost exclusively of quartz grains, which had been cleaned with hot hydrochloric acid, washed with distilled water, and then sorted by means of sieves into seven grades. These were used separately and in a mixture of equal parts by volume of each grade.

It is here unfortunate for our purposes, as it was with his experiments with water, that Wollny has eliminated what have appeared to be small irregularities in his measured flows in order to show more clearly such a regular gradation as might reasonably be expected. It is further to be noted that in his Table III, dealing with the relation of pressure to flow of air through quartz sand, only the results with pressures of 20, 40, 60, 80, and 100 mm. were obtained by experiment, the others being computed.

The diameters of grains used by him were as follows:

I.	II.	III.	IV.	V.	VI.	VII.
Mm. 0. 01–0. 071	*Mm.* 0. 071–0. 114	*Mm.* 0. 114–0. 171	*Mm.* 0. 171–0. 25	*Mm.* 0. 25–0. 5	*Mm.* 0. 5–1	*Mm.* 1–2

The lengths of his columns were varied from 25 cm. to 100 cm., while his pressures ranged from 10 to 100 mm. of water.

With his Nos. I to V inclusive his tables show a complete agreement with the Poiseuille-Meyer law both as regards pressure and length of column. In his mixed sample, containing equal parts by volume of the several sizes, his tables also show a complete agreement with the law, as do his clay and humus samples. Only his Nos. VI and VII show a marked departure from the law.

[1] E. Wollny, Forschungen auf dem Gebiete der Agrikultur-Physik, Vol. XVI, 1893, pp. 193–222.

Below are given Wollny's results with the samples VI and VII, together with the percentage departures which have been computed from the flow under the lowest pressure in each case. Only the values which were observed have been presented for consideration.

Table showing the relation of pressure to flow of air through sand, in cubic centimeters per hour, by Wollny.

Kind of sand.	Pressure of water.	Soil 25 centimeters thick.			Soil 50 centimeters thick.		
		Observed flow.	Computed flow.	Percentage departure.	Observed flow.	Computed flow.	Percentage departure.
	Mm.	*Cubic cm.*	*Cubic cm.*		*Cubic cm.*	*Cubic cm.*	
Quartz sand No. VI, diameter 0.5 to 1 mm....	20	57,040	....	....	28,510	....	....
	40	114,080	114,080	0.00	57,040	57,040	0.00
	60	169,410	171,120	— 1.00	85,560	85,560	.00
	80	222,460	228,160	— 2.50	114,080	114,080	.00
	100	273,220	285,200	— 4.20	142,030	142,600	— .40
Quartz sand No. VII, diameter 1 to 2 mm	20	233,580	....	....	120,400	....	....
	40	452,700	467,160	— 3.10	234,780	240,800	—2.50
	60	662,200	700,740	— 5.50	344,340	361,200	—4.67
	80	862,060	934,320	— 7.73	449,090	481,600	—6.75
	100	1,052,300	1,167,900	—10.59	549,020	602,000	—8.80

Kind of sand.	Pressure of water.	Soil 75 centimeters thick.			Soil 100 centimeters thick.		
		Observed flow.	Computed flow.	Percentage departure.	Observed flow.	Computed flow.	Percentage departure.
	Mm.	*Cubic cm.*	*Cubic cm.*		*Cubic cm.*	*Cubic cm.*	
Quartz sand No. VI, diameter 0.5 to 1 mm....	20	19,010	....	....	14,260	....	....
	40	38,030	38,020	+ .03	28,520	28,520	0.00
	60	57,040	57,030	+ .02	42,780	42,780	.00
	80	76,060	76,040	+ .03	57,040	57,040	.00
	100	95,070	95,050	+ .02	71,300	71,300	.00
Quartz sand No. VII, diameter 1 to 2 mm	20	80,200	....	....	60,200	....	....
	40	159,200	160,400	— .75	120,400	120,400	.00
	60	233,380	240,600	—3.00	178,790	180,600	—1.00
	80	302,750	320,800	—5.63	234,780	240,800	—2.50
	100	367,320	401,000	—8.40	288.360	301,000	—4.20

In another experiment Wollny compares the flow of air through finely pulverized loam when filled into the apparatus loosely, and that through similar loam when firmly packed, and the results are given in the table below:

Table showing the relation of pressure to flow of air through loosely and firmly packed loam, by Wollny.

[Flow of air per hour in cubic centimeters.]

Condition of soil.	Water pressure.	Soil 25 cm. thick.	Soil 50 cm. thick.	Soil 75 cm. thick.	Soil 100 cm. thick.
	Mm.				
Pulverized loam loosely packed, (0.0 to 0.25 mm.).	20	2.040	2.000	1.960	1.920
	40	3.380	3.330	3.280	3.240
	60	4.720	4.670	4.610	4.560
	80	6.060	6.000	5.940	5.880
	100	7.400	7.330	7.260	7.200
Pulverized loam firmly packed (0.0 to 0.25 mm.).	20	.190	.095	.063	.047
	40	.380	.190	.127	.095
	60	.570	.285	.190	.143
	80	.760	.380	.253	.190
	100	.950	.475	.317	.237

In this table we have results which are, in some respects, quite peculiar. It will be noted that in the loosely packed loam there is a very wide departure from the Poiseuille-Meyer law, both as regards pressure and as regards length of column. The flow does not increase nearly so rapidly as the pressure increases, and yet it does not decrease with the length of the column to anything like the extent which is called for by the law. Taking the flow through the column 100 cm. long and under a pressure of 100 cm., the observed flow is 7,200 c. c. per hour, while the flow which would be computed from the observed flow through the 25 cm. column under a pressure of 20 mm. is 2,550 c. c., an amount only a little more than one-third as large. Indeed, it will be seen that while the flow has decreased rapidly with the pressure from what should be expected, it has lost but little in increasing the length of the column.

Referring now to the closely packed samples, it will be observed that the Poiseuille-Meyer law is much more nearly obeyed, both as regards length and pressure. It will be seen that in the case of the columns having lengths of 75 cm. and 100 cm., respectively, the flow has even increased faster than the pressure by amounts equal to about 1 per cent in the largest column and in the shorter column nearly 0.6 per cent, as the writer has found in so many of his own observations. In the case of the columns 25 and 50 cm. long the law is exactly fulfilled, both as regards length and pressure, as is indicated by the results given in the table.

It is plain, therefore, that Wollny's results show some radical departures from the Poiseuillean law when an attempt is made to apply them generally to the flow of air and water through sands and soils. It is of course true that his tables show a remarkable agreement with the law in many portions, both for air and for water, but he expressly states that he has set aside what have appeared to be irregularities, and hence it should be remembered that the agreement may possibly not have been so close as his tables indicate.

DEPARTURES FROM THE POISEUILLE-MEYER LAW OBSERVED WITH CAPILLARY TUBES.

In considering the concordance of observed flow of fluids through porous media with the flow through capillary tubes, it is a matter of supreme importance to note what agreements and what discrepancies are found to exist among the experimental data which have led to the acceptance of the Poiseuille-Meyer law.

Results of Poiseuille.[1]—In referring to the results of this investigator it is the purpose to show here chiefly the closeness of agreement which he was able to secure in some of his experiments and the percentage departures which he observed in others where the agreement was not so close. With his tube A, 100.5 mm. long, having a diameter of about .1415 mm., the flow under pressures of 385.78 mm., 739.114 mm., and 773.443 mm. of mercury increased faster than the pressure, but only 0.04 and 0.06 per cent when the second and third are computed from his first. With his tube A^{i}, which was a portion of A, 75.8 mm. long, the pressures ranged from about 51 mm. up to 775 mm., and in a series of seven trials there was an agreement to less than 0.1 per cent in every case but one, where the departure was —1.244 per cent. Two of the departures were plus, four were minus.

With a still shorter piece, A^{ii}, of the same tube, 51.1 mm. long, and with pressures of 98 to 775 mm., three of the departures were plus and one minus, but all were less than 0.2 per cent.

With his tube A^{iii}, 25.55 mm. long and about 0.1425 mm. in diameter, a pressure of 774.895 mm. gave a flow increasing faster than the pressure by 1.798 per cent when compared with that which occurred under a pressure of 387.52 mm.

[1] See report in Comptes rendus, meeting of December 26, 1842.

With tube A^{iv}, 15.75 mm. long and 0.1415 mm. in diameter, the percentage departures were as follows:

Percentage of departure of flow from Poiseuille-Meyer law in capillary tube 15.75 mm. long and 0.1415 in diameter.

Pressure.	Departure.
Millimeters.	*Per cent.*
24.661	....
49.591	—1.286
98.233	—1.094
148.233	—1.169
194.257	—1.702
388.000	—3.853
775.160	—7.718

With Tube A^{v}, 9.55 mm. long and 0.1415 mm. in diameter, the percentage departures were as follows:

Percentage of departure of flow from Poiseuille-Meyer law in capillary tube 9.55 mm. long and 0.1415 mm. in diameter.

Pressure.	Departure.
Millimeters.	*Per cent.*
23.638	....
49.185	— 0.8256
99.221	— 2.489
148.623	— 3.681
193.315	— 5.421
387.737	—12.20
774.62	—21.78

With Tube B, 100.05 mm. long and with a diameter about 0.1135 mm., the agreement was within less than 0.06 per cent for three trials, the departures being minus. Tube B^{i}, which was a piece of B, also gave very close agreement with the law in seven trials, the flows all being a little too fast. Tubes B^{ii} and B^{iii}, still shorter pieces of B, also satisfied the law quite closely, the departures being five plus and three minus.

With the Tube C, 100.325 mm. long and having a diameter of about 0.085 mm., and also its pieces C^{i}, C^{ii}, C^{iii}, and C^{iv} down to a length of 10 mm., all agree with the law within narrow limits, the flow increasing faster than the pressures with C, C^{i}, and C^{iii}, but slower with C^{ii}, except the last, and faster with all of C^{iv} but the two under the highest pressures.

With his Tube D, having a length of 100.3 mm. and a diameter about 0.044 mm., and his pieces of the same tube, D^{i}, D^{ii}, and D^{iii}, down to a length of 9.95 mm., all under rather high pressures, there was a close agreement with the law, the departures being nearly equally divided, eleven plus and six minus.

With Tube E, 23.1 mm. long, having a diameter of 0.029 mm., and E^{i} and E^{ii}, the agreement of the law is as close as about 0.1 per cent, there being eight cases with the flow a little too fast and four too slow.

With his Tube F, having a length of 383.825 mm. and a diameter at the two ends of 0.616 mm. and 0.6932 mm., he used water pressures ranging from 126.92 mm. to 10462.08 mm., and secured an agreement of about +.25 per cent at the lowest pressure and —1.6 per cent under the highest.

Then with a piece of the same tube, F^{i}, 200 mm. long, he obtained the following results:

Relation of flow to pressure with capillary tube 200 mm. long and 0.616 mm. to .6932 mm. in diameter.

No.	Pressure of water.	Observed flow per second.	Computed flow per second.	Percentage departure.
	Millimeters.	*Cubic cm.*	*Cubic cm.*	
1	83.36	0.01356	....	....
2	127.60	.02096	0.02076	+ .9632
3	163.71	.02673	.02664	+ .3386
4	328.82	.05388	.05350	+ .7102
5	661.29	.10840	.10510	+ 3.1380
6	1,321.87	.21550	.21070	+ 2.2310
7	1,981.76	.31220	.32240	— 3.164
8	2,626.58	.41820	.42750	— 2.176
9	5,210.27	.78070	.84780	— 7.915
10	10,459.10	1.40500	1.70200	—17.450

With a still shorter piece of the same tube, F^{ii}, 99.725 mm. long, he found the following results:

Relation of flow to pressure in capillary tube 99.725 mm. long and 0.616 mm. to .6932 mm. in diameter.

No.	Pressure of water.	Observed flow per second.	Computed flow per second.	Percentage departure.
	Millimeters.	*Cubic cm.*	*Cubic cm.*	
1	81.83	0.02638	....	....
2	163.97	.053555	0.05286	+ 1.314
3	331.51	.10650	.1068	— .2808
4	664.36	.20790	.21415	— 2.919
5	1,323.58	.39040	.42675	— 8.518
6	1,984.95	.56660	.63980	—11.44
7	2,585.33	.70260	.83320	—15.68
8	5,207.73	1.17100	1.17900	—30.26
9	10,454.54	1.9520	3.36800	—42.04

The relations of the observed to the computed flows in this table and in the one preceding are represented graphically in fig. 38.

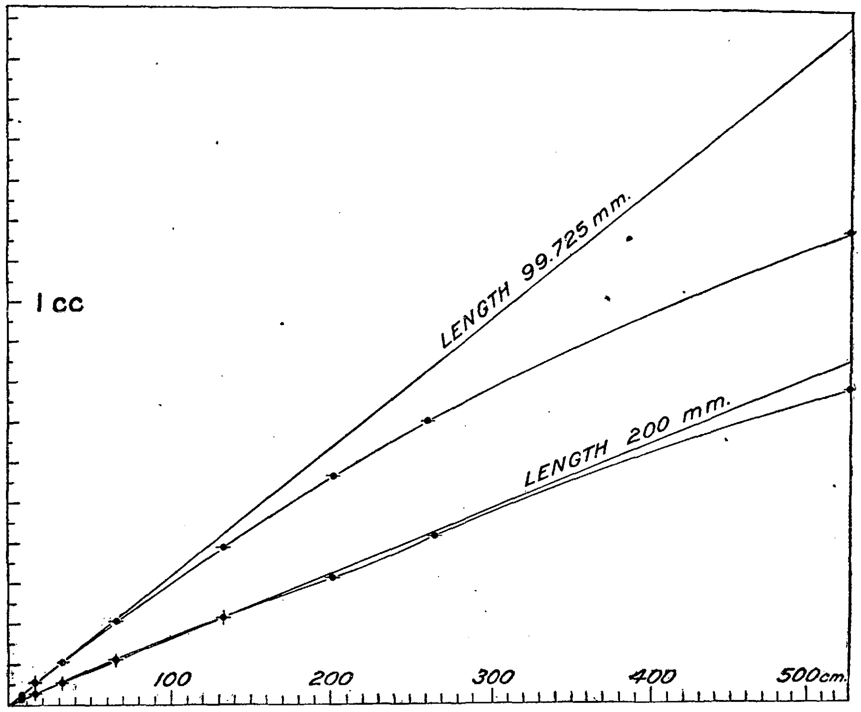


FIG. 38.—Diagram showing relation of pressure to flow through Poiseuille's capillary tubes F and F[1]. Straight lines show theoretical flow; + dots, observed flow increasing faster than pressure; — dots, flow increasing slower than pressure. Abscissas indicate pressure and ordinates flow.

It is quite remarkable that in Poiseuille's Tube I, 258 mm. long and with a diameter of about 0.09 mm., the flow increased faster than the pressure by amounts ranging from 1.552 per cent to 4.182 per cent, even under such high pressures as 3,850.16 mm. up to 6,130.08 mm. of mercury. This departure from the law appears to be entirely analagous to those cases which have been cited for sands, soils, and rock where the flow increases faster than the pressure.

It has been shown that in the case of wire gauze the flow of water through it was at first a little too slow to conform with the law; then, as the pressures were made larger, it increased faster than the pressure, but finally came to increase less rapidly than the pressures as the head was augmented. And in Poiseuille's tube K he observed the same phenomena, the flow being at first too slow, then too fast, and finally too slow to conform with his law, the departures from the law, when expressed in percentages, standing as follows: —0.09565, —0.01688, +0.0513, +1.618, +2.237, —0.9306, —0.4409, —3.851, —0.4553, —0.6886, —0.6366. This tube, too, had a length of 364 mm. and a diameter of 0.1316 mm., while the pressures ranged from 5 mm. to 6,136 mm.

The similarity of Poiseuille's results to those which have been cited for porous media is further shown when it is stated that of thirty-nine tubes used by him, having lengths greater than 1 mm., twenty-three gave flows increasing faster than the pressure throughout the experiment, or through the lowest pressures. Of the seventeen tubes which are longer than 51 mm., all but two have the flow increasing faster than the pressure for the lowest heads. Of the seventeen tubes less than 27 mm. long, there are seven in which the flow increased faster than the pressure under the lowest heads, and of these seven there are four in which the flow increases faster than the pressure throughout the range of the experiment. The shortest tube used by Poiseuille, in which the flow increased faster than the pressure throughout the range, was only 8.5 mm., while a still shorter piece of the same tube, 2.1 mm., gave a flow increasing faster than the pressure in all but the highest, yet the pressures ranged from 24 mm. to 773 mm. of mercury. The diameter of these two pieces of tubes was about 0.0297 mm.

Results of Cohen.[1]—Investigations made by R. Cohen on the influence of pressure on the viscosity of fluids appear also to indicate that under even very high pressures the flow of water increases faster than the pressure. This author states that the experiments of Röntgen and of Warburg and Sachs show that the viscosity of water is decreased by pressure, which is equivalent to saying that the flow increases faster than the pressure.

Cohen made his experiments with water, with salt solutions, and with turpentine, measuring the flow through capillary tubes under pressures as high as 100, 200, 300, 400, 500, 600, 900 atmospheres. One of his tubes had a length of 20 cm. and a diameter of 0.24 mm.

It should also be noted that Cohen used both air-free water and that which contained the normal amount, and found practically no difference between his results.

The quantity of water flowing through the capillary tube with each experiment is not given, but the results are expressed in the mean time of flow in seconds computed for one atmosphere, and these for pure water, with the percentage departures, are given in the table which follows:

Table showing the relation of pressure to flow of air through capillary tubes under wide variations of pressure, by Cohen.

Pressure in atmospheres.	Time of flow in seconds, computed to 1 atmosphere.	Percentage departure.	Time of flow in seconds, computed to 1 atmosphere.	Percentage departure.	Time of flow in seconds, computed to 1 atmosphere.	Percentage departure.
1	2,836.25	....	2,600.62	....	3,147.40	....
100	2,816.00	+ .71	2,587.50	+ .51	3,132.5	+ .47
200	2,800.58	+1.26	2,568.25	+1.25	....	....
300	2,794.42	+1.47	2,559.50	+1.60	3,100.30	+1.49
400	2,775.50	+2.14	2,544.17	+2.17	....	....
500	2,778.50	+2.03	2,535.50	+2.50	....	....
600	....	....	....	....	3,073.83	+2.33
700	2,772.50	+2.24	2,538.50	+2.40	....	....
900	2,761.75	+2.63	....	....	3,060.50	+2.76

[1] Annalen der Physik und Chemie, new series, Vol. XLV, 1892, p. 666.

These three sets of experiments are closely concordant in showing that the time becomes shorter relatively as the pressures are increased, and hence that the flow increases faster than the pressure. These flows are either all at a temperature of 15° or else they have been reduced to that temperature.

Cohen shows, both from his own observations and from those of Röntgen and of Warburg and Sachs, that the viscosity decreases faster under low pressures than it does under high pressures, and that it also decreases faster under high temperatures than it does under low temperatures up to 40° at least.

These observations, therefore, appear to be in accord with what has been cited from the observations both of the writer and of others regarding the flow of water through porous media, and they are certainly not contradicted by the observations of Poiseuille, for it has been shown that there was a marked tendency for the flow to increase faster than the pressure, especially under his lower heads.

Cohen further concludes from his observations that with strong salt solutions (25.7 per cent of NaCl to 13.8 per cent, and 26 per cent of NH_4Cl) the viscosity increases with the pressure, but that when these solutions are not so strong, as for example 4 per cent to 8 per cent of NaCl, the viscosity again decreases with the pressure, as he found it with pure water; but when the viscosity decreased with increase of pressure in these dilute solutions at 2° there came a reversal again at 14.5° for the 8 per cent solution of NaCl.

These data indicate that there is a certain strength of solution and pressure where Poiseuille's law may hold, while with weaker solutions the flow would increase faster than the pressure, and with stronger solutions the flow would not increase so fast as the pressure.

Or, further, a given strength of solution may obey Poiseuille's law at one temperature, while at a lower temperature the flow will increase faster than the pressure, and above the same temperature the flow will not increase so fast as the pressure; thus, Cohen found that with an 8 per cent solution of NaCl under pressures of 1 and 600 atmospheres the flow was proportional to the pressure at 11° C., but greater below 11° C., and less above.

It follows, therefore, from these considerations, if the conclusions stated are true, that it is only when a fortunate combination of various conditions occur that a set of observed flows of a fluid through either capillary tubes or porous media will be found to be exactly proportional to the pressure, and that it is much more likely to be true that the flow will be either too fast or too slow to conform with the law.

Results of Meyer[1] *with air.*—If we now refer to some of those results of O. E. Meyer which are held as establishing the law of Poiseuille for air, we shall find that while under certain conditions of length and diameter of tube and of pressure there is a close agreement with the

[1] Annalen der Physik und Chemie, Vol. CXLVIII, 1873, pp. 1–44.

law, yet there are real departures which are of the same general character as those shown by these observations for air, while at the same time they are in essential agreement with those cited for water.

Taking the observations which Meyer made with his Tube II, having a mean area of cross section of .001114 sq. cm., we get the results given in the table below, where his logarithmic differences have been used and departures found from the constant given by the flow under the highest pressure expressing the variations from the standard as (+) or (−), according as the flow increased faster than the pressure or not so fast. As there was a leak in the apparatus during experiment 6, these data are omitted from the table.

Table showing the relations of pressure to flow of air in capillary Tube II, by Meyer.

	Experiment—						
	1	2	3	4	5	7	14
Length of tube.......cm..	155.3	155.3	155.3	155.3	155.3	155.3	41.2
Pressures of mercury, mm	1,346.7 to 344.9	1,326.7 to 392.8	631.7 to 152.0	663.4 to 386.6	700.4 to 195.2	619.0 to 131.0	1,395.9 to 353.5
First logarithmic differences....................	.0362	.0373	.0528	.0205	.0195	.0552	.0706
Departures from the first logarithmic differences.	+3	−3	−1	+8	+1	−2	−16
	−2	−4	0	+2	+3	−6	−31
	−9	−5	+5	+4	+2	−8	−32
	−5	−6	+10	+5	+1	....	....
	−7	−5	+13	+6	+2	....	....
	−6	−5	....	....	....	....	....
	−9	....	....	....	....	....	....
Percentage departures, largest...	2.486	1.609	2.462	3.903	1.538	1.449	4.533
Percentage departures, smallest..	.553	.804	.000	.976	.513	.362	2.266

	Experiment—							
	16	19	20	21	22	23	24	25
Length of tube......cm..	66.4	66.4	66.4	66.4	66.4	66.4	66.4	66.4
Pressures of mercury, mm	1,410.7 to 475.3	1,422.7 to 262.2	862.7 to 140.1	441.1 to 115.5	822.9 to 123.1	700.9 to 153.7	728.6 to 188.3	767.2 to 187.4
First logarithmic differences..................	.0756	.136	.0975	.0853	.198	.0751	.0812	.0773
Departures from the first logarithmic differences.	−15	−3	−17	+6	−2	−10	+9	−24
	−22	−6	−27	+16	−5	−17	+4	−26
	....	−8	−18	+13	−6	−21	+3	−24
	....	−9	−24	+9	....	−26	+9	−24
	....	....	−25	+18	....	−23	0	−27
	....	....	−25	+20	....	−16	−2	−27
	....	....	−12	....	....	....	0	−22
	....	....	....	....	....	....	0	−25
	....	....	....	....	....	....	....	−25
Percentage departures, largest...	2.910	6.618	2.769	2.345	3.030	3.462	.902	3.493
Percentage departures, smallest..	1.984	2.206	1.231	.703	1.010	1.332	.000	2.846

Table showing the relations of pressure to flow of air in capillary Tube I, by Meyer.

	Experiment—						
	8	9	10	12	13	17	18
Length of tube.......cm..	156.2	156.2	156.2	76.7	79.75	49.45	26.85
Pressures of mercury, mm	1,447.4 to 353.8	1,379.4 to 512.8	1,399.6 to 472.5	1,398.6 to 581.8	1,414.7 to 608.4	1,424.4 to 399.0	1,399.6 to 364.2
First logarithmic differences	.0408	.0409	.0439	.0375	.0365	.0541	.0890
Departures from the first logarithmic differences.	+1	+18	+6	−2	+4	+7	−4
	−1	+13	+5	−1	+2	0	−7
	0	+14	+4	−3	+2	−5	....
	−1	+13	+4	−2	+1	−6	....
	....	+13	+4	....	....	....	....
	....	+14	+6	....	....	....	....
	....	+14	+5	....	....	....	....
	....	+15	+4	....	....	....	....
	....	+15	+4	....	....	....	....
	....	+13	+3	....	....	....	....
Percentage departures, largest...	.25	4.401	1.367	.800	1.096	1.295	7.865
Percentage departures, smallest..	0	3.179	.633	.266	.274	.000	4.494

It will be seen from these tables that there is a marked tendency for the flows to be either too rapid or too slow to conform with the law, the largest percentage departures in the first table ranging from 1 per cent to 4.5 per cent and the smallest departures from 0 to 2.85 per cent.

Referring now to his whole series of experiments the following statements are true. With his longest tubes there were 37 cases where the flow increased faster than the pressure and 19 where it increased less rapidly, a ratio of nearly 2 to 1; but with his medium and short tubes there were but 15 cases where the flow increased faster than the pressure, while there were 45 in which the flow increased less rapidly than the pressure.

These relations would appear to show that under certain conditions there is a tendency for the flow of air to increase faster than the pressure, while under others the tendency is in the opposite direction, and that the observations of Meyer are qualitatively in accord with those cited relating to the flow through various porous media, both of water and of air.

SUMMARY OF OBSERVATIONS ON THE RELATION OF PRESSURE TO FLOW OF FLUIDS THROUGH POROUS MEDIA.

1. Reference has been made to 222 comparisons of observed and computed flows of water through capillary tubes, obtained from the use of 44 different tubes. Of these 44 tubes there were 16 in which the entire series of observations gave flows increasing faster than the pressure.

2. Of the 44 tubes used there were 22 longer than 5.1 cm., and of these 20 gave flows increasing faster than the pressure for the lowest heads used.

3. Of the 44 tubes used 17 did not exceed a length of 2.7 cm., and of these there were 7 in which the flow increased faster than the pres-

sure under the lowest heads, while of these 7 there were 4 in which the flow increased faster than the pressure throughout the range of the experiment.

4. The shortest tube used by Poiseuille in which the flow increased faster than the pressure throughout the range of the experiment was only 0.85 cm., while a still shorter piece of the same tube, only 0.21 cm., gave a flow increasing faster than the pressure in all but the highest head.

5. Of 55 comparisons of flow of water through wire gauze under pressures of 1 cm. to 30 cm., in all but 5 the flow increased faster than the pressure; while in 25 other cases, under pressures of 88 to 916 cm., there were 18 in which the flow did not increase as fast as the pressure.

6. Of 75 comparisons by Newell of the flow of water through rock 0.5 inch thick or less and under pressures of 69 to 2,758 cm. of water, there are 44 cases where the flow increased faster than the pressure.

7. Of 147 comparisons of the flow of water through rock from 1.5 inches to 6 inches thick under pressures of 21 to 1,055 cm. of water, in all but 3 cases the flow has increased faster than the pressure.

8. Of 132 comparisons of the flow of water through columns of sand from 105.4 to 1,022 cm. long under pressures from 1 cm. to 1,150 cm. of water, in all but 32 cases the flow increased faster than the pressure.

9. The flow of water has increased faster than the pressure by amounts varying with the sands from 0 to 45.79 per cent; with rock from 0 to 85.9 per cent; with capillary tubes from 0 to 20.9 per cent.

10. Of 59 comparisons made by the writer of the flow of air through sand, sandstone, dust, shot, bundles of knitting needles, and capillary tubes, under pressures from 1 mm. to 50 mm. of water, in all cases but 10 the flow has increased faster than the pressure.

11. Of 84 comparisons made by the writer of the flow of air through columns of sand and dust shot from 175.26 cm. to 87.63 cm. long, under pressures of 105.4 cm. of water to 1,022 cm., the flow failed to increase as fast as the pressure by amounts ranging from 59 to 128 per cent.

12. Of 84 comparisons made by the writer of the flow of air through sandstones from 4.1 cm. to 14.3 cm. long, under pressures of 105.4 to 1,022 cm. of water, the flow failed to increase as fast as the pressure by amounts ranging from 5.5 per cent to 17.8 per cent.

13. Of 160 comparisons of the flow of air through sands and soils under pressures of 2 to 10 cm. and through lengths of columns of 25 to 100 cm., Wollny finds the flow directly proportional to the pressure in all but 20 cases, of which 4 are faster and 16 slower.

14. Of 124 comparisons of the flow of air through sands and soils under pressures of 2 to 18 cm. of water and through lengths of 20 to 300 cm., Welitschkowsky, Renk, and Ammon found the flow not increasing as fast as the pressure in all cases but 12, of which 11 agreed with the law and 1 was too fast.

15. Of 121 comparisons of the flow of air through capillary tubes 26.8 to 156 cm. long and under pressures of 149 to 1,548 cm. of water,

Meyer found 64 cases of the flow increasing faster than the pressure, 52 where it was not so fast, and 5 agreements with the law.

16. Of 58 comparisons with his tubes about 150 cm. long the flow of air increased faster than the pressure in 37, or about two-thirds of the cases; but with his shorter tubes the flow increased faster than the pressure in only 15 out of 63 cases.

17. With all the observations of all of the observers, whether with sands, rock, or capillary tubes, whether with high or low pressures, and whether with long or short tubes or columns, the departures from the Poiseuille-Meyer law have been systematically either plus or minus instead of first one side and then the other, as should be expected if the departures were due to errors of observation, unless indeed some peculiarity in the many forms of apparatus is responsible for the systematic departures which have been so persistently found by nearly every observer.

SIGNIFICANCE OF THE DIFFERENCES IN THE VALUE OF THE COEFFICIENT OF VISCOSITY AS DETERMINED BY DIFFERENT METHODS.

The evidence which has been presented regarding the flow of water through rock and through sands demonstrates beyond question that it does, under certain conditions, increase faster than the pressure. The magnitude of the observed departures from the Poiseuille-Meyer law and the persistency with which the results have recurred are too great to be explained by errors of observation. So, too, regarding the flow of water through capillary tubes, the results which have been reviewed have been obtained by such careful methods and with such acknowledged skill that there is left little room for doubt that under certain conditions the flow of water through capillary tubes does increase faster than the pressure. Likewise regarding the flow of air through porous media, the large number of cases which have been cited, the magnitude of the departures and the persistency with which like results have recurred, together with the acknowledged care and skill under which some of the results were obtained, appear to leave little room to doubt that with air also the flow may increase faster than the pressure when conditions are favorable.

It has from the first been recognized that under certain relations of length and diameter of tube to velocity of flow the Poiseuille-Meyer law did not hold and that the discharge fell below the amount which would be computed. This falling away in the amount of visible work done has been explained by the absorption of energy at the ends and within the body of the tube through the setting up of vortex or other movements of the water more or less transverse to the axis of the main stream, which necessarily absorbed more or less of the energy, tending to produce flow and thus to diminish the amount discharged in a unit of time. But the fact that the flow may increase faster than the pressure does not appear to have been generally recognized, and the writer has nowhere seen it explicitly stated in any discussion of the laws of capillary flow.

It is true that a flow increasing more rapidly than the pressure could occur only under conditions where the resistance to the flow became less as the pressure became greater, and as the earlier theoretical investigations of Maxwell led to the deduction that the viscosity of gases must be independent of pressure there was no apparent means of explaining a flow which increased more rapidly than the pressure.

The later experimental investigations of Röntgen,[1] Warburg and Kundt,[2] Warburg and Sachs,[1] and Cohen[3] appear to have established the fact that the viscosity of both water and air does change with pressure, that of water appearing to decrease in some ratio or amount with the increase of pressure. At any rate their observations indicate that for water the flow through capillary tubes increases faster than the pressure, even when that pressure is very great, and this has been interpreted as meaning that the viscosity has decreased with increased pressure.

It is a significant fact in this connection that all determinations of the viscosity of water and of air by the capillary or transpiration method have given results which are lower than those derived from observations of oscillating disks or spheres or swinging pendulums. And while various corrections have been applied from time to time which have tended to bring the results of the different methods into closer agreement, it is still true that those derived from flows through capillary tubes are smaller than those obtained by other methods. But this relation of determined values is what should be expected did the flow of fluids through capillary tubes and porous media increase faster than the pressure. The extremely careful work, therefore, which has been done to determine the viscosity of fluids, it appears, may be legitimately placed in evidence in support of the view that the flow of air and of water through capillary tubes and through sands, soils, and rock may increase more rapidly than the pressure.

It is difficult to see, however, on the principles of the conservation of energy, how it is possible for the flow to increase faster than the pressure, and except for the observations which have been presented the proposition would appear absurd.

It has already been pointed out, in connection with the flow of water through wire gauze, that if entangled air were present its reduction in volume with increase of pressure might increase the effective cross sections of the pores so far as to permit a series of increasing flows to take place; but the amount of entangled air which would be required under those pressures to explain the observed increase in flow is greater than could probably be present.

Even if it is admitted that in some manner entangled air in porous

[1] Annalen der Physik und Chemie, Vol. XXII, 1884, pp. 510, 518.
[2] Annalen der Physik, Vol. CLV, 1875, p. 337.
[3] Annalen der Physik und Chemie, Vol. XLV, 1892, p. 666.

media is responsible for the increase of flow faster than the increase of pressure which has been observed, it is not easy to see how the same explanation is applicable to the cases which have been observed with the straight capillary tubes, for here the air should be easily swept forward and out by the moving stream. Were it possible for a small bubble or series of bubbles of air to remain fixed to the walls of the capillary tube through which the water was flowing, an increase of pressure would, by compressing the air, increase the cross section of the tube and thus permit the augmented flow observed.

But, admitting that this explanation is applicable to the flow of water through the capillary tubes, we are still confronted with the cases where the flow of air through the sands, dust shot, sandstones, bundles of knitting needles, and even the capillary tubes under the manipulation of Meyer, has been too rapid to conform with the law, by amounts as great as 3.1 to 4.4 per cent in his series 9, Tube I, while in these experiments the dust shot gave flows increasing faster than the pressure by as much as 11 per cent, and the longest piece of thermometer tubing used gave a departure in the same direction larger than this.

Were it admissible to suppose that the stationary or comparatively stationary film of fluid adhering to the walls of the tube through which the water or air is flowing could itself become thinner as the pressure is increased, then this change would have the effect of increasing the effective diameter of the tube or pore and thus of allowing the flow to increase faster than the pressure, while at the same time the viscosity might remain unchanged and yet appear to decrease with the pressure.

It is a common experience that if a vessel filled with water is turned bottom up and held for a second for the water to run out, and is then set down to rest for a short interval, the water left adhering to the side will drain to the bottom in such amount that a very perceptible quantity may be poured out on again inverting the vessel. This demonstrates that there is a film of water of some thickness which moves quite slowly along the walls when urged under the influence of its full weight, while the balance of the water in the vessel, when urged by the same intensity of force, much more quickly leaves the vessel.

We have found the first drainage from a bright tin vessel under these conditions to be 2.63 c. c. from 986 sq. cm. of surface, and the second drainage, after standing a second interval, to be 0.257 c. c., the first representing a thickness of film of about 0.026 mm. and the second about one-tenth this amount. These results are only roughly approximate, and are cited only as giving some basis for judgment.

If it could be shown that this slowly moving film has its velocity accelerated at a rate which increases more rapidly than the pressure increases, then the phenomena which have been observed could be accounted for, provided the quantitative relations were right. It is not clear, however, that sure grounds can be assigned for thinking that such a relation exists.

CHAPTER III.

RATE OF FLOW OF WATER THROUGH SAND AND ROCK.

In the preceding chapter an attempt has been made to show how the observed flows of both water and air through sand and rock, as well as other porous media, are related to the pressure, and at the same time to show in how far these observed relations conform to the Poiseuille-Meyer law. It is the purpose in this chapter to deal with the results from the standpoint of quantity of flow per unit of time as it is related to various factors.

INFUENCE OF THE FORM, DIAMETER, AND ARRANGEMENT OF SOIL AND SAND GRAINS ON THE AMOUNT OF FLOW.

It has become sufficiently evident from the data and discussion already presented that both the diameter of the sand or soil grains and the amount of pore space which has resulted from the massing of the grains together are factors of fundamental importance in determining the amount of water which may pass a given section of any stratum in a unit of time. It is not enough to know the percentage volume of empty space in a given medium when the possible amount of flow under stated conditions is to be determined from theoretical considerations; but the extent of subdivision and the form of the pores must also be known.

In his paper in this volume Professor Slichter has considered the mathematical relations of spherical soil grains of uniform diameter to the pore space, and he finds that the minimum value for such a case is 25.95 per cent. This occurs when each sphere touches adjacent spheres in twelve points and forms an element of volume which is a rhombohedron, having face angles equal to 60° and 120°. On the other hand, when the spheres touch one another in but eight points and form an element of volume which is the cube, then the pore space has its maximum value of 47.64 per cent. In the former condition of packing, a cubic foot of sand made up of such grains will contain 25.95 per cent of its volume into which water may be poured and through which it may flow, while in the second arrangement nearly one-half of the space will be unoccupied and may take part in the transmission of fluids through it. Between these two extremes of packing there may result all variations in the value of the pore space between 25.95 per cent and 47.64 per cent.

It is evident that the value of the pore space for spherical grains is in no way altered by their diameters so long as all have the same value and are packed in like manner; quite the opposite, however, is true with the diameter of the pore through which fluids may move, for doubling the diameter of the grain or sphere increases the area of cross section fourfold, and hence permits an increase of flow which is more rapid than the increase in diameter.

But as the grains of soil and of sand are, as a rule, neither spherical in form nor uniform in diameter, and as no one has yet investigated the properties of the pores of masses built out of units of irregular form and size, it is a matter of fundamental importance to know in how far the actual pores through which the movements of water take place may conform with those which have been assigned to grains spherical in form.

OBSERVED PORE SPACE IN SOIL AND ROCK.

The method used in determining the pore space of soils and sands consists in filling a cylindrical vessel of known capacity with the medium whose pore space is to be determined and then computing the pore space from the weight of the material used and its specific gravity.

In undertaking this work it was early found that quite widely different arrangements of the grains resulted from different methods of filling the vessel. To pour the material into the receptacle rapidly or to put it in in considerable quantities at a time usually resulted in a large pore space. On the other hand, in the case of sands, if they were allowed to fall into the receptacle in a fine, steady stream, a uniform packing would result which was much closer than could be secured by the other method. The closest packing and the most uniform results were obtained by adding the material in small lots at a time and gently tamping with a broad, flat-faced pestle until the vessel was filled. But by whatever method the material was introduced it was found that a still closer packing could be obtained by gently jarring at the close. The vessel, after being filled by tamping, was "struck off" with a piece of plate glass, then held firmly while, with light blows, the walls of the tube were struck gently but repeatedly as long as any reduction in volume could be produced. If the cylinder was not held rigidly, or if severe blows were resorted to, the pore space was usually increased. If the material had been put in rapidly or in considerable quantities at a time, it was seldom possible by any amount of careful jarring to secure the minimum pore space.

The receptacles used for most of the work were brass cylinders holding nearly either 100 cc. or 200 cc. and having a length of 8.678 cm. for the shorter one and 16.7 cm. for the longer, their diameters being 3.817 and 3.812 cm., respectively.

The per cent of pore space is given by the formula,

$$\frac{Vd-W}{100\ Vd}=P.$$

Where V is the volume of the vessel in cubic centimeters, d is the specific gravity of the sand, and W is the weight of the sand in grams.

All determinations have been made with the material in the air-dry condition, and no correction has been applied for hygroscopic moisture. The presence of hygroscopic moisture would increase the weight of the sample beyond its due value, and hence when a correction is made for it the per cent of pore space would be increased. As the hygroscopic moisture is found in greater percentage in fine-grained media than in those which are coarser, the general tendency would be for the values found for the pore space of the finer grained materials to be most in error.

In the following table are given the observed pore spaces of a number of sands, soils, and rocks, together with the time required for 5,000 c. c. of air to pass through them under the conditions there stated. In this table is given the data needed for computing the effective diameter of grain from Professor Slichter's formula—

$$d^2=k\frac{h}{spt}[8.9434-10],$$

where d = diameter of soil grain,

h = length of aspirator or sand column,

s = area of aspirator or sand column,

p = pressure in centimeters of water at 20° C.,

t = time in seconds for 5,000 c. c.,

[8.9434 − 10] = logarithm of a constant.

The values of h and s for the several aspirators used are given below:

	1	3	A	B	C
h ..	11.69	15.8	8.674	8.678	16.7
s...	4.47812	6.3291	11.3903	11.4427	11.4084

Table showing effective diameters of sands and soils with observed pore space and rate of air movement through them.

Material used.	Number of sample.	Aspirator tube.	Pressure of water.	Temperature.	Time for flow of 5,000 c. c.	Per cent of pore space.	Approximate effective diameter.
			Cm.	*° C.*	*Seconds.*		*Mm.*
No. 20 quartz sand......	1	3	2.835	....	1,275	32.92	0.4830
No. 20 quartz sand......	2	3	2.860	....	1,245	33.43	.4743
No. 20 quartz sand......	3	3	2.865	....	1,540	32.94	.4371
No. 20 after washing....	4	B	2.300	19.8	230	37.68	.5128
No. 20 after washing with HCl	5	B	2.400	18.9	350	34.26	.5248
No. 20 after rescreening.	6	B	2.300	20.1	270	35.33	.5819
No. 20 after third screening	7	B	2.200	24.6	260	35.25	.6112

Table showing effective diameters of sands and soils with observed pore space and rate of air movement through them—Continued.

Material used.	Number of sample.	Aspirator tube.	Pressure of water.	Temperature.	Time for flow of 5,000 c. c.	Per cent of pore space.	Approximate effective diameter.
			Cm.	° *C.*	*Seconds.*		*Mm.*
No. 20, used in well point No. 50 and in percolation experiment, p. 86	8	A	2.330	13	1,485	31.46	.2941
No. 40 quartz sand	9	1	3.01	23.3	6,105	36.60	.1848
No. 40 quartz sand	10	1	2.975	....	5,945	36.56	.1886
No. 40 quartz sand	11	3	2.820	....	6,353	32.25	.2274
No. 40 quartz sand, used in well point No. 80 and percolation experiment, p. 86	12	B	2.380	13	3,300	33.92	.1717
No. 60 quartz sand	13	1	3.010	....	8,710	36.45	.1551
No. 60 quartz sand (duplicate)	14	1	2.688	....	9,175	36.98	.1562
No. 60 quartz sand (duplicate)	15	3	2.845	....	8,452	34.20	.1777
No. 60 quartz sand (duplicate)	16	B	2.50	20.2	2,900	34.97	.1708
No. 60 quartz sand (duplicate)	17	B	2.45	19.5	2,925	34.97	.1758
No. 60 quartz sand (duplicate)	18	B	2.55	19.9	3,125	35.14	.1627
No. 60 quartz sand (duplicate)	19	B	2.55	20	3,120	35.14	.1628
No. 60 quartz sand (duplicate)	20	B	2.55	20.1	3,240	34.87	.1603
No. 60 quartz sand (duplicate)	21	B	2.55	20.2	3,230	34.87	.1601
No. 60 quartz sand (duplicate)	22	B	2.55	20.3	3,235	35.06	.1600
No. 80 quartz sand	23	1	3.15	20	14,565	37.25	.1143
No. 80 quartz sand	24	1	2.80	....	14,555	37.81	.1165
No. 80 quartz sand	25	3	2.91	....	16,195	34.91	.1213
No. 80 quartz sand, used in percolation experiment, p. 86	26	A	2.65	13	11,200	32.58	.09513
No. 100 quartz sand	27	1	3.37	....	16,420	38.68	.09593
No. 100 quartz sand	28	1	2.863	....	21,619	39.49	.08856
No. 100 quartz sand	29	3	2.94	....	24,845	35.32	.09714
No. 100 quartz sand	30	3	3.055	....	33,635	35.32	.08191
No. 100 quartz sand	31	3	3.030	....	32,540	35.51	.08188
No. 100 quartz sand	32	B	2.325	19.9	9,966	39.10	.07963
No. 100 quartz sand, washed	33	B	2.300	....	8,450	35.63	.1018
No. 100 quartz sand, washed in HCl and water	34	B	2.55	18.7	6,350	35.75	.1092

Table showing effective diameters of sands and soils with observed pore space and rate of air movement—Continued.

Material used.	Number of sample.	Aspirator tube.	Pressure of water.	Temperature.	Time for flow of 5,000 c. c.	Per cent of pore space.	Approximate effective diameter.
			Cm.	° *C.*	*Seconds.*		*Mm.*
No. 100 rescreened from No. 80	35	B	2.575	24.7	2,985	36.81	.1521
No. 8 quartz sand *a*	36	C	1.000	16.5	50	37.60	2.54
No. 7 quartz sand *a*	37	C	1.090	16.5	83.33	38.44	1.808
No. 6 quartz sand *a*	38	C	1.120	16.5	120.8	38.85	1.451
No. 5½ quartz sand *a*	39	C	1.150	16.5	163.3	39.26	1.217
No. 5 quartz sand *a*	40	C	1.180	16.5	211.6	39.88	1.095
No. 4 quartz sand *a*	41	C	1.180	16.5	300	38.53	.9149
No. 3 quartz sand *a*	42	C	1.190	16.5	475	36.26	.7988
No. 2 quartz sand *a*	43	C	1.200	16.5	693.3	34.66	.7146
No. 1 quartz sand *a*	44	C	1.210	16.5	976.67	34.43	.6006
No. 0 quartz saild *a*	45	C	1.220	16.5	1,308	34.42	.5169
Sorted sands mixed 20 per cent each of 1, 9, 13, 23, and 27	46	3	3.050	....	17,300	30.09	.1399
90 per cent of 1+10 per cent of 27	47	3	2.900	....	4,605	30.00	.2934
80 per cent of 1+20 per cent of 27	48	3	3	....	7,249	27.81	.2567
70 per cent of 1+30 per cent of 27	49	3	2.950	....	14,960	25.55	.2084
60 per cent of 1+40 per cent of 27	50	3	3.060	....	23,980	25.43	.1670
50 per cent of 1+50 per cent of 27	51	3	3.060	....	35,350	26.91	.1223
40 per cent of 1+60 per cent of 27	52	3	3.075	....	42,010	27.66	.1085
30 per cent of 1+70 per cent of 27	53	3	3.075	....	45,010	28.79	.09646
20 per cent of 1+80 per cent of 27	54	3	3.060	....	40,225	31.17	.09148
10 per cent of 1+90 per cent of 27	55	3	3.070	....	44,760	31.62	.08147
95 per cent of 7+5 per cent of 35	56	B	2.400	24.7	335	34.23	.5336
90 per cent of 7+10 per cent of 35	57	B	2.400	24.9	410	32.93	.5112
85 per cent of 7+15 per cent of 35	58	B	2.500	25	655	31.95	.4164
80 per cent of 7+20 per cent of 35	59	B	2.45	25	680	31.79	.4133
75 per cent of 7+25 per cent of 35	60	B	2.55	24.9	780	31.87	.3780
70 per cent of 7+30 per cent of 35	61	B	2.50	24.9	840	31.79	.3681

a Sorted sands used in experiments on pp. 231-240.

Table showing effective diameters of sands and soils, with observed pore space and rate of air movement—Continued.

Material used.	Number of sample.	Aspirator tube.	Pressure of water.	Temperature.	Time for flow of 5,000 c. c.	Per cent of pore space.	Approximate effective diameter.
			Cm.	*° C.*	*Seconds.*		*Mm.*
65 per cent of 7+35 per cent of 35	62	B	2.35	24.9	1,150	31.34	.3330
60 per cent of 7+40 per cent of 35	63	B	2.55	24.9	1,800	30.29	.2760
55 per cent of 8+45 per cent of 35	64	B	2.50	23.2	2,060	30.12	.2607
50 per cent of 7+50 per cent of 35	65	B	2.45	23.0	2,380	30.69	.2384
45 per cent of 7+55 per cent of 35	66	B	2.425	22.9	2,795	31.03	.2155
40 per cent of 7+60 per cent of 35	67	B	2.50	22.2	2,765	31.15	.2132
35 per cent of 7+65 per cent of 35	68	B	2.35	22.2	2,825	31.60	.2120
30 per cent of 7+70 per cent of 35	69	B	2.50	22.2	3,200	32.21	.1880
25 per cent of 7+75 per cent of 35	70	B	2.50	19.7	3,070	32.63	.1874
20 per cent of 7+80 per cent of 35	71	B	2.40	19.5	3,015	33.62	.1836
15 per cent of 7+85 per cent of 35	72	B	2.50	19.4	2,880	34.30	.1759
10 per cent of 7+90 per cent of 35	73	B	2.475	20.2	2,925	35.04	.1708
5 per cent of 7+95 per cent of 35	74	B	24.75	20.3	2,825	35.86	.1661
Unsorted sands:							
Los Angeles—							
No. 1	75	C	3.000	15.5	1,162.5	38.75	.29185
No. 2	76	C	3.000	15.5	1,510	33.05	.3301
No. 3	77	C	3.000	15.5	9,505	35.96	.1139
No. 4	78	C	3.000	15.3	7,375	34.89	.4289
No. 5	79	C	3.000	15.2	4,015	37.20	.1671
No. 6	80	C	3.000	15.4	2,260	31.42	.2913
No. 7	81	C	3.000	15.5	23,975	42.28	.05542
Sands of drainage experiment	82	B	2.60	16.7	1,450	31.11	.2881
Sands of percolation well:							
Second foot	83	B	2.81	17.2	11,995	38.57	.06745
Third foot	84	A	2.65	17.1	9,325	39.38	.07579
Fourth foot	85	B	2.56	17.2	1,575	39.45	.1872
Fifth foot	86	B	2.62	17.2	2,000	37.94	.1746
Sixth foot	87	B	2.57	17.2	2,135	38.15	.1673
Seventh foot	88	B	2.65	17.2	4,475	35.32	.1312

Table showing effective diameters of sands and soils with observed pore space and rate of air movement—Continued.

Material used.	Number of sample.	Aspirator tube.	Pressure of water.	Temperature.	Time for flow of 5,000 c. c.	Per cent of pore space.	Approximate effective diameter.
Sands of percolation well—Continued.			*Cm.*	*° C.*	*Seconds.*		*Mm.*
Eighth foot	89	A	2.60	17.2	2,575	34.57	.1818
Ninth foot	90	B	2.62	....	2,965	31.37	.1728
Tenth foot	91	A	2.64	16.6	2,025	38.08	.2191
Eleventh foot	92	A	2.66	16.6	5,940	30.25	.1470
Twelfth foot	93	A	3.03	17.2	11,925	28.76	.1055
Thirteenth foot	94	B	3.04	17.2	38,610	29.32	.0566
Unsorted soils:							
Pine barrens, Minong, Wisconsin—							
Surface foot	95	3	2.945	....	7,530	38.57	.1509
Second foot	96	3	2.93	....	11,540	34.91	.1432
Third foot	97	3	2.91	....	4,310	36.15	.2240
Sandy soil:							
Minong, Wisconsin—							
Surface	98	3	3.24	....	32,680	34.49	.02619
6 to 12 inches	99	3	3.145	....	133,700	29.96	.0523
Stevens Point, Wisconsin—							
Surface	100	3	3.275	....	270,900	32.30	.03149
8 to 16 inches	101	3	3.045	....	33,030	32.30	.09352
Tomahawk, Wisconsin—							
Surface	102	3	3.21	....	100,100	34.57	.04751
12 to 18 inches	103	3	3.03	....	20,630	31.43	.1242
Superior Junction, Wisconsin—							
Surface	104	3	3.10	....	171,600	36.19	.03439
6 to 12 inches	105	3	3.12	....	105,000	29.32	.03589
Nekoosa, Wisconsin—							
First foot	106	3	3.14	....	217,900	40.68	.02501
Second foot	107	3	3.115	....	100,300	32.87	.05197
Prairie loam, Oasis, Wisconsin:							
Surface	108	3	3.20	....	164,800	38.83	.03035
Second foot	109	3	3.225	....	98,460	34.64	.04777
Clayey loam:							
Drummond, Wisconsin—							
Surface	110	3	3.135	....	197,400	44.87	.02206
12 to 24 inches	111	3	3.19	....	205,200	44.15	.02197
Bruce, Wisconsin—Second foot	112	3	3.125	....	234,900	48.27	.01804

Table showing effective diameters of sands and soils with observed pore space and rate of air movement—Continued.

Material used.	Number of sample.	Aspirator tube.	Pressure of water.	Temperature.	Time for flow of 5,000 c. c.	Per cent of pore space.	Approximate effective diameter.
			Cm.	° *C.*	*Seconds.*		*Mm.*
Loamy clay, St. Croix County, Wisconsin—Second foot	113	3	3.17	....	348,700	47.10	.01810
Heavy clay, Ashland, Wisconsin:							
Surface, 6 inches	114	3	3.17	....	466,900	45.32	.01402
6 to 18 inches	115	3	3.24	....	808,200	44.15	.01111
Whitney's Maryland soils:							
471 early truck land	116	3	2.995	....	23,590	32.49	.1119
563 early truck land	117	3	3.035	....	41,960	34.45	.07555
141 average wheat land	118	3	3.25	....	1,056,000	42.79	.01011
1,045 average wheat land	119	3	3.26	....	993,300	48.00	.008612
173 finest wheat and grass land	120	3	3.22	....	2,112,500	52.94	.004956
934 finest wheat and grass land	121	3	3.23	....	1,477,300	45.96	.007657
Sorted soils:							
116 not passing 60 screen	123	B	2.475	19.2	525	37.46	.5468
116 passing 60 screen	124	B	2.90	19.2	166,300	32.21	.02421
124 not passing 100 screen	125	B	2.40	19.0	8,925	38.58	.0848
124 passing 100 screen	126	B	2.55	19.7	195,000	32.78	.01809
Angular grains. (Well drillings from well of physical laboratory):							
Depth 120 to 122.5 feet	127	B	2.81	17.3	26,215	33.80	.05612
Depth 122.5 to 127.16 feet	128	A	2.81	17.2	13,525	33.99	.07817
Depth 127.16 to 133.83 feet	129	B	2.63	17.2	8,065	31.22	.1214
Depth 133.83 to 140.83 feet	130	A	2.73	17.2	2,638	30.40	.2006
Crushed limestone washed and sorted:							
No. 20 screen	131	B	2.21	....	1,825	37.96	.6319
No. 40 screen	132	B	2.217	....	425	42.03	.3500
No. 60 screen	133	B	2.342	....	690	44.55	.2426
No. 80 screen	134	B	2.435	....	1,125	45.87	.1767
No. 100 screen	135	B	2.325	....	3,050	46.65	.1038
No. 100 screen duplicate	136	B	2.35	....	5,745	42.16	.09236
Limestone dust	137	B	3.075	....	432,000	43.35	.008933

Table showing effective diameters of sands and soils, with observed pore space and rate of air movement—Continued.

Material used.	Number of sample.	Aspirator tube.	Pressure of water.	Temperature.	Time for flow of 5,000 c. c.	Per cent of pore space.	Approximate effective diameter.
Crushed and sorted glass:			*Cm.*	*° C.*	*Seconds.*		*Mm.*
No. 20 screen	138	B	2.30	....	215	41.04	.5030
No. 40 screen	139	B	2.40	....	810	43.91	.2257
No. 60 screen	140	B	2.50	....	1,005	45.55	.1875
No. 80 screen	141	B	2.50	....	1,880	45.67	.1369
No. 100 screen	142	B	2.55	....	5,160	46.22	.08034
Crushed friable sandstone, not sorted:							
Dunnville sandstone No. 2	143	B	2.96	13.0	42,855	37.60	.03635
Madison sandstone No. 1	144	B	2.71	16.7	13,355	33.43	.08188
Madison sandstone Nos. 4, 5, 6, 7	145	C	3.00	16.0	21,820	34.34	.08237
Soils of percolation experiment in plant house:							
Surface layer of sand	146	A	2.573	16.7	1,065	35.83	.28448
Section I	147	A	3.00	16.5	71,100	33.65	.03380
Section II	148	B	2.965	16.6	46,575	33.76	.04144
Section III	149	A	2.99	16.0	47,055	33.88	.04084
Section IV	150	A	2.765	16.7	30,890	34.37	.05261

It will be seen from this table that both the upper and lower theoretical limits of pore space for the ideal soil are passed, Nos. 49 and 50 giving a pore space of 25.55 and 25.43 per cent, respectively, while Nos. 112, 119, and 120 give pore spaces of 48.27, 48, and 52.94 per cent, the theoretical limits being 25.95 and 47.64 per cent.

It appears to be generally true that the well-rounded grains of nearly uniform diameter tend to give a pore space which lies between 32 and 40 per cent. The mean theoretical pore space for spherical grains of a single size is 36.795 per cent, and this is very close to the mean observed limit for the more simple sands of rounded grains. For simple sands with angular grains the pore space is much larger than it is for the rounded sands of the same sizes of grains, and in the case of the crushed glass, whose grains are more angular than those of the crushed limestone, which have a tendency to be cuboidal in form, the pore space is the largest of all.

Comparison of pore space in different materials.—In fig. 39 the pore space of several kinds of grains has been plotted in curves, which bring before the mind these relations more clearly than a mere statement is able to do. Referring to the figure, it will be seen, when the whole range of sizes of soil and sand grains is taken into consideration, that the full theoretical range of the ideal soil is only a little overstepped at both the upper and lower limits by actual soils and

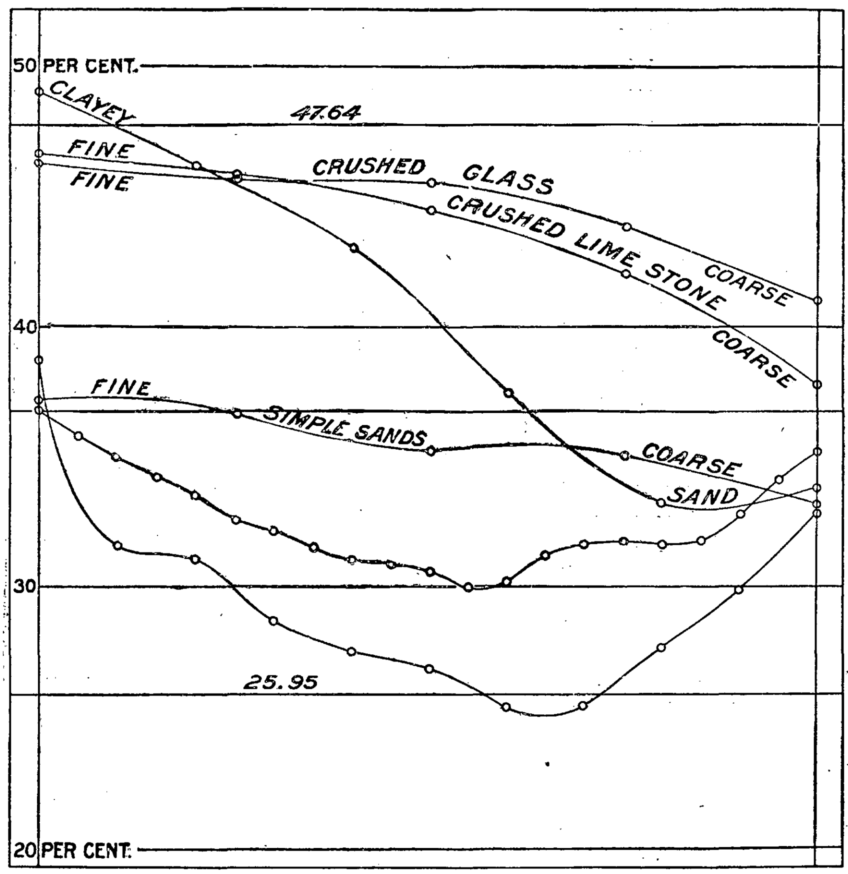


FIG. 39.—Curves showing the variations in the percentage of pore space in various samples of sands, soils, and crushed rocks.

sands, with their mixtures. It will be observed, in the second place, that the fine-grained elements of all sorts tend to give a larger pore space than results from the massing together of those having larger diameters, the finest of the clay soils exceeding the upper theoretical limit by several per cent.

The simple sands with well-rounded grains lie close to the mean value when they have a diameter of about 0.15 mm.; but when finer than this the pore space curve rises above the mean line, and when the diameters are larger it falls below, as the curve marked "simple sands" shows.

The two curves of pore space which reach the lowest limits in the figure show what results are secured when two sands having rounded grains but quite dissimilar diameters are mixed in various proportions. The upper of these two curves has resulted from mixing sand No. 35 with No. 7. Beginning with the curve on the left with 100 per cent of the sand whose grains have diameters of 0.1521 mm., and mixing with this a sand whose grains have a diameter of 0.6112 mm. by increments of 5 per cent until on the right there is the simple sand of the coarsest texture, it will be seen that the smallest pore space is attained when the two sands are mixed in nearly equal proportions by weight.

The curve which has given the smallest pore space is also obtained by mixing two sorted sands, Nos. 1 and 27, but the No. 27 had mixed with it all of the grains which would pass a screen of 100 mesh contained in the original mixed sand from which it was derived, while the No. 35 sand used with the No. 7 for the other curve was secured by resifting a sand from a No. 80 screen and which therefore did not contain any of the very fine sand grains that were mixed with the other No. 100 sand. On this account there were many very fine grains in this grade which could sift into the pores of the coarser sand and thus more nearly occupy the entire space.

The curve showing the pore space of the natural soils begins very high with the heavy clays, but falls as the coarser textured varieties are reached, until in the case of the coarse, sandy soils a pore space considerably below the mean is reached. It should be noted that the pore space reaches a minimum and then begins to increase again as the soils become coarser, just as occurred in the mixed grades made by using different proportions of a coarse and fine sand.

Both the crushed glass and the crushed limestone have very high pore spaces and suggest that the large pore space of the clay soils may be due in part to a greater angularity of their particles, which interferes with close packing. It is not at all clear, however, from the curves plotted, that even the rounded sand grains might not develop so large a pore space as the clays show if the diameters of these sands were only reduced until they became as small as those of the fine clay soil are. The change in the diameter of the soil grains between the two ends of the soil curve is about as 18 to 1, while between the two ends of the simple sand curve it is 5 to 1; but in the soil curve the pore space increases 15 per cent, while in the sand curve the increase is 3.94 per cent, giving the proportion

$$5:18::3.94:x,$$

whence $x=14.18$, which is nearly large enough to account for the excess of pore space in the fine clay soil over that in the sands.

This is an important point to have established, because if the difference in pore space, which increases in an inverse ratio to the diameter, is not due to increase of angularity in the grains, there will be stronger grounds for the belief that the same laws of flow may hold through a wider range of soil diameters than could be expected if an increasing angularity of the grain occurred with decrease of diameter. The relation just pointed out, however, should not be given much weight unless other evidence can be found to confirm it.

DETERMINATION OF THE DIAMETER OF SOIL AND SAND GRAINS.

One of the most evident facts brought out in the table of pore spaces which has been presented is that the time which was required for 5,000 c. c. of air to pass through a given sample holds no very apparent relation to the pore space which was found, except, indeed, that generally the larger the per cent of pore space the slower the air was in passing through.

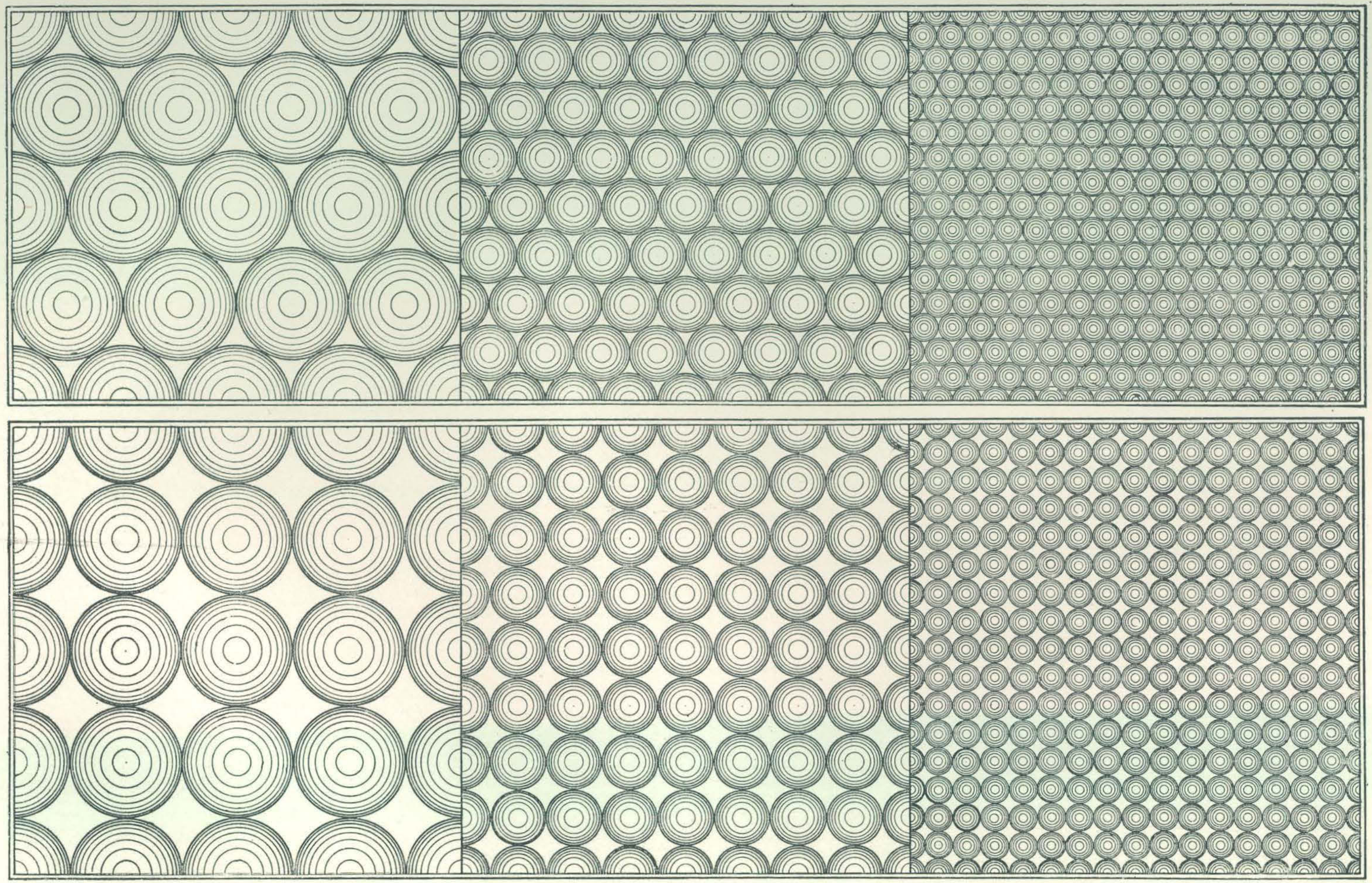
If we take, for example, the case on the soil curve in fig. 39, which falls nearly upon the line of mean theoretical pore space, and compare the time which was required for 5,000 c. c. of air to pass through the aspirator column when filled with this soil with the time required for the same amount of air under like conditions to pass through the sample on the simple sand curve and the one on the mixed sand curve, which has very nearly the same pore space, it will be found that the times in the three cases stand nearly as given below:

Time required for flow of 5,000 cubic centimeters of air through different materials.

Material.	Seconds.	Proportion.
Mixed soil	170,448	151.2
Nearly simple sand	16,747	14.8
Simple sand	1,127	1

That is to say, while the aggregate amount of pore space in each of these three cases through which water or air may travel is very nearly the same, yet the time required for the same amount of air to pass through columns of soil of the same area of cross section and the same length, under the same pressure and temperature, is 150 times as long in one case and 15 times as long in the other as was required by the first.

One of the reasons for this great difference in time of flow is found in the fact that, while the total area of cross section through which the flow may take place is very nearly the same in the three cases, the number of tubes through which the air must move is very different,



MAXIMUM AND MINIMUM PORE SPACE OF SPHERICAL SOIL GRAINS.

and at the same time their diameters are extremely unlike in size, the pores being very many, but small, where the flow is slow, and much fewer and relatively larger where the flow is rapid. Pl. IX shows at a glance how the size of the soil grains affects the character of the pore space where the grains are arranged in the manner which gives it the maximum value of 47.64 per cent and also the minimum value of 25.95 per cent.

It will be seen that at the left, where the unit cross section is filled by 16 of the larger spheres, there remain 16 large pores between them, through which the water may flow; in the center, where the spheres have just one-half the diameter, it requires the equivalent of 64 spheres to fill the same cross section, thus forming four times as many pores through which the water may flow, but leaving each pore with only one-fourth the area of cross section. Then, again, on the right, where the spheres or grains have a diameter only one-fourth that of the largest spheres, it requires 256 grains to fill the sections which form the same number of smaller pores, but each one has only one-sixteenth the area of cross section possessed by the largest pore. In such cases as these, with the aspirator filled with grains first of one and then of another size, the air would be forced to travel in one case in 16 streams, in another in 64 streams, while with grains of a third size there would be 256 streams moving along the same unit area of cross section. If, then, there is the same absolute amount of friction per each equal unit area of sliding surface, it is evident that where the pore space has been most divided there must be the largest loss of energy per unit of time, and hence the smallest flow, just as has been observed.

Since the extent to which the pore space of a soil, sand, or rock is divided is one of the most important characteristics which determine the flow of fluids through it, and since this subdivision is determined chiefly by the diameter of the grain, it follows that a quantitative study of the flow of ground water stands in need of most exact knowledge of the diameters of the pores through which the flow must take place and of the grains themselves.

Methods of determination in common use.—There have been two methods in common use for determining the diameters of soil grains—first, that of direct measurement with micrometer and microscope or other means, and, second, that of counting and weighing a known number of grains and then computing the diameter of the mean grain from the number, weight, and specific gravity.

During this investigation it has been found that even with a screened and sorted sand it was necessary to include in the count more than 1,000 grains in order to secure results which agreed by weight to the third decimal place; in illustration of observed variations a single instance may be cited.

Table showing the computed mean diameter of the sand grains used in the experiments described on pp. 162–166.

	Number of grains.	Net weight.	Weight per 1,000.	Computed diameter.
		Grams.	*Grams.*	*Millimeters.*
First count	1,600	0.39445	0.24653	0.5622
Second count	1,507	.35155	.23361	.5519
Third count	1,217	.28805	.23669	.5546
Fourth count	1,033	.25045	.24245	.5591

The largest percentage departure in this case is 1.8.

Closeness of results obtained by counting and by weighing.—But no matter how close duplicates may be secured by this method, the results can give accurate values only when the diameters of all the grains are practically equal, because the weights of grains vary with the cubes of their diameters. To divide the weight of 1,000 grains whose diameters are 0.1, 0.2, and 0.3 mm. by 1,000 gives the mean weight of one grain, but it does not give the weight of the mean grain whose diameter is sought in investigating the flow of fluids through a soil or sand. It is evident that the weights of such grains as those considered would stand to one another as 1 to 8 to 27, showing that 27 small grains are required to equal the weight of a single large grain, and any system of counting and weighing which does not take account of the number of grains of each dimension can not give a safe value for the purposes under consideration. But even when the numbers and dimensions of each size of grain in a gram of the sample are known the two methods of computing the mean diameter from weight and from measurement do not give the same result, as the following definite case will show.

Let a sand be considered whose grains have the specific gravity 2.65, and whose diameters are: $(a) = 0.1657$ mm. and $(b) = 0.00085$ mm. Let these be mixed in the following proportions:

A. 90 per cent of *a* by weight with 10 per cent of *b* by weight.

B. 10 per cent of *a* by weight with 90 per cent of *b* by weight.

C. 50 per cent of *a* by weight with 50 per cent of *b* by weight.

The aggregate surface presented by 1 gram of this mixture would be—

A.

	Sq. cm.
90 per cent of *a*	123
10 per cent of *b*	2,664
Aggregate surface	2,787

B.

10 per cent of *a*	13.66
90 per cent of *b*	23,973.37
Aggregate surface	23,987.03

C.

	Sq. cm.
50 per cent of *a*	68.32
50 per cent of *b*	13,318.50
Aggregate surface	13,386.82

If, now, we compute the number of grains of each kind in 1 gram of the mixture we get the following:

A.

	Grains.
90 per cent of *a*	142,570
10 per cent of *b*	117,354,324,324
Total number	117,354,466,894

B.

10 per cent of *a*	15,841
90 per cent of *b*	1,056,189,320,388
Total number	1,056,189,336,229

C.

50 per cent of *a*	79,206
50 per cent of *b*	586,771,621,622
Total number	586,771,700,828

We may now compute the diameter of the mean grain by dividing the total surface of all grains by the number of grains, and from $D=\sqrt{\frac{S}{\pi}}$ find the value of the diameters to be—

	Millimeters.
For A	0.0008694
For B	.0008502
For C	.0008522

But if the sum of the diameters of all grains is divided by the number of grains the following diameters are found:

	Millimeters.
A	0.0008502
B	.00085000196
C	.00085002157

Again, if the total weight of all grains is divided by the number of grains we get the following:

	Millimeters.
A	0.001831
B	.0008804
C	.001071

We have here three different mean diameters:

1. Computed from the surface of the mean grain.
2. Computed from the sum of all diameters.
3. Computed from the weight of the mean grain.

No two of them agree, and yet each is right judged from its own standpoint, but substituted in the formula for computing the flow of water each would give a different value, and yet but one value should be found.

To test how far these mean values fail in giving a real value, each may be used to compute the total surface in one gram of the soil from which the mean diameters were computed.

	A	B	C
	Sq. cm.	*Sq. cm.*	*Sq. cm.*
Actual surface per gram	2, 787	23, 987. 03	13, 386. 82
Computed from grain of mean surface	26, 041. 2	26, 568. 17	26, 568. 78
Computed from grain of mean diameter	26, 630. 8	26, 637	26, 636. 4
Computed from grain of mean weight	12, 363. 8	25, 717. 8	21, 141. 8

It is to be observed regarding these results that in every case the computed surfaces are too large, but not by equal amounts. The grain of mean surface gives nearly the same values for the three mixtures, whereas they are related to one another as 1 to 8.608 to 4.804. The same relations are also found when the surfaces are computed from the grain of mean diameter, and the two sets of results are very nearly alike, so that it may be said that each of these methods is equally far from the truth.

When the grain of mean weight is used for computing the total surface in each case the relations stand:

	A	B	C
Actual	1 to	8. 608 to	4. 804
Computed	1 to	2. 081 to	1. 71

It is evident from these considerations that great difficulties stand in the way of the investigator who attempts to determine experimentally the influence of the size of soil grains or sand grains upon the movement of fluids through them.

NEW METHOD OF DETERMINING THE DIAMETER OF SAND AND SOIL GRAINS.

After these difficulties were encountered along the lines of mechanical analysis of soils it occurred to the writer in 1894 that it might be possible to take advantage of the known laws of flow of air through capillary tubes to determine the character of soil grains by aspirating air through a known volume of the soil under known conditions of pressure and temperature. When it had been learned that fairly uniform results could be secured experimentally the assistance of Professor Slichter was sought and he kindly consented to undertake a mathematical investigation of the problems involved, and this led to the formula which he has presented in another paper in this volume and which is also given on a preceding page of this paper.

Description of the apparatus.—The apparatus which has been devised to use with this method is represented in fig. 40 and consists of an aspirator A, whose capacity varies with the coarseness of the sample to be investigated; a pressure gage B; a meter for measuring the air C, and an aspirator tube D, in which the sample is placed whose character is to be investigated.

The aspirator is a bell 1, placed in a water receptacle 2, under which rises, above the level of the water, the air tube 3,3,3,3, connecting the

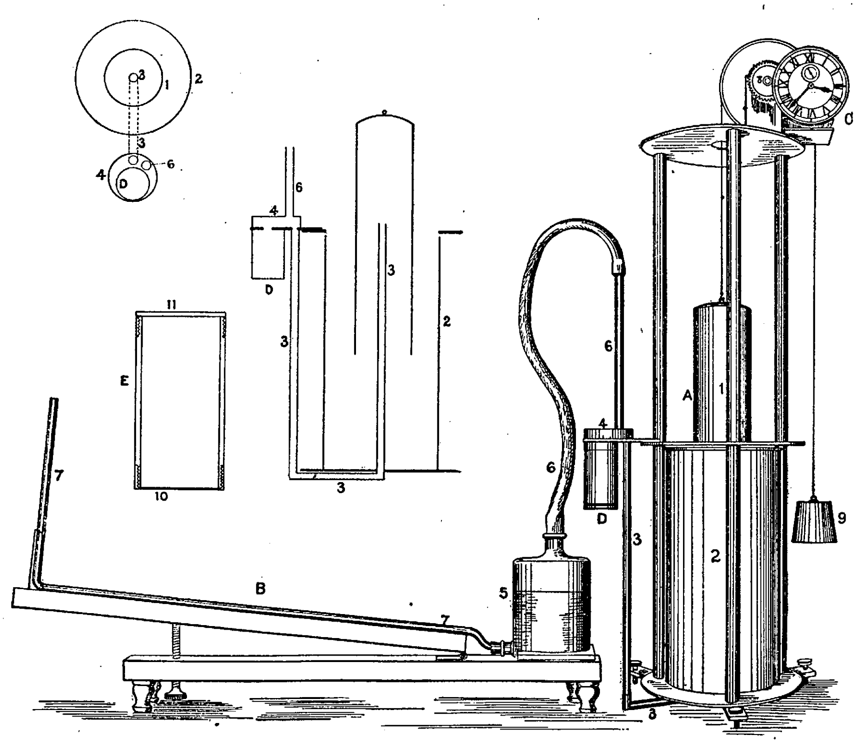


FIG. 40.—Aspirator for determining the mean effective diameter of soil grains. A, aspirator bell; B, pressure gage; C, air meter; D, aspirator tube for sample.

air chamber 4,4, above the aspirator tube D, with the bell A, of the aspirator.

The pressure gage consists of a bottle 5, partly filled with water and connected with the air chamber 4, by means of the tube 6, 6. The pressure is measured in a bent tube 7, 7, placed upon a scale inclined so as to rise 1 in 10, thus permitting direct eye readings of changes of pressure to less than 0.1 mm. of water. The pressure tube has a diameter equal to one thirty-fifth of that of the water receptacle 5, and the object of the arrangement is to avoid the necessity of taking two readings of the gage for the pressure.

The air meter is a clock gear, with dial and hands attached, which are driven by the gear wheel 8, as the bell of the aspirator rises under the tension of the cord operated by the weight 9, or by means of a crank, as already described, when a constant pressure is desired. The fact that the bell rising out of the water becomes heavier as it rises makes the pressure one which is constantly decreasing by a small amount.

The aspirator tube is provided with two caps 10 and 11, which screw to place with an accurately cut fine thread. These joints are made perfectly air-tight by the use of a little thick vaseline on the threads. The upper cap 11, screws down so as to press hard upon the edge of the soil tube, and the lower cap 10, is simply a ring covered with fine wire netting, which holds the soil in place while it permits the air to enter the aspirator through the contained samples.

To fill the aspirator tube the lower cap, 10, is removed and the upper one, 11, screwed down to place, which now serves as a bottom until the tube is full and the screen cap put in place. When the aspirator tube has been filled and is to be attached to the aspirator the tube is reversed, the cap removed, and then screwed to place on the air chamber. The method of filling the tube has already been described.

Results of the aspiration method.—The results which have been secured with this method have been given in the tables on pages 209 to 215, but in order to show how results obtained with it compare with those obtained by counting and weighing we have selected from the foregoing tables four sets of samples in which the diameters of the same grains have been determined by the method of counting and weighing a large number of grains, usually in duplicate lots, as already cited.

Table giving the sizes of soil grains.

Number.	Methods of determination.	
	By aspirator.	By count and weight.
Series I, water-worn sand:	*Mm.*	*Mm.*
20	0.4745	0.4690
40	.1848	.1745
60	.1551	.1472
80	.1143	.1075
100	.0826	.0759
Series II, crushed glass, by J. A. Jeffery:		
20	.5028	.5365
40	.2845	.3577
60	.1868	.2329
80	.1380	.1688
100	.0797	.1050
Series III, rounded sand, by J. A. Jeffery:		
20	.5180	.4658
40	.3329	.2999

Table giving the sizes of soil grains—Continued.

Number.	Methods of determination.	
	By aspirator.	By count and weight.
Series III, rounded sand, by J. A. Jeffery—Continued.	*Mm.*	*Mm.*
60	.2225	.2092
80	.1658	.1670
100	.1116	.1210
Series IV, rounded sand:		
8	2.540	2.755
7	1.808	1.993
6	1.451	1.588
5½	1.217	1.345
5	1.095	1.157
4	.9149	1.106
3	.7988	.8017
2	.7146	.6653
1	.6006	.5824
0	.5169	.4891

In this table it will be seen that while there is a general agreement between the two methods, yet there are disagreements which, considered in percentages, are quite large. It must be borne in mind, however, as has been already pointed out, that we have in reality no standard for comparing the method, for we know that the values obtained by counting and weighing can not be exact. Search has been made thus far in vain for some medium consisting of spherical grains of perfectly uniform diameter with which to secure a rigid test of the method, but as yet none has been found. It was hoped that a suitable medium would be found in double-fine dust shot, but the specific gravity of this is so high that small variations in diameter make large differences in results even by the method of counting and weighing.

The most rigid test yet found for the method is that furnished by comparing the observed flows of water through a series of sands with those which would be computed on theoretical considerations from the diameters as determined by the aspirator. To make such a test as this, and in order also to test the general accuracy of his two formulas, one for determining the diameter of soil grains by means of the aspirator and the other for computing the flow of water through sands, Professor Slichter has, upon request, computed the effective sizes and flows of 10 samples of sand through which the flow of water and air were carefully measured under low pressures and uniform conditions of temperature; the results for the flow appear in the following table:

Rate of flow of air and of water through soils having grains of different size under a pressure of 1 centimeter.

[Time, 10 minutes.]

Grade.	Flow of water.				Flow of air.			
	Computed.		Observed.		Computed.		Observed.	
	Temperature.	Flow.	Temperature.	Flow.	Temperature.	Flow.	Temperature.	Flow.
	° C.	C. c.	° C.	C. c.	° C.	C. c.	° C.	C. c.
8.....	17	2, 680	15. 2	2, 296	17	62, 700	16. 5	60, 000
7.....	17	1, 370	15. 5	1, 080	17	38, 320	16. 5	33, 027
6.....	17	909. 1	15. 3	756	17	24, 040	16. 5	22, 170
5½.....	17	638. 6	15. 3	542	17	18, 900	16. 5	15, 970
5.....	17	499. 6	17. 6	504. 6	17	14, 430	16. 5	12, 010
4.....	17	326. 6	16. 8	329. 2	17	9, 296	16. 5	8, 475
3.....	17	194	16. 3	210	17	4, 937	16. 5	5, 307
2.....	17	106. 2	16. 6	138. 6	17	2, 953	16. 5	3, 606
1.....	17	75. 7	16. 5	94. 8	17	2, 295	16. 5	2, 539
0.....	17	59. 8	16. 2	72. 3	17	1, 597	16. 5	1, 879

In this table the computed flows have been derived from the diameter determined by weighing and counting. It will be noted that the observed flows, both for air and for water, are slower than those computed for the coarse-grained soils and faster for the finer grained soils.

When the diameters determined by the aspirator method are used for computing the flow of water through the same soils then the results stand as given in the next table:

Table showing agreement between observed and computed flows of water through sand.

Grade.	Time.	Flow computed from aspirator diameter.	Observed flow.	Flow computed from count and weight diameter.
	Minutes.	*Grams.*	*Grams.*	*Grams.*
8................................	10	2, 277	2, 296	2, 680
7................................	10	1, 132	1, 080	1, 372
6................................	10	757	756	909. 1
5½................................	10	522	542	638. 6
5................................	10	453. 2	504. 6	499. 6
4................................	10	297. 5	329. 2	326. 6
3................................	10	193	210	194
2................................	10	122	138. 6	106. 2
1................................	10	80. 6	94. 8	75. 7
0................................	10	66. 8	72. 3	59. 8

It will be seen that in this table, while the agreement is closer than in the preceding, it is not so close in all parts as could be wished, nor even so close as should be expected if the laws of capillary flow hold rigidly for water through soils under these very low pressures.

The fact that the departures are in one direction for sands of large grains and in the opposite direction for those which are smaller appears to indicate either that the formulas do not quite meet the demands which should reasonably be expected of them, or else that there is some systematic error in the observations or the apparatus.

This method of determining the effective size of sand and soil grains is very easy and expeditious, and since it takes into account both the absolute amount of pore space by directly determining it and also the extent to which it is subdivided by measuring the time required for a given volume of air to pass through a section of determined dimensions, the method would appear theoretically to be much more satisfactory than those which have heretofore been in general use, and since the computed flows from the aspirator diameters are, on the average, closer to the observed flows than are those derived from the count and weight diameters, it would appear that more confidence may be placed in the results obtained in this way. In the table below are given the percentage departures of the computed flows by the two methods from the observed flows.

Table showing the departures of computed flows from the observed flows of water through sands Nos. 36–45.

Grade.	By aspirator.		By count and weight.	
		Per cent.		*Per cent.*
8.....	Too small...	0.8275	Too large...	16.72
7.....	Too large...	4.815	.....do......	26.85
6.....	.....do......	.1323	.....do......	20.25
5½....	Too small...	3.690	.....do......	17.82
5.....	.....do......	10.19	Too small...	.9247
4.....	.....do......	9.629	.....do......	.7898
3.....	.....do......	8.095	.....do......	7.619
2.....	.....do......	11.98	.....do......	23.38
1.....	.....do......	14.98	.....do......	20.15
0.....	.....do......	7.607	.....do......	17.29

It will be seen that when the flow is computed by either method results which are too small are obtained for the smallest sizes of grains when judged by the observed flows, but for the larger sizes the aspirator gives values which are about right, while the weight and count method gives values which are as much too large as they were too small for the smaller sizes.

INFLUENCE OF DIAMETER OF GRAIN ON THE RATE OF FLOW.

Method and apparatus used.—In order to study the influence of the diameter of soil grains upon the rate at which water will move through them under different pressures a series of 10 grades of quartz sand was procured by screening them through screens having circular openings, and then washing each grade upon its screen by allowing a strong stream of water to play upon the sample for some time, in order not only to free the sample from silt and dust, but also to wash through the screen any grains which were small enough to pass the openings, if only they could be presented to the opening in the right way. After they had been washed with clean well water the samples were dried and introduced into the percolator in this condition, a small quantity at a time, and gently but thoroughly tamped with a broad, flat-faced pestle as the filling progressed.

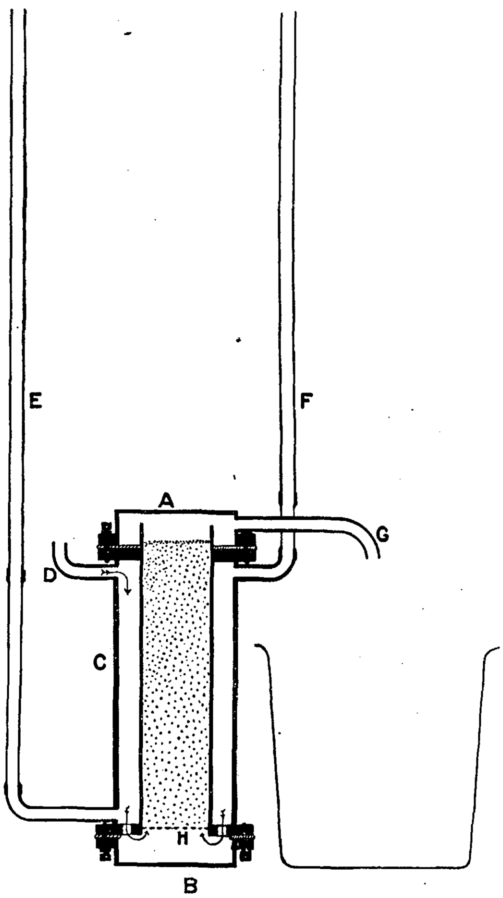


FIG. 41.—Percolator for measuring flow of water through sand. A, B, flanged cups; C, water jacket; D, supply tube; E, pressure gage; F, air vent; G, discharge pipe; H, sand.

The object of introducing the sand into the percolator dry was to avoid as far as possible any stratification of the materials, which greatly modifies the rate of flow, and also to secure an accurate measure of the pore space, and at the same time to have this pore space as small as it was practicable to make it.

The apparatus used for this work is represented in fig. 41, and consists of an inner heavy brass tube, nickel plated, to lessen the liability of clogging the sand by chemical action, having a length a little greater than 12 inches, so that the flow could be measured through a column of sand 30.4816 cm. long and 7.242 cm. in diameter, and this length of column was used in every experiment in this series.

Surrounding the percolator tube is a water jacket, into which the water flows through a tube at the upper end, and thence by two ports into a water chamber below, which is cut off from the percolator tube by a nickel-plated fine brass screen, through which the water passes to the sand above. In order to avoid any sagging of the screen it was supported by parallel round brass wires, also nickel plated. After passing through the sand in an upward course the water overflows the rim of the tube into a water chamber similar to the one below, and from this the water was discharged through a tube of one-half inch inside diameter, provided with an opening in its upper side to admit air and prevent any siphoning action from taking place to disturb the pressure which it was desired to maintain.

The object of the water jacket was to control better the temperature of the walls of the percolation tube and to lessen the liability of changes in its volume by changes in temperature. The water chambers themselves consisted of two flanged covers, which were held in place by flange bolts and made water-tight by means of rubber gaskets.

The pressure was measured by means of a water manometer, not shown in the figure, which consisted of a long barometer tube, carried by a rigid bed, that could be raised or lowered from an incline, rising 1 in 10 to two or three times this amount if desired. The rigid bed carried a scale graduated in centimeters and millimeters, so that when the rise of the bed was 1 in 10, as was generally the case, the pressures could be read to one-tenth of a millimeter. The zero of the apparatus was secured by allowing water to fill the apparatus and overflow until no more would be discharged, and then by means of a set of leveling screws the percolator was lowered or raised until the water in the pressure gage stood at the zero of the scale.

To maintain any constant desired head the water came from a reservoir to an adjustable overflow receptacle which could be raised or lowered as desired upon a sliding bar and fixed by means of a set screw. To make fine adjustments of head this bar was provided with a friction kneejoint, which permitted slight flexing one way or the other until the desired level was secured.

Filtered distilled water was always used in this work, and the water passed through a sand filter placed between the overflow and the supply reservoir after the first series of experiments had been made, to hold back dust particles, which tended to gather in the water as it was used over and over in the work.

The measurements of flow under each pressure had a duration of ten minutes, unless the rate of discharge was too great to permit the water to be collected and weighed on the Springer torsion balance used.

After filling the percolator with the dry sand and weighing, in order to be able to compute the exact pore space under which the flow was to be studied, hot water, kept boiling, was run through the sample from the bottom upward during about thirty minutes, in order to remove all air from between the sand grains; then the source of heat was removed from the water, and it was still kept running through until the temperature had fallen nearly to that of the air of the laboratory.

All measurements of flow were made in the constant-temperature room, and the apparatus, after filling, was allowed to stand in this room not less than twelve hours before experiments were begun, in order to insure an equilibrium of temperature between the apparatus and the room.

The diameters of the grains of the ten grades of sand used in this series are given in the table on page 225, as they were determined by counting and weighing, and also by the aspirator method. They are Series IV of that table. The grains are also shown in natural size in Pls. X-XIV.

The pore spaces, as determined from the weight of the material used and the specific gravity of the grains, are given in the table below, and a comparison made between these values and those found when the same sands were used in the aspirator to determine the diameter of the grains will show why the observed and computed flows do not and can not exactly agree.

Table showing pore space of sands 36 to 45 used in flow of water.

Grade of sand.	Specific gravity of sand.	Pore space of sands used with—	
		Air.	Water.
8	2.725	37.60	39.71
7	2.758	38.44	39.46
6	2.755	38.85	39.97
5½	2.773	39.26	39.71
5	2.744	39.88	40.12
4	2.726	38.53	39.40
3	2.700	36.26	37.77
2	2.668	34.66	35.21
1	2.669	34.43	34.33
0	2.661	34.42	35.54

The larger pore space which usually occurs in the percolator is due chiefly to the fact that with this apparatus it was not practicable to jar it after filling, as was the case with the aspirator, and this lack of agreement between the pore spaces must tend to make a part of the discrepancy which has been shown between the observed and the computed flows.

Results obtained.—In the tables which follow are given the observed rates of flow under the various pressures at which they were measured. There are also added three other columns. The first shows the flow divided by the pressure, which indicates in how far the flow failed to be directly proportional to the pressure. The second column shows what the flow should be, computed from the diameter of the grains as determined by the aspirator, while the third and last column shows what flow would be computed for the sample from the observed flow which took place under the highest pressure in each case.

Flow of water through sand No. 36 (Pl. X, A).

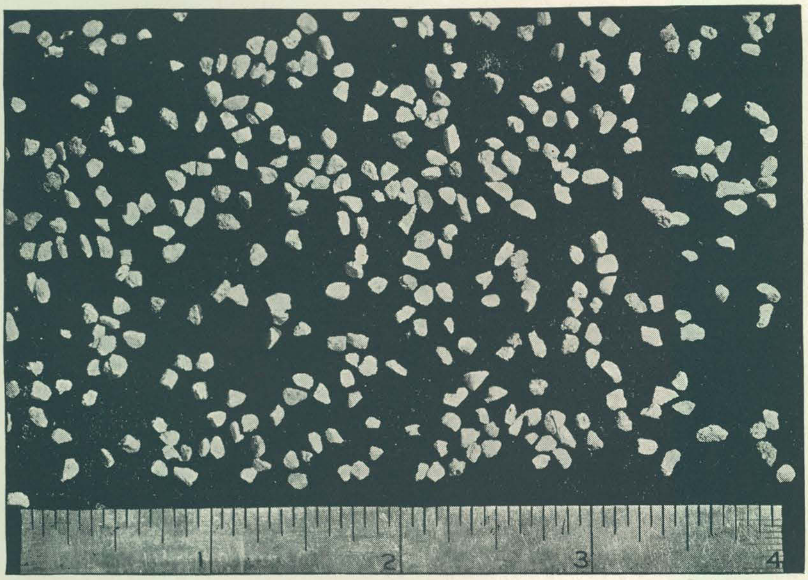
Pressure of water.	Temperature.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from— Aspirator diameter.	Flow for 10 minutes computed from— Observed highest pressure flow.
Cm.	° *C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
0.5	15.2	10	1,494.3	2,988.6	1,152.3	1,001.4
.5	15.25	10	1,491.6	2,983.2	1,152.3	1,001.4
1.0	15.2	10	2,661.0	2,661.0	2,304.6	2,002.8
1.2	15.2	10	*a* 3,063.6	2,553.0	2,765.5	2,403.3
1.4	15.2	10	3,455.6	2,468.3	3,226.4	2,803.9
1.6	15.2	10	3,889.6	2,428.8	3,687.4	3,204.4
1.8	15.1	10	4,364.4	2,424.7	4,648.3	3,605.0
2.0	15.0	10	4,664.0	2,332.0	4,609.2	4,005.5
2.2	15.05	10	5,093.8	2,425.6	5,070.1	4,406.1
1.8	15.1	10	4,280.2	2,377.9	4,148.3	3,605.0
2.4	15.25	10	5,482.2	2,284.2	5,531.0	4,806.6
2.6	15.15	10	5,806.5	2,233.3	5,992.0	5,207.2
2.8	15.2	10	6,236.0	2,225.0	6,452.9	5,607.8
3.0	15.3	10	6,576.5	2,192.1	6,913.8	6,008.3
3.2	15.4	10	6,969.0	2,177.8	7,374.7	6,408.9
3.4	15.2	10	7,259.0	2,135.0	7,835.6	6,809.4
3.6	15.3	10	7,624.0	2,117.8	8,296.6	7,210.0
3.8	15.3	10	8,022.5	2,111.2	8,757.5	7,610.5
4.0	14.9	10	8,396.5	2,099.1	9,218.4	8,011.1
4.2	15.0	10	8,720.5	2,076.3	9,679.3	8,411.6
4.4	15.1	10	9,114.5	2,078.4	10,140.2	8,812.2
4.6	15.2	10	9,511.5	2,067.7	10,601.2	9,212.7
4.8	15.2	10	9,786.5	2,038.8	11,062.1	9,613.3
5.0	15.3	10	10,192.5	2,038.5	11,523.0	10,013.9
5.2	15.3	10	10,549.0	2,028.6	11,983.9	10,414.4
5.4	15.3	10	10,882.0	2,015.2	12,444.8	10,815.0
5.6	15.5	10	11,215.5	2,002.8	12,905.8	11,215.5
1.0	15.5	10	2,696.1	2,696.1	2,304.6	2,002.8
2.0	15.5	10	4,607.4	2,303.7	4,609.2	4,005.5

a The weights below computed to ten minutes, the observed time being less.

Flow of water through sand No. 37 (Pl. X, B).

Pressure of water.	Temperature.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from—	
					Aspirator diameter.	Observed highest pressure flow.
Cm.	° *C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
1.0	15.1	10	1,013.4	1,013.4	1,227.0	1,092.8
1.0	15.1	10	1,030.0	1,030.0	1,227.0	1,092.8
1.2	15.2	10	1,249.4	1,041.17	1,472.4	1,311.3
1.4	15.15	10	1,481.4	1,058.14	1,717.8	1,529.9
1.6	15.2	10	1,705.8	1,066.12	1,963.2	1,748.4
1.8	15.3	10	1,933.8	1,073.88	2,208.6	1,967.0
2.0	15.4	10	2,165.5	1,082.75	2,454.0	2,185.8
2.2	15.5	10	2,396.0	1,089.09	2,699.4	2,404.1
2.4	15.4	10	2,610.8	1,087.83	2,944.8	2,622.6
2.6	15.4	10	2,854.6	1,097.92	3,190.2	2,841.2
2.8	15.4	10	3,060.4	1,093.00	3,435.6	3,059.7
3.0	15.4	10	3,270.4	1,090.13	3,681.0	3,278.3
3.2	15.4	10	3,456.4	1,080.12	3,926.4	3,496.8
3.4	15.4	10	3,688.0	1,084.71	4,171.8	3,715.4
3.6	15.5	10	3,916.6	1,087.94	4,417.2	3,933.9
3.6	15.5	10	3,898.4	1,082.89	4,417.2	3,933.9
3.8	15.45	10	4,131.2	1,087.66	4,662.6	4,152.5
4.0	15.4	10	4,344.0	1,086.00	4,908.0	4,371.0
4.2	15.45	10	4,583.0	1,091.19	5,153.4	4,589.6
4.4	15.5	10	4,776.6	1,085.60	5,398.8	4,808.1
4.6	15.5	10	5,018.4	1,090.95	5,644.2	5,026.7
4.8	15.3	10	5,218.4	1,087.16	5,889.6	5,245.2
5.0	15.4	10	5,452.4	1,090.48	6,135.0	5,463.8
5.2	15.4	10	5,677.0	1,091.73	6,380.4	5,682.3
5.4	15.4	10	5,910.5	1,094.44	6,625.8	5,900.9
5.6	15.4	10	6,121.5	1,093.04	6,871.2	6,119.4
5.8	15.5	10	6,336.0	1,090.69	7,116.6	6,338.0
6.0	15.5	10	6,556.5	1,092.75	7,362.0	6,556.5

(A)



(B)

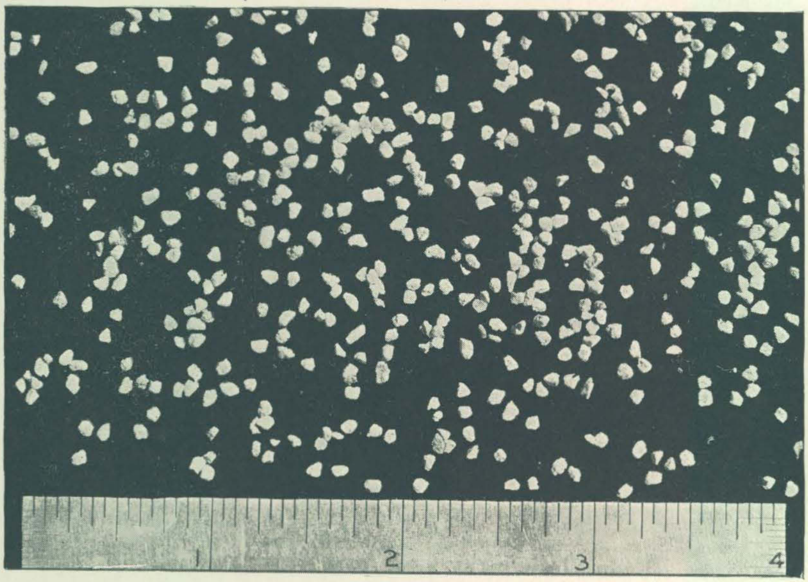
A, SAND NO. 36, NATURAL SIZE; *B*, SAND NO. 37, NATURAL SIZE.

Flow of water through sand No. 38 (Pl. XI, A).

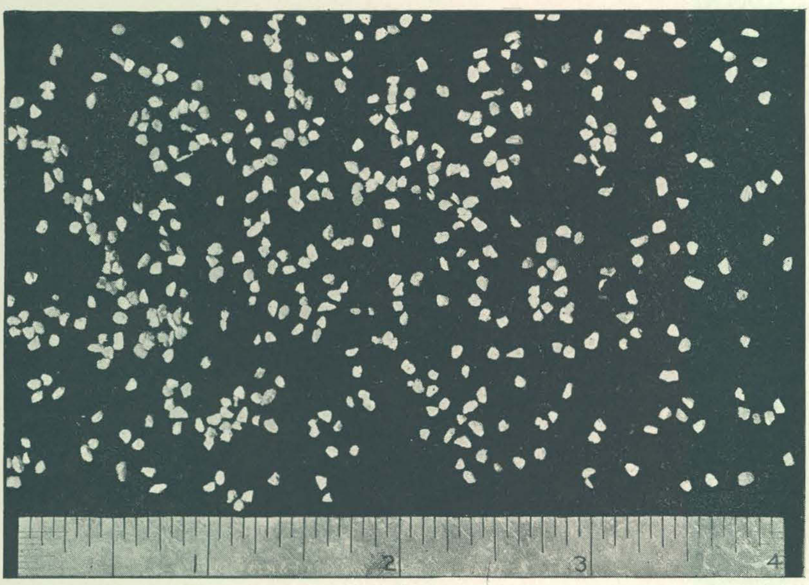
Pressure of water.	Temperature	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from—	
					Aspirator diameter.	Observed highest pressure flow.
Cm.	*° C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
3.4	15.7	10	2,612.2	768.23	2,584	2,582.9
3.4	15.6	10	2,602.6	765.47	2,584	2,582.9
3.6	15.53	10	2,768.0	768.88	2,736	2,734.8
3.8	15.58	10	2,927.8	770.47	2,888	2,886.7
4.0	15.52	5	1,544.0	772.00	3,040	3,038.7
4.2	15.56	5	1,622.2	772.47	3,192	3,190.6
4.4	15.56	5	1,702.4	773.81	3,344	3,342.5
4.6	15.6	5	1,779.3	773.61	3,496	3,494.5
4.8	15.6	5	1,853.8	772.42	3,648	3,646.4
5.0	15.6	5	1,926.4	770.56	3,800	3.798.4
1.6	15.6	10	1,184.1	740.06	1,216	1,215.5
1.6	15.6	10	1,181.6	738.50	1,216	1,215.5
1.6	14.6	10	1,192.1	745.06	1,216	1,215.5
5.0	14.75	5	1,946.4	778.56	3,800	3,798.4
5.2	14.95	5	1,989.1	765.04	3,952	3,950.3
1.6	14.95	5	586.4	733.00	1,216	1,215.5
5.4	15.1	5	2,057.9	762.18	4,104	4,102.2
1.6	15.2	10	1,173.1	733.18	1,216	1,215.5
5.6	15.2	5	2,125.4	759.07	4,256	4,254.2
1.6	15.3	5	585.2	731.50	1,216	1,215.5
5.8	15.4	5	2,206.4	760.82	4,408	4,406.1
1.6	15.3	5	589.2	736.50	1,216	1,215.5
6.0	15.28	5	2,281.6	760.53	4,560	4,558.0
1.6	15.2	5	574.2	717.75	1,216	1,215.5
6.2	15.25	5	2,355.0	759.67	4,712	4,710.0
1.6	15.3	5	585.7	732.12	1,216	1,215.5

Flow of water through sand No. 39 (Pl. XI, B).

Pressure of water.	Temperature.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from— Aspirator diameter.	Flow for 10 minutes computed from— Observed highest pressure flow.
Cm.	°*C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
9.0	15.3	5	2,436.5	541.44	4,710.7	4,757.5
9.5	15.3	5	2,563.4	539.58	4,972.4	5,021.8
1.0	15.3	10	566.3	566.30	523.4	528.6
10.0	15.3	5	2,688.4	537.68	5,234.1	5,286.1
10.5	15.3	2	1,130.6	537.09	5,495.8	5,550.4
11.0	15.3	2	1,172.7	533.04	5,757.5	5,814.7
1.0	15.3	10	568.7	568.70	523.4	528.6
11.5	15.3	2	1,229.4	534.52	6,019.2	6,079.0
12.0	15.3	2	1,285.4	534.33	6,280.9	6,343.3
12.5	15.3	2	1,335.7	534.28	6,542.6	6,607.6
13.0	15.3	2	1,378.2	530.08	6,804.3	6,871.9
1.0	15.32	10	566.5	566.50	523.4	528.6
1.0	14.8	10	552.8	552.80	523.4	528.6
2.0	14.9	10	1,111.3	555.65	1,046.8	1,057.2
3.0	15.0	10	1,676.8	558.93	1,570.2	1,585.8
4.0	15.1	10	2,218.5	554.62	2,093.6	2,114.4
5.0	15.15	10	2,790.0	558.00	2,617.1	2,643.1
6.0	15.2	5	1,653.1	551.03	3,140.5	3,171.7
7.0	15.2	5	1,909.8	545.65	3,663.9	3,700.3
8.0	15.2	5	2,170.4	542.60	4,187.3	4,228.9
9.0	15.25	5	2,428.3	539.62	4,710.7	4,757.5
10.0	15.3	5	2,684.9	536.98	5,234.1	5,286.1
11.0	15.3	2	1,182.3	537.41	5,757.5	5,814.7
12.0	15.3	2	1,276.6	531.92	6,280.9	6,343.3
13.0	15.3	2	1,375.5	529.04	6,804.3	6,871.9
14.0	15.32	2	1,495.7	534.18	7,327.7	7,400.5
15.0	15.32	2	1,582.1	527.36	7,851.2	7,929.2
16.0	15.32	2	1,694.7	529.59	8,374.6	8,457.8
17.0	15.36	2	1,809.1	532.08	8,898.0	8,986.4
18.0	15.38	2	1,903.0	528.61	9,421.4	9,515.0



(A)



(B)

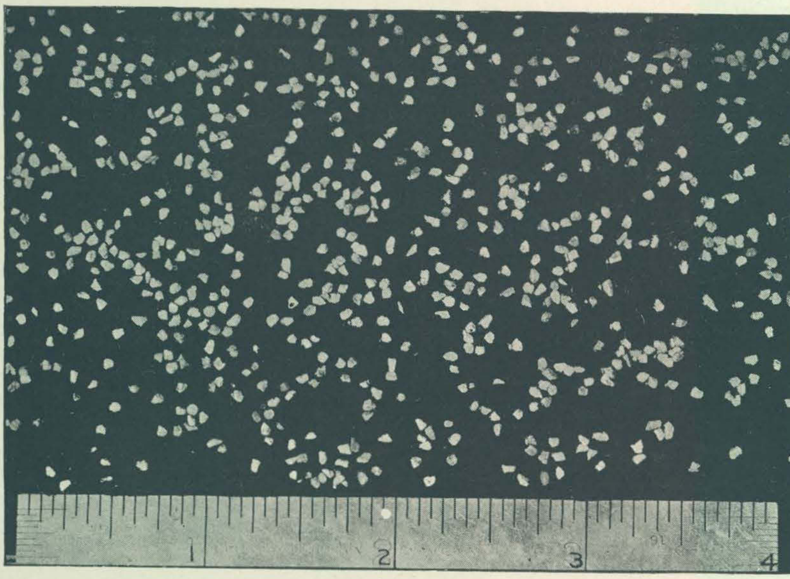
A, SAND NO. 38, NATURAL SIZE; B, SAND NO. 39, NATURAL SIZE.

Flow of water through sand No. 40 (Pl. XII, A).

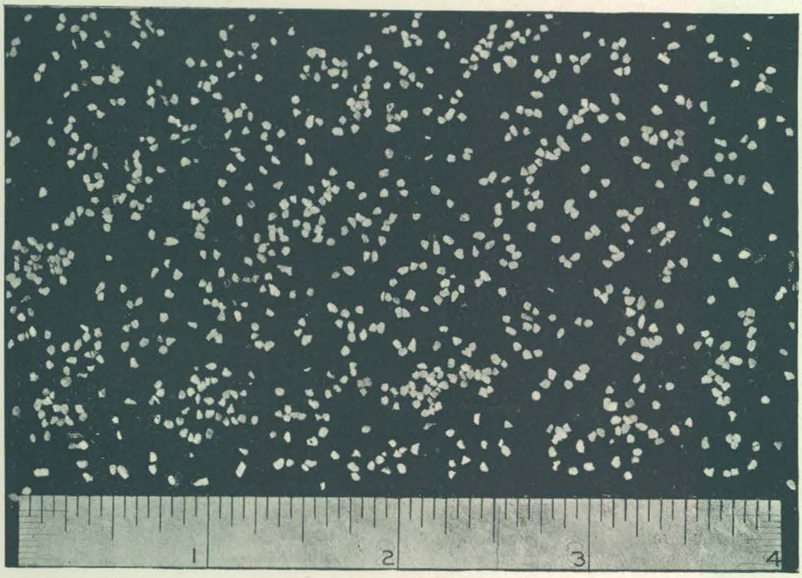
Pressure of water.	Temperature.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from—	
					Aspirator diameter.	Observed highest pressure flow.
Cm.	° *C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
1.0	17.60	10	530.6	530.60	453.2	469.7
1.0	17.60	10	538.6	538.60	453.2	469.7
1.5	17.59	10	772.4	514.93	679.8	704.5
2.0	17.40	10	1,022.9	511.45	906.4	939.3
2.5	17.39	10	1,275.2	510.08	1,133.0	1,174.1
3.0	17.40	10	1,514.1	503.36	1,359.6	1,408.9
3.5	17.40	10	1,759.8	502.80	1,587.2	1,643.8
4.0	17.42	10	2,025.7	506.42	1,812.8	1,878.6
4.5	17.46	10	2,272.0	504.88	2,039.4	2,113.4
2.0	17.38	10	1,018.6	509.30	906.4	939.3
5.0	17.36	10	2,502.7	500.54	2,266.0	2,348.2
5.5	17.38	5	1,366.9	497.05	2,492.6	2,583.0
6.0	17.35	5	1,485.2	495.06	2,719.2	2,817.9
6.5	17.35	5	1,597.5	491.54	2,945.8	3,052.7
7.0	17.35	5	1,705.3	487.23	3,172.4	3,287.5
7.5	17.36	5	1,819.7	485.25	3,399.0	3,522.3
8.0	17.38	5	1,936.1	484.02	3,625.6	3,757.1
8.5	17.38	5	2,055.6	483.67	3,852.2	3,992.0
9.0	17.38	5	2,168.7	481.93	4,078.8	4,226.8
9.5	17.38	5	2,275.4	478.95	4,305.4	4,461.4
2.0	17.39	10	1,003.0	501.50	906.4	939.3
10.0	17.38	5	2,381.8	476.36	4,532.0	4,696.5
11.0	17.38	5	2,611.9	474.89	4,985.2	5,166.2
12.0	17.38	2	1,134.0	472.50	5,438.4	5,635.8
13.0	17.38	2	1,227.6	472.14	5,891.6	6,105.5
14.0	17.40	2	1,324.0	472.86	6,344.8	6,575.1
15.0	17.42	2	1,419.7	473.23	6,798.0	7,044.8
16.0	17.45	2	1,503.1	469.69	7,251.2	7,514.4

Flow of water through sand No. 41 (Pl. XII, B).

Pressure of water.	Temperature.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from—	
					Aspirator diameter.	Observed highest pressure flow.
Cm.	*° C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
1.0	16.74	10	306.0	306.00	297.5	323.0
1.0	16.74	10	300.5	300.50	297.5	323.0
1.5	16.50	10	477.5	318.33	446.3	484.5
2.0	16.48	10	669.1	334.55	595.1	646.1
2.5	16.48	10	847.9	338.16	743.9	807.6
3.0	16.48	10	1,017.5	339.17	892.6	969.1
3.5	16.49	10	1,192.4	341.15	1,041.4	1,150.6
4.0	16.51	10	1,363.9	340.97	1,190.2	1,292.1
4.5	16.51	10	1,531.8	340.40	1,338.9	1,453.6
5.0	16.52	10	1,693.6	338.72	1,487.7	1,615.1
5.5	16.52	10	1,859.6	338.11	1,636.5	1,776.6
6.0	16.54	10	2,028.5	338.02	1,785.2	1,938.1
6.5	16.56	10	2,187.8	336.59	1,934.0	2,099.6
7.0	16.58	10	2,349.1	335.59	2,082.8	2,261.2
7.5	16.58	10	2,511.2	334.82	2,231.6	2,422.7
8.0	16.58	5	1,335.0	333.75	2,380.3	2,584.2
9.0	16.58	5	1,490.8	331.29	2,677.9	3,068.7
10.0	16.60	5	1,649.1	329.82	2,975.4	3,230.3
11.0	16.62	5	1,797.4	326.80	3,272.9	3,553.3
2.0	16.64	5	325.8	325.80	595.1	646.1
2.0	16.64	10	653.3	326.65	595.1	646.1
2.0	16.66	10	655.0	327.50	595.1	646.1
12.0	16.68	5	1,953.6	325.60	3,570.5	3,876.4
13.0	16.68	5	2,107.7	324.26	3,868.0	4,199.4
14.0	16.72	5	2,266.8	323.83	4,165.6	4,522.4
15.0	16.74	5	2,416.1	322.15	4,463.1	4,845.5
15.0	16.76	5	2,429.8	323.97	4,463.1	4,845.5
15.0	16.76	5	2,427.1	323.61	4,463.1	4,845.5
15.0	16.77	5	2,417.9	322.38	4,463.1	4,845.5
2.0	16.79	10	653.3	326.65	595.1	646.1



A



B

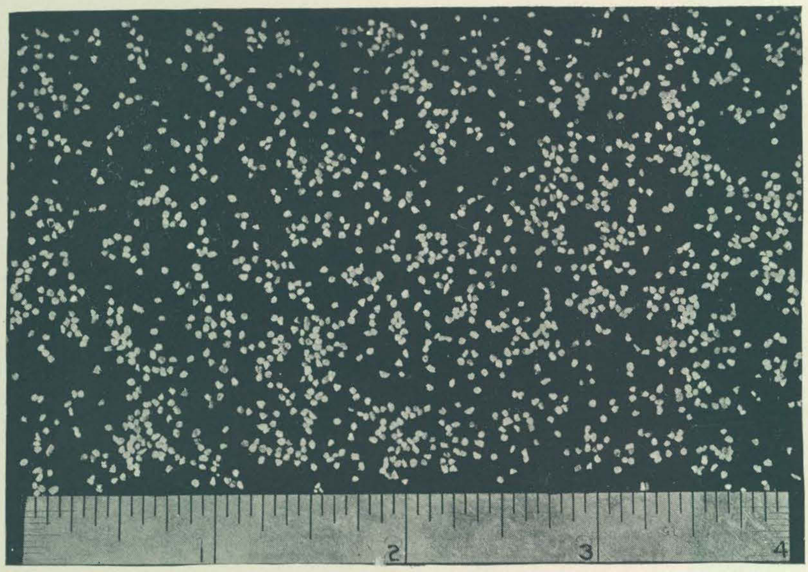
A, SAND NO. 40, NATURAL SIZE; B, SAND NO. 41, NATURAL SIZE.

Flow of water through sand No. 42 (Pl. XIII, A).

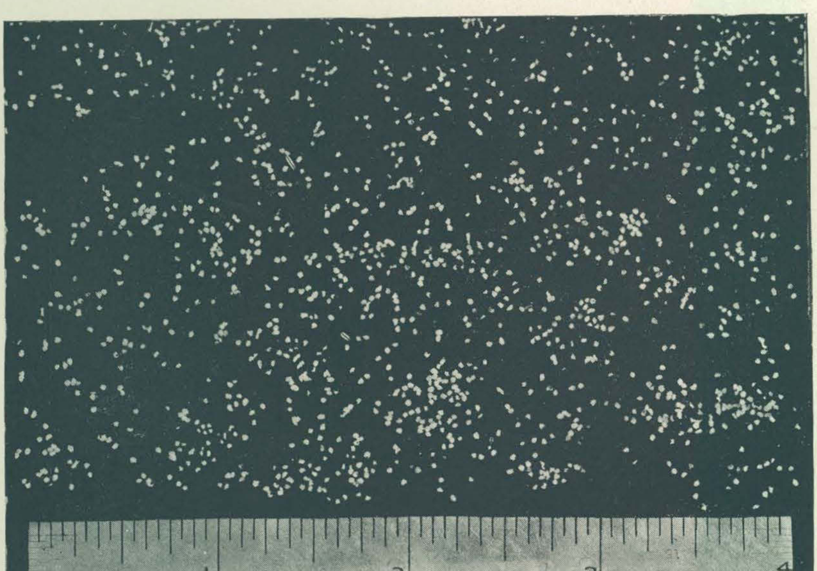
Pressure of water.	Temperature.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from—	
					Aspirator diameter.	Observed highest pressure flow.
Cm.	*° C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
1.0	16.05	10	185.5	185.50	193.6	215.9
1.5	16.05	10	294.5	196.46	290.4	323.8
2.0	16.05	10	404.7	202.35	387.2	431.7
2.5	16.05	10	520.6	208.24	484.0	539.7
3.0	16.05	10	627.6	209.20	580.8	647.6
3.5	16.05	10	733.1	209.46	677.6	755.5
4.0	16.08	10	843.3	210.82	774.4	863.5
4.5	16.10	10	948.7	210.82	871.2	971.4
5.0	16.08	10	1,058.5	211.70	968.0	1,079.3
5.5	16.10	10	1,169.0	212.54	1,064.8	1,187.2
6.0	16.10	10	1,278.1	213.02	1,161.6	1,295.2
6.5	16.10	10	1,384.5	213.00	1,258.4	1,403.1
7.0	16.10	10	1,494.5	213.50	1,355.2	1,511.0
7.5	16.10	10	1,601.0	213.46	1,452.0	1,619.0
7.5	16.10	10	1,597.3	212.97	1,452.0	1,619.0
7.5	16.10	10	1,598.3	213.11	1,452.0	1,619.0
7.5	16.10	10	1,594.5	212.33	1,452.0	1,619.0
7.5	16.10	10	1,596.7	212.89	1,452.0	1,619.0
8.0	16.12	10	1,706.2	213.27	1,548.8	1,726.9
8.5	16.15	10	1,818.8	213.97	1,645.6	1,834.8
9.0	16.18	10	1,920.8	213.42	1,742.4	1,942.8
9.5	16.18	10	2,023.9	213.04	1,839.2	2,056.7
10.0	16.18	10	2,134.6	213.46	1,936.0	2,374.6
11.0	16.20	10	2,339.4	212.67	2,129.5	2,590.4
12.0	16.20	5	1,277.9	212.98	2,323.1	2,806.3
13.0	16.20	5	1,378.2	212.03	2,516.7	3,022.2
14.0	16.20	5	1,487.6	212.51	2,710.3	3,238.1
15.0	16.20	5	1,595.4	212.72	2,903.9	3,453.9
15.0	16.20	5	1,592.7	212.36	2,903.9	3,453.9

Flow of water through sand No. 43 (Pl. XIII, B).

Pressure of water.	Temperature.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from—	
					Aspirator diameter.	Observed highest pressure flow.
Cm.	*° C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
1.0	16.60	10	144.6	144.60	124.2	142.3
1.5	16.40	10	187.1	124.73	186.3	213.4
2.0	16.35	10	264.1	132.05	248.4	284.6
2.5	16.30	10	332.7	133.08	310.6	355.8
3.0	16.30	10	406.8	135.60	372.7	426.9
3.5	16.25	10	477.8	136.50	434.8	498.1
4.0	16.25	10	550.7	137.67	496.9	569.2
4.5	16.25	10	623.1	138.46	559.0	640.4
5.0	16.24	10	689.7	137.95	621.1	711.5
5.5	16.25	10	766.1	139.27	683.2	782.7
6.0	16.25	10	839.7	139.95	745.3	853.8
6.5	16.30	10	909.8	138.71	807.4	925.0
7.0	16.30	10	991.5	141.64	869.5	996.1
7.5	16.30	10	1,045.8	139.44	931.7	1,067.3
8.0	16.30	10	1,121.6	140.20	993.8	1,138.4
8.5	16.30	10	1,182.6	139.13	1,055.9	1,209.6
9.5	16.30	10	1,337.8	140.82	1,180.1	1,351.9
9.0	16.30	10	1,262.3	140.25	1,118.0	1,280.7
10.0	16.30	10	1,406.1	140.61	1,242.0	1,423.0
11.0	16.30	10	1,541.5	140.14	1,366.4	1,565.3
12.0	16.30	10	1,671.1	139.26	1,490.6	1,707.6
13.0	16.35	10	1,835.8	141.21	1,614.9	1,849.9
14.0	16.35	10	1,984.8	141.82	1,739.1	1,992.2
16.0	16.35	10	2,276.8	142.30	1,987.5	2,276.8



(A)



(B)

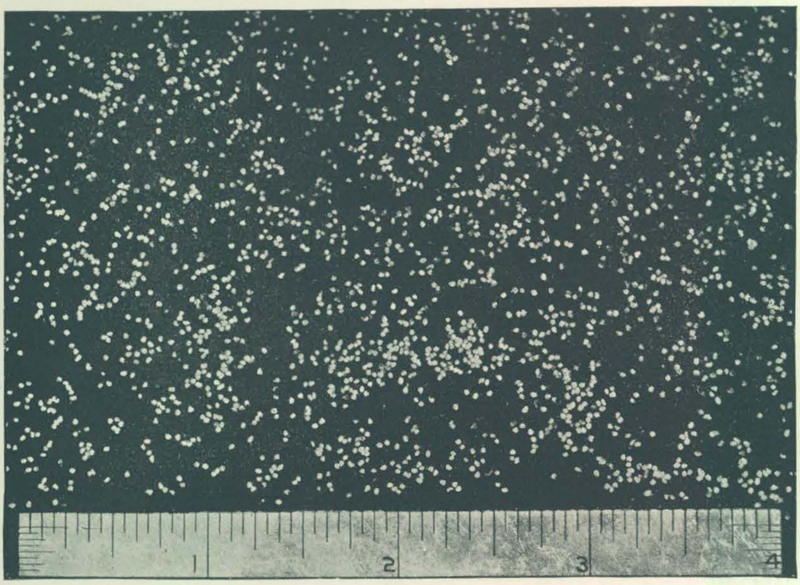
A, SAND NO. 42, NATURAL SIZE; *B*, SAND NO. 43, NATURAL SIZE.

Flow of water through sand No. 44 (Pl. XIV, A).

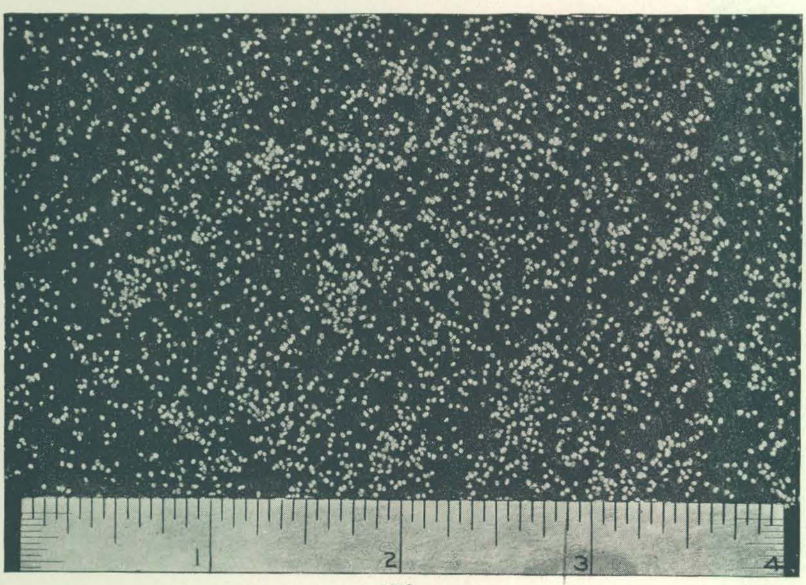
Pressure of water.	Temperature.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from—	
					Aspirator diameter.	Observed highest pressure flow.
Cm.	*° C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
3.0	16.65	10	286.6	95.53	242.8	285.2
3.5	16.65	10	336.7	96.20	283.3	332.7
4.0	16.65	10	383.5	95.84	323.7	380.3
4.5	16.65	10	429.2	95.38	364.2	427.8
5.0	16.65	10	476.3	95.22	404.7	478.3
5.5	16.65	10	524.6	95.38	445.1	522.9
6.0	16.65	10	572.5	95.42	485.6	570.4
6.5	16.65	10	615.7	94.72	526.0	617.9
7.0	16.65	9	(?) 593.8	94.25	566.5	665.5
7.5	16.65	10	702.5	93.66	607.0	713.0
8.0	16.65	10	749.0	93.62	647.4	760.5
8.5	16.65	10	798.8	93.98	687.9	808.1
9.0	16.65	10	842.6	93.62	728.4	855.6
9.5	16.65	10	891.0	93.79	768.8	903.1
10.0	16.65	10	941.2	94.12	809.3	950.7
10.5	16.65	10	981.6	93.49	849.8	998.2
11.0	16.65	10	1,030.0	93.64	890.2	1,045.7
11.5	16.65	10	1,077.0	93.65	930.7	1,093.3
12.5	16.65	10	1,177.6	94.21	1,011.6	1,188.3
12.0	16.65	10	1,127.1	93.92	971.2	1,140.8
13.0	16.65	10	1,228.6	94.51	1,052.1	1,285.9
13.5	16.68	10	1,271.5	94.18	1,092.6	1,283.4
14.0	16.68	10	1,323.5	94.50	1,133.0	1,331.0
14.5	16.66	10	1,370.8	94.54	1,173.5	1,378.5
15.0	16.66	10	1,420.5	94.70	1,214.0	1,426.0
15.5	16.66	10	1,466.4	94.61	1,254.4	1,473.6
16.0	16.66	10	1,512.5	94.53	1,294.9	1,521.1
16.5	16.66	10	1,561.7	94.71	1,335.3	1,568.6
17.0	16.66	10	1,612.1	94.83	1,375.8	1,616.2
17.5	16.66	10	1,663.7	95.07	1,416.3	1,663.7

Flow of water through sand No. 45 (Pl. XIV, B).

Pressure of water.	Tempera-ture.	Time.	Observed flow.	Flow divided by pressure.	Flow for 10 minutes computed from—	
					Aspirator diameter.	Observed highest pressure flow.
Cm.	*°C.*	*Minutes.*	*Grams.*		*Grams.*	*Grams.*
3.8	16.25	10	268.9	70.76	252.6	280.7
4.0	16.25	10	283.4	70.85	265.9	295.5
4.2	16.25	10	298.2	71.00	279.2	310.3
4.4	16.25	10	314.4	71.45	292.5	325.0
4.6	16.28	10	329.5	71.63	305.8	339.8
4.8	16.25	10	344.7	71.81	319.1	354.6
5.0	16.25	10	359.9	71.98	332.4	369.4
5.2	16.25	10	374.8	72.08	345.6	384.1
5.4	16.25	10	390.9	72.40	358.9	398.9
6.0	16.25	10	436.3	72.70	398.8	443.2
1.0	16.25	10	64.5	64.50	66.5	73.9
5.6	16.28	10	405.3	72.37	372.2	413.7
5.8	16.29	10	420.9	73.57	385.5	428.4
6.0	16.29	10	435.9	72.65	398.8	443.2
6.2	16.29	10	451.5	72.98	412.1	458.0
6.5	16.29	10	473.1	72.79	432.1	480.2
7.0	16.3	10	508.4	72.63	465.3	517.1
7.5	16.3	10	544.9	72.55	498.5	554.0
8.0	16.31	10	582.3	72.79	531.8	591.0
8.5	16.33	10	619.0	72.82	565.0	627.9
9.0	16.35	10	657.3	73.03	598.2	664.8
9.5	16.35	10	692.4	72.88	631.5	701.8
10.0	16.35	10	729.1	72.91	664.7	738.7
10.5	16.38	10	766.9	73.04	697.9	775.6
11.0	16.38	10	804.3	73.12	731.2	812.6
11.5	16.4	10	839.3	72.98	764.4	848.5
12.0	16.4	10	876.4	73.03	797.6	886.4
12.5	16.4	10	913.9	73.11	830.9	923.4
13.0	16.42	10	952.2	73.25	864.1	960.3
13.5	16.45	10	990.0	73.33	897.3	997.2
14.0	16.55	10	1,028.7	73.48	930.6	1,034.2
14.5	16.48	10	1,066.6	73.56	963.8	1,071.1
15.0	16.45	10	1,108.1	73.87	997.1	1,108.1



(*A*)



(*B*)

A, SAND NO. 44, NATURAL SIZE; *B*, SAND NO. 45, NATURAL SIZE.

A study of these tables reveals the fact that in this series of experimental data there are particular cases where the flows conform very closely to the Poiseuille-Meyer law; but, on the other hand, there are many more cases where the flow has been too rapid, while in others it has been too slow, and yet the pressures have been relatively very low, in no case reaching 8 inches.

This failure to conform with the law amounts to as much as 10 per cent too rapid and 49 per cent too slow; while the closest agreement is found in sample No. 44, where the departures vary from a little more than 1 per cent too slow to 1.5 per cent too fast.

In Nos. 45, 44, 43, and 42 the flow increases faster than the pressure; in No. 41 the flow increases faster than the pressure at first, up to 1.5 cm., but not so rapidly after that; while the remainder of the sands, Nos. 40, 39, 38, 37, and 36, give flows which do not increase so fast as the pressure.

The general conclusion which appears to be indicated by this series is that with the smaller sizes, where the grains give a minimum pore having diameters of 0.0117 mm., 0.01361 mm., 0.01619 mm., and 0.01809 mm. and under pressures not exceeding a gradient of about 3 to 5, the flow increases faster than the pressure; but when the diameters of the pores are 0.02756 mm., 0.0248 mm., 0.03249 mm., 0.04094 mm., and 0.05821 mm. the flow does not increase so rapidly as the pressures, even when the gradient is no steeper than 1 to 5 in the three coarsest.

In other words, the flow becomes so turbulent in the larger pores that considerable amounts of energy are absorbed even under very low pressures.

Since the length of the sand columns in these cases was 12 inches (30.48 cm.), the ratio of diameter to length of tube is as 1 to 5,236 in the coarsest and as 1 to 26,000 in the finest-grained sand, whereas in Poiseuille's tube A^{ii} the ratio of diameter to length was 1 to 361; yet a very close agreement with the law was found under a pressure 58 times the highest pressure used here.

It would appear, therefore, that Poiseuille's law for sands and other porous media holds only within very much narrower limits than has been found true for capillary tubes.

Referring now to the influence of the size of the sand grains upon the quantity of water flowing through, under otherwise like conditions, it is assumed in Professor Slichter's formula that the flows are proportional to the squares of the diameters of the sand grains as given below:

$$q=(1.0094)\,\frac{pd^2s}{mhk}=\text{c. c. per sec.}$$

Seelheim's[1] results conform somewhat closely to this relation.

[1] Zeitschrift für analytische Chemie, Vol. XIX, 1880, p. 402.

If we take the squares of the aspirator diameters of the sand grains in the series under consideration and plot them as abscissas and the observed and computed flows as ordinates, we shall get the results shown in fig. 42, where the observed flows fall nearly in a straight line, as should be expected if the law holds. In fig. 42 the flows are taken for a pressure of 1 cm. and the observed flows are numbered 2, those computed from the aspirator diameters are numbered 1, while those from count and weight are unnumbered, except the finest two, which are numbered 3.

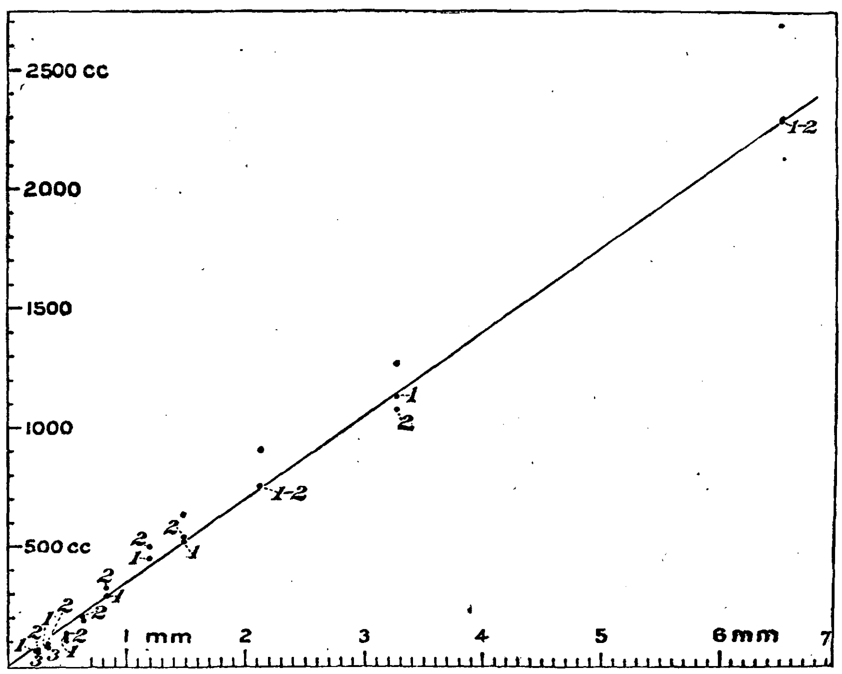


FIG. 42.—Diagram showing the relation of observed and computed flow of water to the squares of the diameters of the grains of sand, shown in Pls. X-XIV. Dots 1, flow computed from aspirator diameter; 2, observed flow; unnumbered and 3, flow computed from count and weight diameter. Abscissas indicate squares of aspirator diameters of sand grains and ordinates flow of water.

In fig. 43 only the flows which were observed and those computed from the aspirator diameters are plotted, the observed flow being designated 2. The pressures in this case were 5 cm.

OBSERVED RATES OF FLOW OF WATER THROUGH SANDS.

The results thus far presented have been given in such a manner as to show their bearing upon the general laws of flow of water through sands and rock, and particularly as to whether they bear out the generally accepted view that the movements of ground water are governed primarily by the accepted laws of capillary flow.

It is the purpose now to present a part of the data in such a way as to show how rapidly the general ground water may flow under certain gradients, per cents of pore space, and effective size of soil grains.

We have shown that under certain conditions the flow of water through sands and rock increases more rapidly than the pressure, while under other conditions the increase is less rapid. It is the purpose now, however, to neglect these observed and known variations and to assume that the flow is directly proportional to the pressure and inversely proportional to the length of the sand column, and that it varies as the squares of the diameters of the sand grains.

To convert the observed flows in the series of sands Nos. 36 to 45, given in the last set of tables, into cubic feet per square foot of section

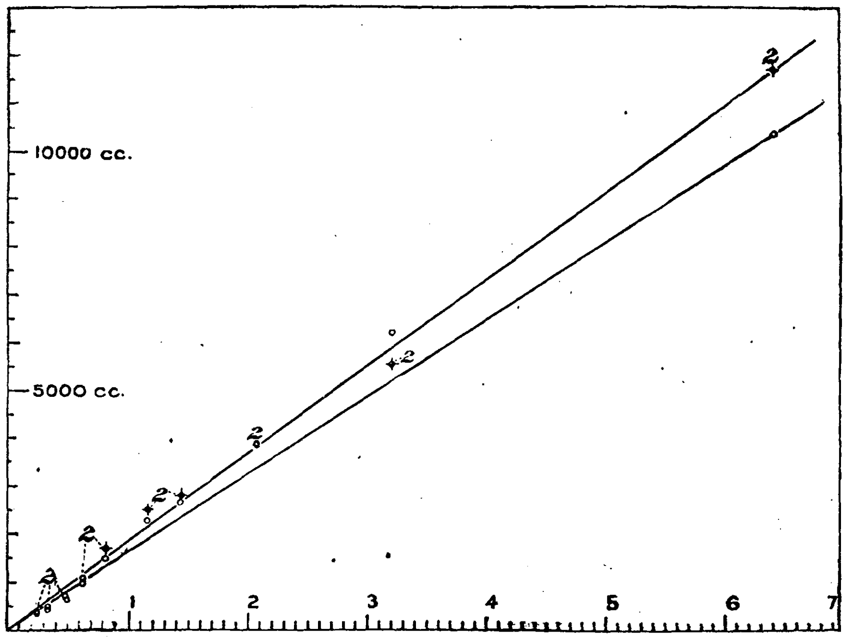


Fig. 43.—Diagram showing the relation of observed and computed flow of water to the squares of the diameters of the grains of sand shown in Pls. X-XIV. Dots 2, observed flow; unnumbered, flow computed from aspirator diameters. Abscissas indicate squares of diameters of sand grains in millimeters and ordinates flow of water.

of the sand, it will be near enough for our purposes to multiply the number of grams given in the table by the factor .0008, or more exactly .000797235. This will give the value of the flow in cubic feet of water at a temperature of 15° C. or 59° F., as it was observed to flow through a column 1 foot long under the pressures there stated and during the times specified in the table.

If we take the coarsest sand in the series we find from the table that under a pressure of 3 cm., about 0.1 foot, the flow during 10 minutes was $6{,}576.5 \times 0.0008 = 5.26120$ cubic feet per square foot of section and column 1 foot long.

Let us imagine a bed of this sand 10 feet thick extending back from a drainage outlet and rising at the rate of 3 cm. a foot, or about 1 foot in every 10 feet, and let it be supplied with water as rapidly as it is able to convey it away. How much water will this layer be able to transmit per each linear section of 1 foot or 10 square feet when the bed has an extension away from the outlet of 100, 1,000, 10,000 and 100,000 feet?

The flow through 1 foot of length in ten minutes was found to be 5.2612 cubic feet per square foot, hence the flow through the 10 square feet of vertical section which has been assumed would be 52.612 cubic feet in ten minutes and 5.2612 feet per minute.

If now the flow is decreased in the same ratio as the distance traversed by the water through the sand is increased, and if the flow is increased in the same ratio as the pressure is increased, the slope or gradient of 1 in 10 will exactly compensate for the loss due to increase in length, and we should have a flow of 5.2612 cubic feet per minute for each linear foot of percolation surface, or 0.8768 second-feet.

We have, of course, assumed an enormous gradient, and one which can only occur over short distances anywhere under natural conditions.

In the table which follows we have given the flow in cubic feet per minute per section of 1 square foot as it was observed for various materials experimented with, assuming a gradient of 1 in 10.

Table showing the flow of water through sands and sandstones in cubic feet per minute per square foot of section, under a pressure gradient of 1 in 10.

Material.	Represented in —[1]	Flow per minute.
		Cubic feet.
Sand No. 36	Pl. X, *A*	5.2268
Sand No. 37	Pl. X, *B*	3.6490
Sand No. 38	Pl. XI, *A*	1.8481
Sand No. 39	Pl. XI, *B*	1.3582
Sand No. 40	Pl. XII, *A*	1.2232
Sand No. 41	Pl. XII, *B*	.8242
Sand No. 42	Pl. XIII, *A*	.5084
Sand No. 43	Pl. XIII, *B*	.3295
Sand No. 44	Pl. XIV, *A*	.2321
Sand No. 45	Pl. XIV, *B*	.1767
Sand No. 33		.004104
Los Angeles sand:		
No. 1	Pl. VIII	.0007196
No. 2	Pl. VIII	.00056847
No. 3	Pl. VIII	.0002775
No. 4	Pl. VIII	.0065951
No. 5	Pl. VIII	.0007270
No. 6	Pl. VIII	.0011866
No. 7	Pl. VIII	.00002612

[1] The numbers given are those of engraved plates appearing in this report.

Table showing the flow of water through sands and sandstones in cubic feet per minute per square foot of section, under a pressure gradient of 1 in 10—Continued.

Material.	Represented in —[1]	Flow per minute.
Dunnville sandstone:		*Cubic feet.*
No. 2	Pl. VII	.00002033
No. 1	Pl. VII	.00002373
Madison sandstone:		
No. 2	Pl. VII	.0001706
No. 6	Pl. VII	.000009993

[1] The numbers given are those of engraved plates appearing in this report.

It will be seen from this table that the rate of flow of water through sands of different degrees of coarseness varies between wide limits; so wide, indeed, is this variation that while No. 36 (Pl. X, *A*) will transmit 5 cubic feet of water per minute under an effective head of 0.1 of a foot, it requires the Los Angeles sand No. 7 more than 138 days to discharge the same amount under like conditions of pressure through the same length of column, namely, 1 foot.

The sandstones studied have also given very small flows under the low pressures.

GENERAL MOVEMENT OF GROUND WATER OVER WIDE AREAS.

With the data which have now been presented and with the systematic studies of Professor Slichter we are placed in a position to deal with the quantitative side of the movements of ground water in a much more definite manner than has heretofore been possible.

In the movement of water over wide distances through the strata of the earth's crust it is important to consider in how far this movement can take place through the capillary pores of the rock itself, and to what extent the movements must be along waterways which have dimensions larger than capillary.

In making the estimates of flow per square foot of section per minute in the last table we have taken a difference of pressure amounting to 0.1 foot of water for each horizontal distance of 1 foot, and have stated what the flow was observed to be through a single linear foot of the medium under experiment.

If it is assumed that we have beds of unfissured sandstone or of perfectly uniform sands, such as were brought under experiment, with a dip of 1 in 10, then vertical and horizontal dimensions may be assigned to these, and the total flow computed for various conditions.

Specific problems stated.—To give definiteness to the problems let it be assumed that we have a bed of porous material 100 feet thick and 200 miles in horizontal extent from north to south, rising westward with a uniform gradient of 1 foot in 10, 1 in 1,000, and 1 in 2,000 feet. Let a canal be cut across these beds along the line of strike which extends entirely through the formation and which can be maintained full of water. What quantity of water may such a canal collect from the west bank, supposing the porous bed to be supplied with water as rapidly as it is able to transmit it to the canal?

As the water pressure will increase in very nearly the same ratio as the distance back from the canal increases it may be assumed from the law of capillary flow that the reduction in rate of flow due to increase of distance back from the canal will be very nearly balanced by the increase in flow due to increase of head, so that the total growth of water in the canal will be given by the product of the area of the west face of the canal into the specific rate of discharge per square foot as found for the different media under the different gradients.

Results obtained.—When this computation is made it will be found that the following amounts of water should be collected by a canal 200 miles long cut in the sands and sandstones indicated:

Table showing computed flow of water through sands and sandstones under different gradients.

Gradient.	Cubic feet per minute.
Sand No 36:	
1 in 10	552, 000, 000
1 in 1,000	5, 520, 000
1 in 2,000	2, 760, 000
Sand No. 33:	
1 in 10	433, 400
1 in 1,000	4, 334
1 in 2,000	2, 167
Madison sandstone No. 2:	
1 in 10	18, 020
1 in 1,000	180. 2
1 in 2,000	90. 08
Madison sandstone No. 6:	
1 in 10	1, 055
1 in 1,000	10. 55
1 in 2,000	5. 276

Comparison of results with Darton's estimates.—Darton's[1] map of the Dakota artesian basin shows an extent north and south of somewhat more than 250 miles, and he estimates that in 1896 the total discharge from about 400 of the deeper wells of this basin was 232 cubic feet per second, or 13,920 cubic feet per minute.

To compare the quantitative relations of water movement in this basin with those in the cases which have been supposed it will not be an unreasonable supposition to make, in view of the known geological structure and relations, that the water which supplies the Dakota basin

[1] Seventeenth Ann. Report U. S. Geol. Survey, Part II, p. 610.

comes from the westward through water-bearing beds having an aggregate thickness of 100 feet, and that the bulk of the water must traverse at least 100 miles before reaching the meridian of the westernmost well. In view of the fact that Darton's map shows more than 200 wells situated in the southern 100 miles of the Dakota basin, it appears clear that the water-bearing beds must be transmitting water at the rate of 13,920 cubic feet per minute through a section of the water-bearing beds not larger than 200 miles from north to south and 100 feet in aggregate effective depth.

If this estimate is within the limits of fact, then the actual observed rate of flow through the Dakota water-bearing beds must exceed the capacity of any of the materials which have been cited under a pressure gradient 1 foot in 1,000 feet, except the coarsest sand, No. 36, whose grains have an effective diameter of 2.54 mm. Even with the clean washed sand No. 33, whose grains have a diameter exceeding 0.1 mm., the total capacity of a section 100 feet by 200 miles is only about one-third that which the Dakota wells are known to be delivering at the surface.

Since in certain sections of the Dakota basin there have been many wells put down within comparatively small areas and since the water is discharged from many of these wells under heavy pressures, it appears clear that the wells now in existence do not nearly tax the water-bearing beds to the limit of their capacity, and probably would not do so were the number of wells in the whole basin made double what it now is. It seems clear, therefore, that either larger dimensions for the water-bearing beds or heavier pressures than we have assumed must exist, or else that the main movement of the water across the long distances which it appears that it must travel must be through waterways offering much less resistance than that required by the sizes of the sand grains which make up most water-bearing beds. But to double the cross section of the water-bearing beds or to double the pressure gradient would only increase the capacity of the coarsest sandstones experimented with to 360.2 cubic feet per minute and to both double the cross section and the pressure gradient as well would give a capacity of only one-twentieth of that observed and one-fortieth of what probably actually exists.

Since a pressure gradient of 1 in 500 feet means a rise of the surface to the westward of the artesian basin amounting to 10.56 feet per mile, it is plain that were it true that the water has its origin in the higher level of the Black Hills or in the Bighorn Mountains the requisite gradient to meet the demands could not be provided with any reasonable estimate of cross section of the water-bearing beds.

Estimates made by Professor Slichter.—We give below Professor Slichter's estimate of the amount of flow of water under the conditions of Problem I, Series A, which was submitted to him for theoretical consideration. The problem stated is as follows:

Given a uniform bed of unfissured sandstone 100 feet thick lying between impervious layers and dipping at the rate of 5 feet to the mile;

Given further—

(*a*) A uniform temperature of 10° C.,

(*b*) A pore space of 30 per cent,

(*c*) An effective size of grains of 0.15 mm.,

(*d*) An effective head of discharge amounting to 10 feet, and

(*e*) Supposing no cementing or clogging material between the grains;

Required the possible discharge in cubic feet per minute per foot of vertical section into a vertical fissure extending along the line of strike and continually filled with water when the fissure is 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 miles from the border of the collecting era, and when the rainfall on the catchment area is sufficient to maintain continuous overflow across its border.

Professor Slichter has presented two solutions of this problem, first, where the water-bearing stratum is horizontal and where an effective head of 10 feet is maintained; and second, where the stratum has a gradient of 5 feet to the mile and besides this an additional effective head of 10 feet. The results obtained are given in terms of the amount of flow per 100 square feet of section of the water-bearing bed, so that to find the total discharge for the 200 miles of north-and-south section the results in the table should be multiplied by 5280 × 200. The results are further given for two sizes of sand grain.

Table showing the theoretical flow of water through 20 to 200 miles of sandstone in cubic feet per 100 square feet of section.

Distance.	Level strata.		Slope of 5 feet to mile.	
	Diameter.	Diameter of grain.	Diameter.	Diameter.
	0.15 mm.	0.25 mm.	0.15 mm.	0.25 mm.
Miles.				
20	0.000062	0.0002139	0.000683	0.002353
40	.000031	.000107	.000652	.002246
60	.000026	.000071	.000642	.002210
80	.000016	.000053	.000637	.002192
100	.000012	.000043	.000633	.002182
120	.000010	.000035	.000631	.002174
140	.000009	.000031	.000630	.002170
160	.000008	.000027	.000629	.002166
180	.000007	.000024	.000628	.002163
200	.000006	.000021	.000627	.002159

When the amounts of flow in this table are computed for the whole 200 miles of fissure exposure the largest aggregate flow is only 721.2 cubic feet per minute where the grains have a diameter of 0.15 mm. and only 2,485 cubic feet per minute where the diameter of the sand grains is 0.25 mm.

This larger amount, it will be seen, must be multiplied by nearly 6 in order to bring the theoretical discharge up to the observed limits in the Dakota artesian basin. It is to be noted that the theoretical limitations to the possible rate of flow through purely capillary passageways agrees fairly well with the observed rates of flow as cited in the foregoing tables.

In making our own calculations of rate of flow from the observed flows we have intentionally used the results derived from the lower pressures, for the reason that the lengths of the columns were so short that it seemed more rational to do this. Had we used the flows under the higher pressures the results would have been larger because the flow increases faster than the pressure. There is, however, no reason to suppose that the difference is large enough to give a flow sufficient to meet the demands.

Movement of ground water through fissures.—It appears clear, therefore, from what has been presented, that the movements of ground water across long distances must take place in considerable measure through passageways larger than those which depend upon the pore space fixed by the diameters of the grains which constitute the beds themselves, and if this conclusion must stand it follows that such problems as we propounded for mathematical treatment by Professor Slichter become inapplicable to natural conditions except those of small areas.

It would appear that all fissures of all rocks must participate in the horizontal movements of ground water to a considerable extent if they lie below the plane of saturation and are in any way connected with a water-bearing stratum. Where two sandstone horizons are separated by rock formations possessing jointed structure developed in a marked degree it may be that these joints and fissures participate to no inconsiderable extent in the horizontal transmission of the water.

It may also be true that such beds separating two sandstone formations will serve to make the water in both beds available to wells which penetrate only the upper horizon, the water reaching the well not directly but by rising in a general way at many places or along numerous lines and networks of fissures and over wide areas in such a manner as to keep the upper sandstone more nearly filled with water and thus maintain the pressure in the rock about the well at a materially higher point than would otherwise exist, especially in such cases as the wells of city waterworks where continuous pumping is maintained.

It may even be true that water from an upper horizon of sandstone may, in certain regions, pass through a general system of fissures into one of lower level, and vice versa, during its horizontal transmission, the water taking in all cases the line of least resistance, so that if in the upper horizon of sandstone in a particular region the texture is closer than that in the lower, the general flow could well divide and become in one section stronger than normal, first in the lower horizon and then in the upper horizon, according as the texture of the two rocks vary in coarseness.

It would appear that the more rational view to take of the movement of underground water is that it is one more or less continuous body receiving accessions at many high levels and discharging its water at many lower levels, but that the water in reaching its lower levels may not all of the way follow continuously one particular geological horizon.

It is of course true that the maximum flow must be concentrated in the sandstone horizons, but it seems also necessary to suppose that even here there must be joints, fissures, or other waterways which materially assist in the transmission of the water.

In the case of wells sunk in rock the flow of water into them may be very much more rapid than that of the general flow of water through the formation in which the well is sunk, because when the water is taken out, either by pumping or by natural discharge, a local effective head is developed, much greater than the general effective head, and as the water approaches the well from all sides, a relatively very slow flow, even a few feet back from the well, will deliver a large amount of water to the well, and if the material is coarse and the bore of the well small the amount delivered may even tax the capacity of the well to deliver the water which is brought to it.

GROWTH OF RIVERS.

It will be desirable, now, to compare the growth of rivers as it is known to take place through measurements of the volume of water carried at different sections, and see how rapid the seepage into the channel must be in order to account for the measured growth.

Los Angeles River.—Through the kindness of Mr. Newell the writer is enabled to use some valuable data regarding the growth of Los Angeles River, California, which have been collected for use in the case of the city of Los Angeles against the West Los Angeles Water Company, and which have been furnished by Mr. J. B. Lippincott, under Mr. Newell's direction.

Careful measurements of this river in the winter of 1897 and 1898 showed that in a distance of 59,088 feet the river increased in volume from 20.41 cubic feet per second to something near 80 cubic feet.

The width of this river, as shown by a map sent, will average perhaps 40 feet, and if we add to this a width of 5 feet on each bank, making 50 feet in all through which water may enter the stream, we shall have a total seepage surface amounting to

$$59{,}088 \times 50 = 2{,}954{,}400 \text{ square feet.}$$

The rate of seepage for seven samples of sands taken from this river valley, in the region of the developments of the Crystal Springs Land and Water Company and the West Los Angeles Water Company, is given in the tables on page 244, and the sands are also represented natural size in Pl. VIII (p. 148). Mr. Lippincott's description of them is as follows:

No. 1 is taken from manhole No. 2. At this place the soil is somewhat stratified, there being a layer of finer sand or silt, from 6 inches to 2 feet in thickness, below which might be expected a coarser sand and gravel. This sample is taken from a silt section about 3 feet below the surface of the ground.

No. 2 is taken from manhole No. 2, 5 feet below the surface of the ground, and is the ordinary sand and gravel which constitutes fully two-thirds of the material in question at this point.

No. 3 is taken from manhole No. 3. The soil is a mixed soil which was thrown out from the excavation over this manhole, and has been quite well mixed by the use of scrapers and back filling. The excavation was about 12 or 15 feet deep.

No. 4 is the ordinary sand and gravel of the river bed taken where the infiltration pipes lie under the river, 200 feet northwest of manhole No 3.

No. 5 is a sample taken from the cut of the West Los Angeles Water Company, block 37, west of house inclosed by small fence (fig. 45). In this excavation the stratification is more pronounced than at the Crystal Springs, the silt or fine sand strata probably composing fully one-half of the material through which the excavation was made, particularly around the bend, which is referred to occasionally as the "Goose-Neck." The layers are probably 3 to 6 feet thick, the sand and gravel strata becoming more pronounced as the cut proceeds toward the Tujunga Wash.

No. 6 was taken from the ordinary sand and gravel stratum west of barn and chicken house on block 37 (fig. 45).

No. 7 was taken at the point where the excavation reapproaches Verdugo avenue. This is in the sharp bend. At this point the material is decidedly finer than at any other point in the cut.

If we use the computed rates of flow per square foot of these soils under a gradient of 1 in 10, as given in the table on page 244, and from them calculate the aggregate seepage into the section of the river in question, we shall get the results given in the table below:

Table showing computed seepage into a section of the Los Angeles River 59,088 feet long under different gradients.

Material.	Flow in cubic feet per second under different gradients.		
	1 in 200.	1 in 80.	1 in 20.
Los Angeles sand:			
No. 1	1.77	4.425	17.7
No. 2	1.3997	3.499	13.99
No. 3	.683	1.7075	6.83
No. 4	16.236	40.59	162.36
No. 5	1.79	4.475	17.90
No. 6	2.9213	7.304	29.2
No. 7	0.0643	.1608	0.643

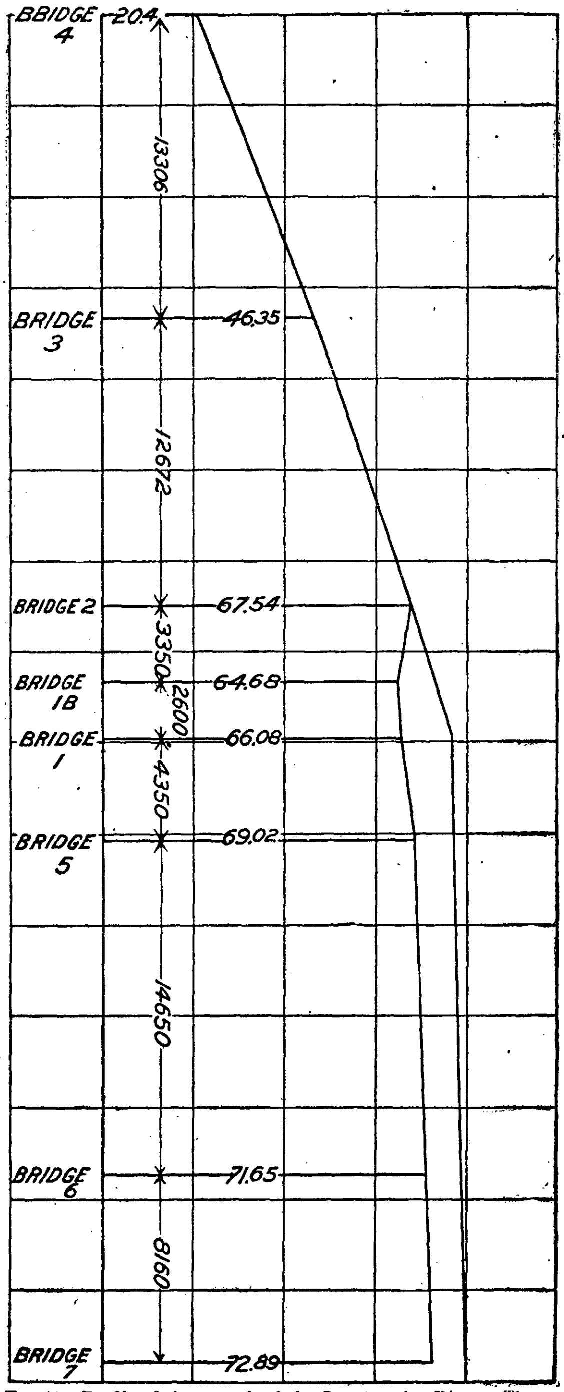
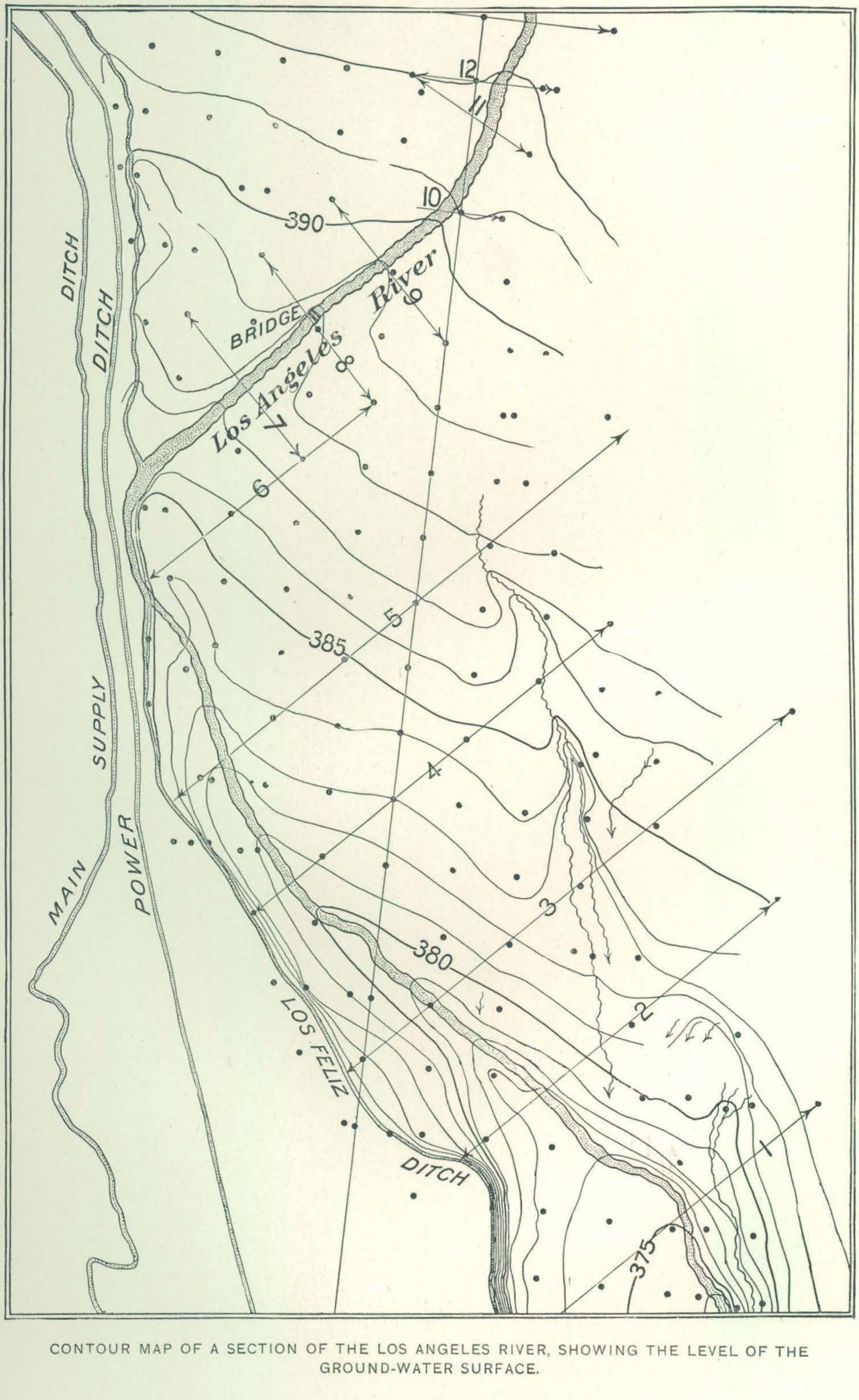


FIG. 44.—Profile of the growth of the Los Angeles River. The ordinates express rates of flow in second-feet at different points. Numbers between arrows designate distances, in feet, between measuring stations.

It will be seen from this table that there is here an apparent shortage in the capacity of even the coarsest material to deliver the water to the river as rapidly as the measurements show that it was received. Even when a pressure gradient of 1 in 20 is taken none of the samples except No. 4 give as much water as is required; No. 4 is a sample of the sands from the river channel itself, and therefore likely to be too coarse, and there is no reason to suppose that there can be an effective pressure gradient as high as 1 in 20 anywhere in this section of the valley, as evidenced by the map, Pl. XV, showing the contours of the ground waters in the lower section of the valley under consideration.

If reference is made to the profile of the growth of the river (fig. 44) it will be seen that much the larger part is made in the upper end, there being 47.13 second-feet out of 60, the total amount, and yet the length of this portion of the river is only 47 per cent of the whole.



CONTOUR MAP OF A SECTION OF THE LOS ANGELES RIVER, SHOWING THE LEVEL OF THE GROUND-WATER SURFACE.

It follows, therefore, that the observed growth of the river is in a considerable part of the distance more rapid even than at the rate of 60 cubic feet per second for a length of 11.19 miles.

It is quite possible that the large growth of this river is to be accounted for by water moving along a submerged river channel filled with coarse gravel leading down from the Verdugo Canyon and possibly others also from the direction of the Tujunga Wash; but it appears more reasonable to suppose that even in these loose river sands the water has developed for itself submerged waterways into which it drains and then flows, under much less resistance, to the river channel in the form of numerous small springs. Indeed Mr. Lippincott states that testimony was given in court by the engineers in charge of the investigation that underground veins were uncovered varying in size from a lead pencil to those large enough to introduce a man's leg and into which a long-handled shovel could be pushed up to the blade.

It would be very helpful in the discussion of this question if the growth were known of some streams in valleys where there is no reason to suspect the existence of such exceptional facilities for the flow of underground water as is found here, but no such data are at hand.

RATE OF SEEPAGE INTO THE FLUME OF THE WEST LOS ANGELES WATER COMPANY.

In fig. 45 is represented the flume of the West Los Angeles Water Company, which now has a measured length, including a short branch, as shown on the map furnished me by Mr. J. B. Lippincott, of about 4,500 feet, sunk below the normal level of the ground water for the purpose of collecting this and delivering it at the surface lower down the valley. The flume is described as being rectangular in cross section 4 feet deep and 5 feet wide with open bottom but covered and provided with wooden sides.

On January 21, 1897, this flume was discharging 7.2 cubic feet per second. On November 19, 1896, it discharged 7.29 second-feet; on March 1, 1896, 8.5 second-feet; on November 23, 1895, it is said to have discharged 10.1 second-feet; but in April, 1898, it was discharging but 6.2 cubic feet per second.

Prior to the construction of this flume it is said that[1]—

> Numerous ranches in the vicinity of the head works of this water company had orchards and fields that for a term of years had been producing crops successfully and uninterruptedly. The West Los Angeles Water Company opened this cut as shown on the map in an old stream channel of the Big Tujunga Wash. They developed a supply of water which originally was flowing about 1.2 feet per second on the surface until it discharged a maximum, according to a statement of the company, of 10.2 feet. The crops in the neighborhood adjoining began to die, orchard trees 7 or 8 years old died in visible streaks along old channel lines. Alfalfa fields did the same. * * * The opening of the cut was synchronous with the dropping of certain wells and the drying up of flowing water in a branch of the

[1] Manuscript notes of J. B. Lippincott.

Tujunga Wash. When the excavation was carried around the "Goose-Neck," in block 37, where a finer line of silts was encountered, the drop in the wells was very apparent.

If the full length of this flume and its branch is taken as 4,500 feet, and the seepage section as equal to the 5 feet on the bottom of the flume and 2 feet on each side, the total seepage area will be 40,500 square feet.

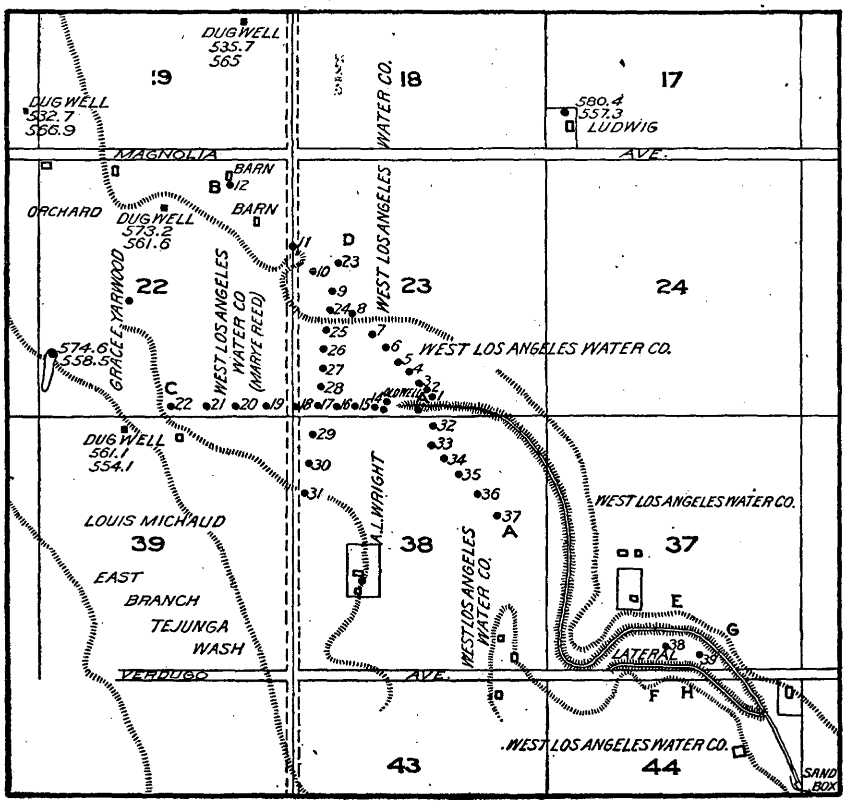


FIG. 45.—Diagram of flume of West Los Angeles Water Company and vicinity. Numbered dots show where level of ground water was measured in wells sunk for the purpose, and correspond with numbers on fig. 46.

In order to ascertain the character of the surface of the ground water in the vicinity of this flume, lines of wells were sunk at the places designated in fig. 45, and the levels of the water in them were determined. The results of these determinations are represented in fig. 46, from which it will be seen that for a distance of a little more than 100 feet back from the flume the surface of the ground water rises rapidly, but nowhere reaches a gradient of 10 feet in 100 feet.

Taking a gradient of 10 feet in 100 feet, or 1 in 10, the amount of water which would be delivered to the flume through the No. 5 sand would be 29.34 cubic feet per minute; through the No. 6 sand, 47.05

cubic feet, and through the No. 7 sand, 0.23 cubic foot, supposing in each case that the water enters both sides and bottom of the flume with equal facility and velocity.

These results, it will be seen, are much too small, the observed flow exceeding the largest computed flow nearly tenfold. Of course it is quite possible that the material through which much of the water enters the flume is considerably coarser than the coarsest sample examined; but it seems probable that even in such a case as this there must be large numbers of pores or waterways which are larger than capillary, and through these the water flows in largest volume. It is true that when the theoretical flow is computed from the aspirator diameters of the sand grains, in this case the amount found is larger than that shown by the flow of water through the same samples; but even then it falls short of the observed flow by a large amount, even for the coarsest sand.

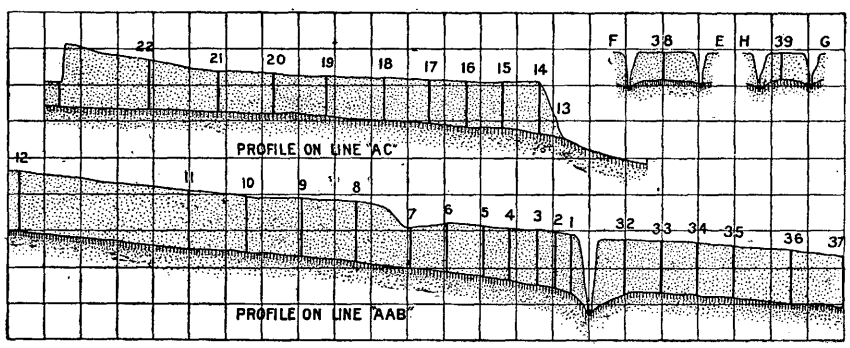


FIG. 46.—Profiles of the surface of the ground water in the vicinity of the West Los Angeles Water Company. The heavily shaded line is the ground-water surface. Each square represents 100 by 10 feet.

RATE OF SEEPAGE INTO THE INFILTRATION PIPES OF THE CRYSTAL SPRINGS LAND AND WATER COMPANY.

In the case of the system of infiltration pipes farther down the same valley, on the tract of the Crystal Springs Land and Water Company, the conditions for producing the flow are too complex to show just what should be expected for the amount of seepage. It may be said, however, that this system consists of an east and west line of infiltration pipes sunk below the normal level of the ground water of the river valley, which join in their lower portion, where they deliver the water collected by them at the surface. The pipes used in this case are glazed sewer tile, laid double upon boards in the bottom of an open ditch, the space immediately around the tile being filled in with coarse gravel and stone, to facilitate the approach of the water to and its entrance into the uncemented joints of the tile, while above the gravel the cut was filled with the materials taken from the excavation. The east infiltration line has a total length of double tile consisting of 1,343 feet of

24-inch tile, 300 feet of 20-inch tile, 1,385 feet of 15½-inch tile, and 619 feet of 12-inch tile, making a total of 3,647 running feet of the double line. The west infiltration line, also double, has a measured length of 1,721 running feet, all 15-inch pipe.

The total water discharged from the entire system on February 1, 1898, was 9.002 cubic feet per second, or a mean rate of 0.001677 cubic foot per second for each linear foot of the whole length.

If we regard the rectangular section of the ditch in which the tile was placed and surrounded by stone and gravel as constituting the flume into which seepage took place, and assume the height of the flume to be equal to the diameter of the pipe with 6 inches of gravel on each side of the line, then the total percolation surface would be as follows, not counting the top, as usually no water stands immediately above it.

Percolating surface of flume of West Los Angeles Water Company.

	Percolation surface.
	Square feet.
West pipes, 1,721 × 5	8,605
East pipes, 1,343 × 8	10,744
East pipes, 300 × 6⅔	2,000
East pipes, 1,385 × 5⅙	7,156
East pipes, 619 × 4	2,476
Total	30,981

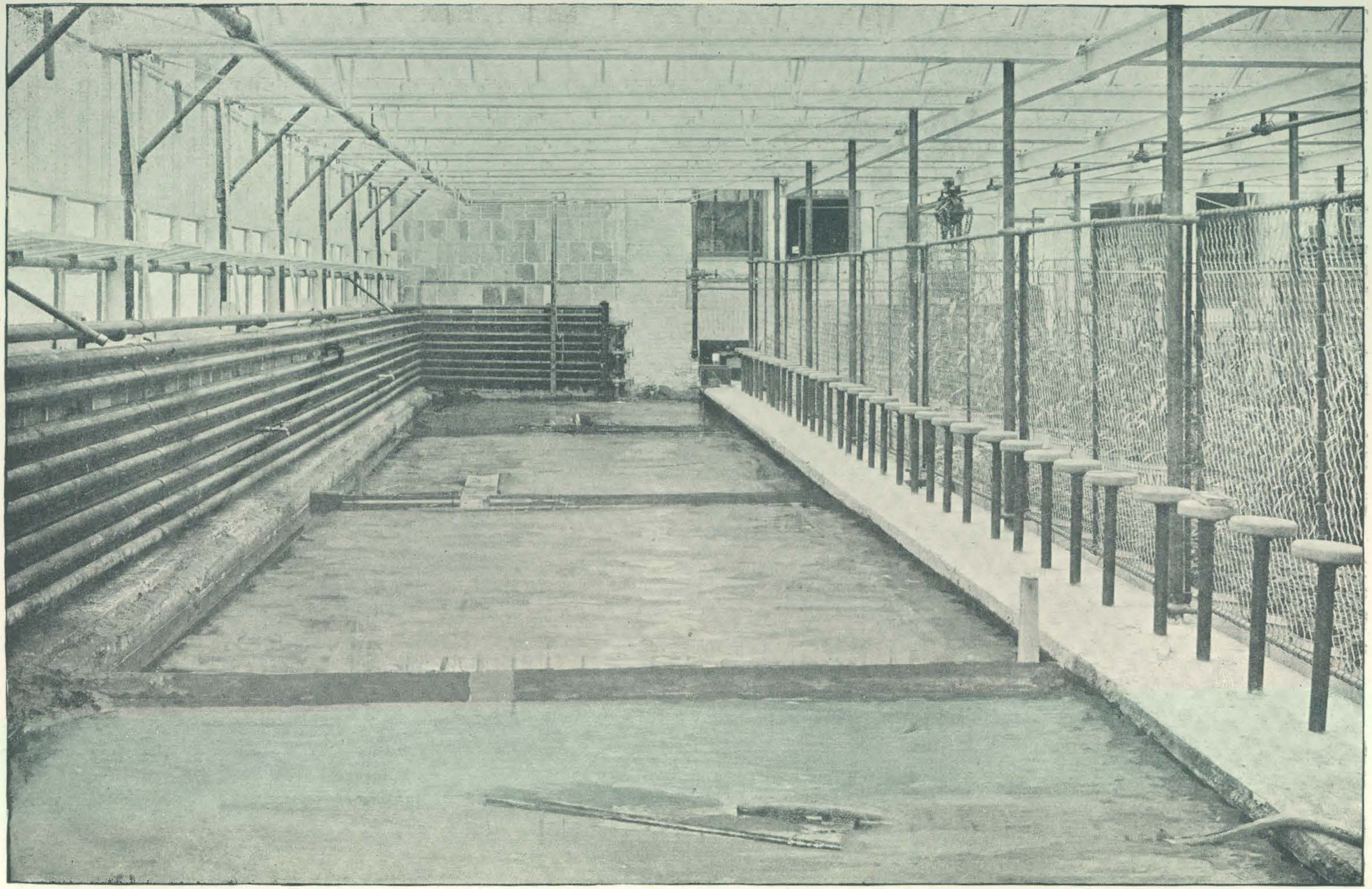
Estimated on this basis, the total seepage on February 1 was at the mean rate of 0.01743 cubic foot per minute, while the measured flow by this investigation, under a gradient of 1 foot in 10, was only 0.0065451 cubic foot per minute for the coarsest sample (No. 4) taken from this section. On the assumption of a pressure gradient of 10 in 10 for the samples experimented with, the observed flow would be at the following rates in cubic feet per minute per square foot:

No. 1	0.007196
No. 2	.0056847
No. 3	.002775
No. 4	.065951

In this case we have for the coarsest sample a computed flow nearly four times the observed flow, but there is no evident reason for assuming that the gradient of effective pressure is as high as 10 in 10.

RATE OF FILTRATION OF WATER THROUGH SOIL.

In the plant-house section of our physical laboratory we have a pit 12.7 feet by 72.7 feet by 8 feet deep, which is cemented on the bottom and sides in the manner of a cistern. The bottom of this pit slopes to a central longitudinal axis and the south end is a little higher than the north end, so as to give drainage from the south toward the north.



DRAINAGE PIT IN PLANT HOUSE OF PHYSICAL LABORATORY, UNIVERSITY OF WISCONSIN, DURING PERCOLATION EXPERIMENTS.

A line of 3-inch tile is placed along the central axis, and leading into this line at intervals of 4 feet on each side there are other lines of similar tile extending from the side walls to the central line.

Into this pit there is filled, to a depth of 5.174 feet, the sandy till of a glacial drumlin from which was separated all stone and gravel which would not pass a screen of a half-inch mesh. This material was at first all wheeled into the pit, nearly filling it. It was then shoveled onto a screen and the coarse material thrown out. This double handling and screening, while it did not secure perfect uniformity throughout the pit, did give an evenness of texture which the soil in its natural condition did not possess.

On the top of this layer of screened material there was placed 1.29 feet of a yellowish sand. The total mean depth of the material was therefore 6.464 feet.

This pit, preparatory to the percolation trials here described, was divided into four sections, as shown in Pl. XVI, by setting up boards crosswise and banking sand against them. Water was then allowed to run into and cover the south section, which is in the foreground of the plate, and the rate of percolation through this section when it reached its maximum was 7.5 pounds per minute from an area of 163.83 square feet, or at the rate of 0.0458 pound per square foot per minute.

Water was next turned upon the north section, having an area of 228.6 square feet, and the maximum discharge reached here was 5.62 pounds per minute, or a rate of 0.0244 pound per square foot per minute. From the section adjoining the north one, having an area of 259.5 square feet, the maximum discharge was 9.47 pounds per minute, or at the mean rate of 0.0365 pound per square foot per minute.

From the remaining section, next to the south end, the maximum discharge was found to be 11.5 pounds per minute from an area of 261.93 square feet, which is at the mean rate per square foot of 0.0439 pound.

If we number the sections of the pit from the north toward the south and tabulate the rates of discharge per square foot per twenty-four hours, we shall have the results below:

Percolation for twenty-four hours.

Section.	Pounds per square foot.	Inches.
I	34.856	6.700
II	52.560	10.104
III	63.216	12.151
IV	65.952	12.678
Mean	54.584	10.408

Samples of soil were taken from two different places in each of these sections after these experiments were completed and after drainage had ceased. In each case a full column of the lower soil was taken with a 4-inch auger and put into a box and mixed, and then a smaller sample taken from these and the water content determined, giving the results in the table which follows:

Water-holding power of soil.

Section.	Per cent of water.	
	Lower soil.	Surface sand.
I	11.48	3.25
II	12.43	3.86
III	10.32	4.51
IV	9.46	4.25

The small variation in the percentage of water in these samples shows that there is not a very wide difference in the texture of the soil in the different sections. The high percentage in No. II was due to a body of red clay, which seemed to lie as a lump, through which one of the borings for this sample was made, the two samples containing 14.12 per cent and 10.73 per cent of water. If for the average, 12.43, we substitute 10.73 per cent, which without doubt is much nearer the truth, then there is the same progression shown in this table as in the table of percolation.

We have also determined the effective sizes of the samples of soil in these several sections, and find them to be as stated in the table below:

Effective size of soil grains.

Section.	Lower soil.	Surface sand.
	Mm.	*Mm.*
I	0.03380	0.28445
II	.04144	.28445
III	.04084	.28445
IV	.05261	.28445

After the percolation through this pit had been studied in sections, then water was thrown over its whole surface and held at nearly a constant level, thus enabling the rate of discharge to be measured by collecting and weighing the water. An autographic rocking meter was constructed to use in this experiment, so as to give a continuous record through a long period of time, but when it was tested, after completion, it was found that the vibrations of the water in the buckets caused them to empty with varying amounts of water, and the use of the meter was abandoned as not being sufficiently exact. The observed variations in this meter were found to be as great as 1 pound in 67 pounds, or 1.5 per cent, and periodic weighings were made instead.

The maximum rate of discharge of water from this pit when the whole surface was under water, was found to be, as an average of ten weighings, 58.01 pounds in four minutes, or 14.5025 pounds per minute. There were more than two hundred weighings, giving the rate of discharge made while this experiment was in progress, but the ten whose mean is given above is taken from that section of the tables where the maximum flow had been observed. The water was kept running on this surface from 9 a. m. April 23 until 5.18 a. m. May 8.

In the early part of this trial the rate of flow was 13.875 pounds per minute, and gradually increased until its higher rate stated above was attained, which was very near the close of the trial.

The temperature of the water as it discharged from the pit varied from 14.2° C. to 14.4° C., and it should be stated that very close to 3 inches of water was maintained above the surface of the sand while the experiment was in progress.

The mean maximum rate of percolation from the whole pit per square foot in twenty-four hours was 22.618 pounds, equal to 4.348 inches, while the mean minimum was 21.6288 pounds, equal to 4.158 inches per square foot. When the water had been shut off from the pit, a record was kept of the rate of discharge for a considerable period, in order to get a measure of the rate at which the soil would give up the water required for complete saturation.

It has been stated that the water was turned off May 8 at 5.18 a. m., and at this time the rate of discharge was the maximum amount stated above, or 14.5025 pounds per minute, but at 2.03 to 2.07 p. m. of the same day it had fallen to 12.8375 pounds per minute, and at midnight on the same day it was only 10.1975 pounds per minute. At 9.59 to 10.03 a. m. May 9 the rate of discharge was 7.9 pounds per minute and the water temperature had risen to 14.9° C.

The rates of discharge on other dates are given below:

		Pounds per minute.
May 9.	Midnight	5.4625
10.	9.02 to 9.06 a. m	4.5875
11.	12.04 to 12.08 a. m	3.0425
11.	9.29 to 9.33 p. m	*a* 1.76
12.	5.20 to 5.24 a. m	1.4125
12.	5.54 to 5.58 p. m	1.0375
13.	5.10 to 5.14 a. m	.825
13.	4.26 to 5.26 p. m	.6458
15.	5.58 to 6.58 a. m	.4394
15.	5.39 to 10.55 p. m	.1504
16.	8.30 a. m. to 5 p. m	.1203

a Water temperature at this time 15.2° C.

Later experiments conducted with this pit showed that there was a large leakage through its bottom or sides, so that the rate of seepage as measured by the outflow is too small by an unknown amount. The figures for the first series of measurements are correct for those conditions, because the water was measured as it went in. This rate, however, should be larger than what would have been observed for the whole surface at once, because then there was no opportunity for the water to spread laterally.

The computed rate of seepage deduced from the formula of Slichter and the aspirator diameter is 0.001160 cubic foot per square foot per minute instead of 0.0006072, the observed amount. These amounts can not be expected to agree, for the water was obliged to enter the lines of tile instead of being permitted to escape from the free bottom, as the conditions of the computed flow assume.

PERCOLATION OF WATER INTO UNDISTURBED FIELD SOIL.

In this experiment an effort was made to measure the rate of flow of water through a soil in its natural undisturbed condition when it was forced to escape from a vertical cylindrical cavity under a constant pressure.

The conditions of the experiment were secured by digging a well 13.5 feet in depth and 7 inches in diameter, reaching from the surface to standing water in the ground. To avoid caving, the well was curbed up with 5-inch unglazed drain tile in 1-foot lengths, standing loosely one upon another. The well was bored with a flat-bit post auger provided with an extension handle. As the tile had an outside diameter of 6.5 inches a space of about one-fourth inch all around it was left at the start. This space, however, became filled very soon after the experiment began with sand from the sides of the wall, which settled in upon the tile when the ground became saturated with water.

The material removed from that cavity was saved in 1-foot sections and an examination of it made with the aspirator, and the results are given in the table on page 212.

In controlling and measuring the water admitted to this well there was used a cylindrical galvanized-iron tank 5 feet high, holding 600 pounds of water and provided with a cock and water gage to read by 100 pounds. Water was brought to this reservoir through a 3-inch pipe provided with a gate, which permitted the reservoir to be filled in a short time.

In carrying out the experiment the tank was first filled, and then the cock was opened until it would supply water enough to maintain the level of the water in the well at 7 inches below the top of the ground. As the head lowered in the tank the cock was opened wider to give the needed supply of water, or it was shut off again if the water in the well was seen to rise. The water level in the well was thus subject to small irregular variations, amounting at times to as much as 1 inch, but ordinarily not exceeding one-fourth of this amount.

When the tank became empty, the cock was closed and the gate to the supply pipe opened, filling the tank as quickly as possible again. With the tank full the cock was opened, at first wide, to bring the water in the well quickly back to the fixed level and then regulated again to maintain it there.

In the table which follows are given the records of the flow of water into this well. When the water was first admitted to the well the cock in the tank had not capacity enough to maintain the water at the surface, although it delivered water at the rate of 25 pounds per minute. This condition did not last long, and was shortened by the fact that the sand soon settled in around the tile, and thus reduced the diameter of the well from 7 inches to 6.5 inches. It is barely possible also that when the sand became packed close about the tile the discharge of water through the open end, through joints between the tile, and through the pores of the tile was not quite rapid enough to deliver the water to the soil as rapidly as it might have been able to lead it away. It hardly seems possible, however, that the retardation to discharge due to this cause was large.

Rate of flow of water out of a well.

Starting time.	Closing time.	Total number of seconds.	Amount of flow.	Time for—	
				100 pounds.	400 pounds.
A. M.	*A. M.*		*Pounds.*	*Seconds.*	*Seconds.*
7.30.00	7.47.00	1,020	400	....	1,020
7.49.30	8.05.20	1,010	400	....	1,010
8.06.30	8.24.50	1,100	400	....	1,100
8.26.10	8.44.30	1,100	400	....	1,100
8.45.44	9.06.35	1,251	400	....	1,251
9.07.50	9.30.10	1,340	400	....	1,340
9.31.40	9.56.10	1,470	400	....	1,470
9.58.30	10.28.35	1,805	400	....	1,805
10.30.00	11.04.20	2,060	400	....	2,060
11.05.40	11.48.41	2,580	400	....	2,580
	P. M.				
11.50.20	12.41.20	3,240	400	....	3,240
P. M.					
12.45.50	12.59.00	790	100	790	....
12.59.00	1.12.45	825	100	825	....
1.12.45	1.25.20	755	100	755	....
1.25.20	1.37.50	750	100	750	3,120
1.39.10	1.51.15	725	100	725	....
1.51.15	2.04.00	765	100	765	....
2.04.00	2.17.50	830	100	830	....
2.17.50	2.31.55	845	100	845	3,165
2.33.20	2.46.45	805	100	805	....

Rate of flow of water out of a well—Continued.

Starting time.	Closing time.	Total number of seconds.	Amount of flow.	Time for—	
				100 pounds.	400 pounds.
P. M.	*P. M.*		*Pounds.*	*Seconds.*	*Seconds.*
2.46.45	3.01.05	860	100	860	....
3.01.05	3.15.25	860	100	860	....
3.15.25	3.31.35	970	100	970	3,495
3.32.50	3.52.00	1,150	100	1,150	....
3.52.00	4.09.10	1,030	100	1,030	....
4.09.10	4.29.55	1,245	100	1,245	....
4.29.55	4.53.36	1,415	100	1,415	4,840
4.55.00	5.23.50	1,730	100	1,730	....
5.23.50	5.52.30	1,720	100	1,720	....
5.52.30	6.20.00	1,650	100	1,650	....
6.20.00	6.42.30	1,350	100	1,350	6,450
6.44.10	7.07.20	1,390	100	1,390	....
7.07.20	7.38.55	1,895	100	1,895	....
7.38.55	8.08.45	1,790	100	1,790	....
8.08.45	8.37.50	1,745	100	1,745	6,820
8.39.20	9.09.05	1,785	100	1,785	....
9.09.30	9.54.00	2,670	100	*a* 2,670	....
9.54.00	10.37.00	2,580	100	2,580	....
10.37.00	11.22.00	2,700	100	2,700	9,735
	A. M.				
11.25.00	12.10.00	2,700	100	2,700	....
A. M.					
12.10.00	12.58.00	2,880	100	2,880	....
12.58.00	1.48.30	3,030	100	3,030	....
1.48.30	2.41.00	3,150	100	3,150	11,760
2.44.00	3.36.00	3,120	100	3,120	....
3.40.00	6.42.25	10,955	300	3,648	14,065
6.42.25	7.38.55	3,395	100	3,395	....
7.40.45	8.40.10	3,565	100	3,565	....
8.40.10	9.40.05	3,595	100	3,595	14,090
9.44.05	10.43.00	3,535	100	3,535	....
10.43.00	11.48.20	3,920	100	3,920	....
	P. M.				
11.49.05	12.51.10	3,725	100	3,725	....
P. M.					
12.51.10	1.56.20	3,910	100	3,910	15,395
1.56.20	2.59.30	3,790	100	3,790	....
2.59.30	4.04.30	3,900	100	3,900	....

a Time too long on account of delay by shutting off.

It will be observed from the data of this table that during the interval from 7.30 a. m. until 4.04.30 p. m. the next day the discharge from the well had decreased from 255 seconds per 100 pounds of water to 3,900 seconds for the same amount, or a rate only about one-fifteenth as fast.

During this interval of time there had been put into the well, between 7.30 a. m. October 14 and 4.04.30 p. m. October 15, 8,900 pounds of water, equal to 142 cubic feet. At this time the section of ground

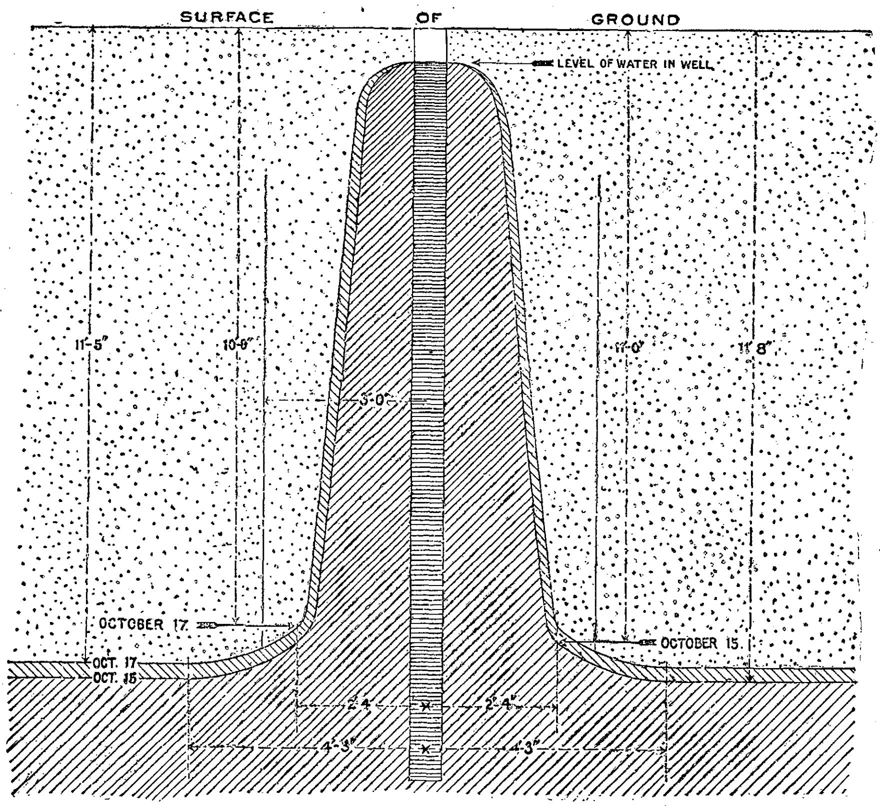


FIG. 47.—Diagram showing contour of ground-water surface produced by water percolating into soil about a well.

entirely filled with water is represented in fig. 47, where the curve marked October 15 shows approximately the water surface as revealed by boring down until standing water was reached.

On October 16 the experiment was continued from 8.25 a. m. until 5.45.10 p. m., and the flow out of the well had decreased from 400 pounds in 4,265 seconds at 9.43 a. m. to 400 pounds in 10,740 seconds. On October 17 water was again run into the well, and at 4.19.25 p. m. the section of ground completely filled with water had the form shown in fig. 47 by the curve marked October 17.

During the four days there were put into this well 12,480 pounds, or 200 cubic feet, of water, the total time during which water was being delivered to the well being 185,405 seconds. The water used in this experiment was pumped from Lake Mendota and was clear except so far as it contained microorganisms. How far these may have been instrumental in decreasing the discharge by clogging the pores of the soil or tile it is not possible to say.

This amount of water, when expressed in flow per square foot per minute, is 0.003379 cubic foot. The computed flow for soil grains having the mean diameter of the fourth to the eleventh foot, inclusive, and the mean pore space, for a gradient of 1 in 10, would be 0.001826 cubic feet per minute.

Since the ground-water level was only raised about 3 inches at a distance of 4 feet radius from the well, the water must have spread away in all directions over quite long distances in order to have accommodated the 200 cubic feet which had been introduced.

RATE OF LATERAL FLOW OF WATER THROUGH SANDS.

To study this problem there was constructed a galvanized iron tank, represented in fig. 48 at A, B, C, D. It has a length of 14.5 feet and is 4 feet deep and 1 foot wide. It is filled with a mixed sand, from

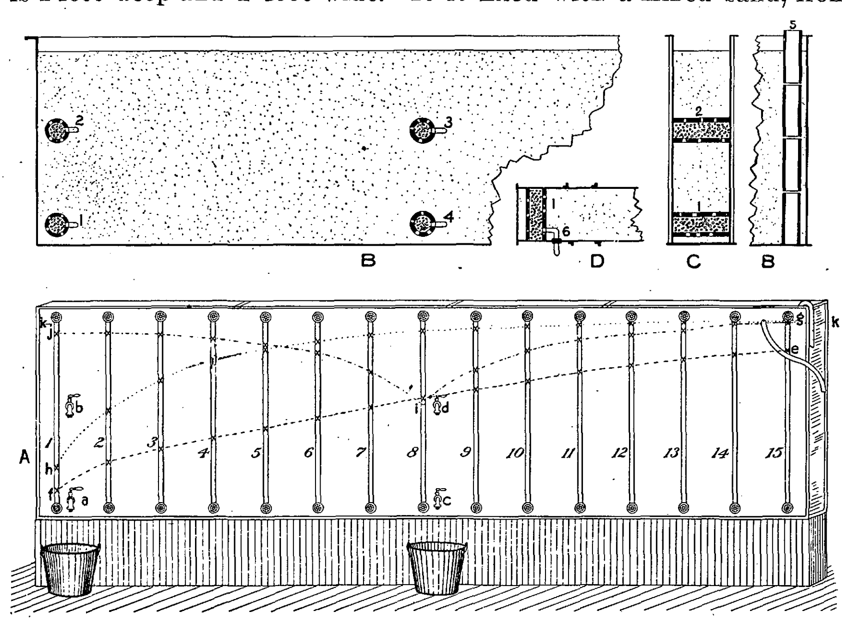


FIG. 48.—Apparatus for measuring the lateral flow of water through sand and the lines of pressure. A, front elevations of tank, with *a*, *b*, *c*, *d*, faucets from drain tile, and 1, 2, 3 . . . . 15, pressure gages; B, B, vertical sections lengthwise, with 1, 2, 3, 4, tile and faucets, and 5, supply tile at end; C, cross section, with 1, 2, tile; D, section at 1 in B, showing connection of faucet with tile.

which were sorted the ten grades used in studying the effect of the diameter of soil grains upon the rate of flow of water through it. When the effective diameter of the grains of this mixture was determined with the aspirator, it was found to be 0.2881 mm., and this was associated with a pore space of 31.11 per cent, much smaller, it will be observed, than was found for any of the separate grades.

Sand was placed in the tank to a depth a little below *kk* in A, and in this was set four 3-inch drain tile, shown in section at 1, 2, 3, 4 in B, C, D. The tile were just long enough to reach across the tank, so that the walls of the tank closed their ends. They were filled with coarse sand and gravel, and their walls were perforated with several holes in order to permit easy, rapid entrance of the water. In order to prevent the fine sand from filling into the tile, the openings were covered with the fiber from coarse manila rope.

The faucets *a*, *b*, *c*, *d* in A opened directly into the tile by means of a bent union, thus permitting the water to flow out freely. There were 15 pressure gages placed in one side of the tank, opening at the bottom and 1 foot apart from center to center. The lower end of each is covered with a shield of metal soldered to the tank on three sides so as to be water-tight, but the lower edge of the shield simply rests upon the bottom of the tank without being water-tight. In this way sand is prevented from rising into the gage glasses, and the bottom pressure is recorded by them at their respective stations.

At B in one end of the tank three vertical lines of 3-inch drain tile are set and left empty, with a view to giving the water unobstructed access to the whole end section of the soil, through which it was to move laterally.

In conducting the experiment water was admitted to the columns of tile and held at a constant level by means of an overflow, shown in the drawing A between 14, 15; then the three-fourths-inch stopcock at *a*, *b*, *c*, or *d* was opened, and the water discharging was collected and weighed at the end of stated intervals of time.

To read the levels of the water in the pressure gages, two engineer's target rods carrying verniers reading to thousandths of a foot were set rigidly at opposite ends of the tank, with their feet on the same level, the targets being left free to slide up or down on their respective rods. Across the horizontal lines of each target was fixed a fine wire, and to the center of these wires was secured a fine thread, which could be stretched so as to give a horizontal line passing the front of every gage and nearly in contact with their faces. In taking the reading of any gage the targets were adjusted until each gave the same reading and the string was on the level of the lower face of the meniscus in the gage where the water pressure was to be measured. The gage tubes were as large as could be used in three-fourths-inch steam-gage fittings, and had an inside diameter varying from a little one side or the other of 0.45 of an inch. No allowance has been made in these measurements for capillarity.

In the first experiment stopcock *b* was opened and the water was allowed to discharge from it until the gage readings had become constant and the water was discharging at a uniform rate. At this time the water was discharging at a mean rate of 20 pounds in 799.8 seconds, or 1 pound in 39.99 seconds.

Referring the gage readings to the level of the overflow in the tank, the pressures in the several gages at the time the rate of flow was as stated above were as given below:

Table showing pressure at bottom of tank at different distances from outlet.

Gage No.	Pressure.	Gage No.	Pressure.
	Feet.		*Feet.*
1	1.215	9	0.630
2	1.171	10	.566
3	1.100	11	.461
4	1.026	12	.395
5	.956	13	.332
6	.878	14	.280
7	.786	15	.251
8	.716		

Gage 1 is so placed as to measure the pressure directly at the outlet by having its opening immediately beneath the tile into which the discharge is taking place. The outlet of the tile was 1.587 foot below the overflow, and hence the gage level was

$$1.587-1.215 = 0.372 \text{ foot}$$

above the outlet. At the same time also the water level in gage 15 was 0.257 foot below the water surface in the tank directly above its mouth. The difference for gage 1 shows for gage 1 a resistance to discharge into the tile, and for gage 15 a flow along the bottom toward the outlet.

In the next experiment the stopcock *b* was closed and *a* opened, allowing the discharge to take place at a lower level and under a greater pressure, *a* being 3.39 feet below the overflow.

The discharge from the lower level was begun at 10.47, with the pressure in all gages the same, and at 12 to 12.20 the rate of discharge was 62.75 pounds in twenty minutes, with the gages still falling; from 12.25 to 12.45 the flow was 59.75 pounds; from 1.11 to 1.31 the flow was 57.25 pounds. The gages had become stationary at 1.35, with a flow at this time of 56.50 pounds in twenty minutes. From this time on until the next morning the apparatus was allowed to discharge continuously, and at 7.33 to 7.53 the flow was 55.30 pounds in twenty minutes, which is 23.387 seconds for 1 pound, the temperature of the water being 25.4° C. At this time the water in the supply tank had become exhausted and the tank required to be refilled. The water used was colder, and this modified the rate of discharge so that it went forward at a decreasing rate as the warm water in the sand was gradually displaced by the colder. In the table which follows the amounts of flow in successive twenty minutes are given, together with the temperature of the water at the inlet and outlet:

Table showing rate of seepage of water into 1 foot of drain tile through coarse sand from one side.

Minutes.	Flow.	Temperature.		Minutes.	Flow.	Temperature.	
		Inlet.	Outlet.			Inlet.	Outlet.
	Pounds.	° *C.*	° *C.*		*Pounds.*	° *C.*	° *C.*
20	55.30	....	....	200	49.15	19.00	22.20
40	53.15	....	....	220	49.00	19.00	22.10
60	50.65	18.4	22.8	240	47.90	19.10	22.10
80	47.40	....	....	260	48.65	19.10	22.10
100	52.10	18.55	22.6	280	48.50	19.15	22.00
120	48.30	18.60	22.3	300	48.55	19.00	21.95
140	47.90	18.80	22.5	320	48.60	19.30	21.90
160	48.90	18.90	22.4	340	48.50	19.30	21.90
180	48.90	19.00	22.3	360	48.50	19.40	21.90

At 10.42 to 11.30, when the rate of discharge averaged 48.68 pounds in twenty minutes, the level of the water in the pressure gages stood as follows:

Table showing pressure along bottom of tank at different distances from the outlet.

Gage No.	Pressure.	Gage No.	Pressure.
	Feet.		*Feet.*
1	3.203	9	1.264
2	2.746	10	1.107
3	2.411	11	.932
4	2.187	12	.804
5	1.990	13	.684
6	1.806	14	.594
7	1.600	15	.541
8	1.446		

These numbers are plotted on the gages in fig. 48, A, and are connected by the line *ef*.

As the outlet in this experiment was 3.39 feet below the overflow, the water in pressure gage 1 stood 3.390 − 3.203 = 0.187 foot higher than the outlet, showing a resistance to discharge here equal to that amount. At the opposite end of the apparatus gage 15 registered a pressure of 0.541 foot below the overflow, and this shows a diminished head at this point of that amount, due to flow toward the tile.

In the third experiment with this apparatus the stopcock was closed and water was admitted until the gages became filled to the same level and water covered the whole surface of the sand in the tank to a depth of about 1 inch. This necessitated closing the overflow and regulating the level of the water in the tank by opening and closing the supply stopcock.

With the supply regulated so as to hold the surface of the sand under water, stopcock *c* was opened wide and the discharge during intervals of five minutes was measured by weighing. The flow was started at 2.55, with a discharge during the first five minutes of 36.50 pounds, where the water temperature at the inlet was 19.3° C. and at the outlet 20.7° C. Succeeding five-minute discharges were as follows: 37.50 pounds, 37.30 pounds, 37.65 pounds, 38 pounds, 37.80 pounds, and 37.85 pounds, closing at 5.35.

Between 3.35 and 4.15, when the gage levels had become stationary, these levels were measured with the results which are given below:

Table showing pressure along bottom of tank at different distances from outlet.

Gage No.	Pressure.	Gage No.	Pressure.
	Feet.		*Feet.*
1	0.186	9	0.895
2	.195	10	.527
3	.239	11	.312
4	.293	12	.210
5	.405	13	.141
6	.569	14	.091
7	.942	15	.082
8	1.587		

These readings are plotted on the gages in fig. 48, A, and the line *g i j* drawn through them. In this case the rate of discharge was 1 pound in 7.976 seconds. The curve shows a very pronounced pressure above the outlet and also that the pressures are less from the gages 1 to 8 than they are from 8 to 15. This is due, in part at least, to the fact that water can enter through the end tiles directly to the bottom of the tank and begin its lateral flow with no vertical resistance. The water was again allowed to come to a level in the pressure gages by shutting the stopcock *c*, and at 4.25 the stopcock *a* was opened, but the surface of the sand was kept covered with water, as in the former case. Under these conditions, with the water entering at a temperature 19.6° C. and discharging at 22.4° C. at the rate of 36.50 pounds during the first five minutes, weighings were made by five-minute intervals with the results below:

Table showing rate of seepage of water into 1 foot of drain tile through coarse sand from both sides.

First.	Second.	Third.	Fourth.
Pounds.	*Pounds.*	*Pounds.*	*Pounds.*
36.50	35.65	35.65	....
Fifth.	**Sixth.**	**Seventh.**	**Eighth.**
Pounds.	*Pounds.*	*Pounds.*	*Pounds.*
34.90	33.50	....	33.50
Ninth.	**Tenth.**	**Eleventh.**	**Twelfth.**
Pounds.	*Pounds.*	*Pounds.*	*Pounds.*
33.00	33.50	32.65	33.80

At the end of these weighings the gage readings had become stationary, and were as given in the table below:

Table showing pressure along bottom of tank at different distances form outlet.

Gage No.	Pressure.	Gage No.	Pressure.
	Feet.		*Feet.*
1	2.765	9	0.100
2	1.667	10	.067
3	1.032	11	.023
4	.685	12	.008
5	.492	13	+ .017
6	339	14	+ .018
7	.213	15	+ .020
8	.153		

These results are plotted on the gage tubes in fig. 48, A, and the curve *hg* has been drawn through them. It will be seen in this case where all water had to approach the outlet from one side instead of two sides as in the last case, the outlet gage shows a much lower reading. The rate of discharge under these conditions averaged 1 pound in 9.002 seconds.

If we group the discharges in these four experiments and express them in cubic feet for twenty-four hours we shall have the results given below:

Experiment.	Surface of sand not covered with water.	Experiment.	Surface of sand covered with water.
1	59.17 cubic feet per 24 hours.	3	173.5 cubic feet per 24 hours.
2	72.36 cubic feet per 24 hours.	4	153.8 cubic feet per 24 hours.

OBSERVED REDUCTION OF GROUND-WATER PRESSURE.

After these experiments were made and the important questions involved in the suits which have been referred to in connection with the Crystal Springs Land and Water Company and the West Los Angeles Water Company were understood, there were introduced into this reservoir three other sets of pressure gages, one set of 15 to show the pressure at the 3-foot level, 15 others to show the pressure at the 2-foot level, and still another set of 15 at the 1-foot level. With this arrangement it became possible not only to know what the conditions of pressure were at 60 different points in the sand while the water was running, but also to ascertain just where the level of the ground water was at any particular time and condition.

This is an important matter to have settled and the apparatus demonstrates the principle in a conclusive manner.

The reservoir was filled with water so that the sand was barely covered and the overflow was arranged so as to maintain a constant level of the water at this horizon; the stopcock *c* was opened and the water was allowed to discharge until the flow became constant and the level of the water in the 60 gages had become stationary. At this point the levels of all the gages were read, with the results which are given in the table and which are shown graphically in fig. 49.

Table showing the distribution of pressure in a section of sand when water is discharging from near the center at the bottom, the water being maintained over the whole surface.

[The surface of water in the reservoir is zero.]

Gage numbers.	Gage readings.			
	Level 1.	Level 2.	Level 3.	Level 3.5.
1	0.151	0.375	0.480	0.518
2	.168	.405	.515	.560
3	.203	.476	.625	.662
4	.195	.508	.745	.805
5	.125	.729	.968	1.225
6	.438	.970	1.295	1.355
7	.526	1.275	1.775	1.970
8	.590	1.432	2.300	3.010
9	.532	1.290	1.830	1.845
10	.428	1.140	1.275	1.275
11	.285	.720	.905	.918
12	.190	.532	.682	.700
13	.090	.366	.523	.533
14	.092	.320	.435	.440
15	.085	.270	.375	.385

It is to be understood that the vertical lines in fig. 49 represent the positions of the pressure gages and that pressure gages were inserted where the horizontal lines cross the vertical lines. The centers of the circles occupy the exact level of the meniscus in the several gages and the lines drawn through these circles show the variations of water pressure at intervening points between the several gages on the levels at which they are inserted.

The new gages which were inserted had to be set 0.1 foot to one side of the original gages, as shown by the position of the circles. Curve I shows the variations of pressure at the distance of 1 foot below the level of the surface of the water above the sand. Curves II, III, and IV show the same relations for the lines 2 feet, 3 feet, and 3.5 feet below the level of the water over the sand. The gages inserted along the 3.5-foot line have been described; those situated at the higher levels consisted of three-sixteenth-inch brass tubes each provided with a conical point made of fine wire gauze soldered to one end. The screen ends of these gages were thrust through the wall of the reservoir and soldered to it water-tight, while to the outer ends were connected, by means of rubber, glass tubes in which the pressure was observed.

It will be seen from this arrangement that each pressure gage really represents a well sunk to a certain depth below the ground-water surface and at a certain distance from the location of an infiltration pipe; and it is this arrangement to which Professor Slichter refers in his paper, Chapter IV, section 4, page 354.

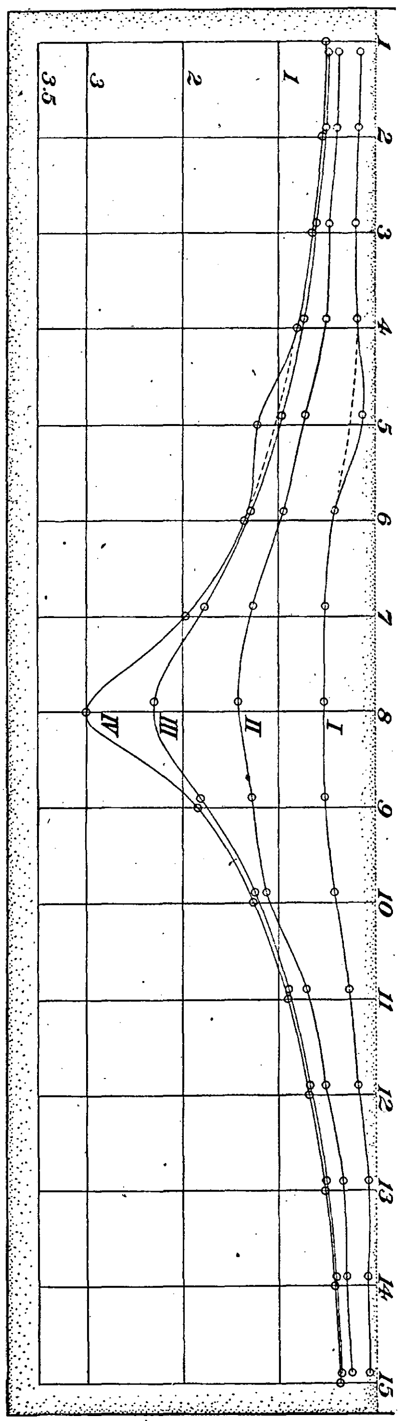


FIG. 49.—Diagram showing distribution of pressure when the water is discharging from stopcock c in fig. 48. Horizontal lines indicate pressure and vertical lines number of gage.

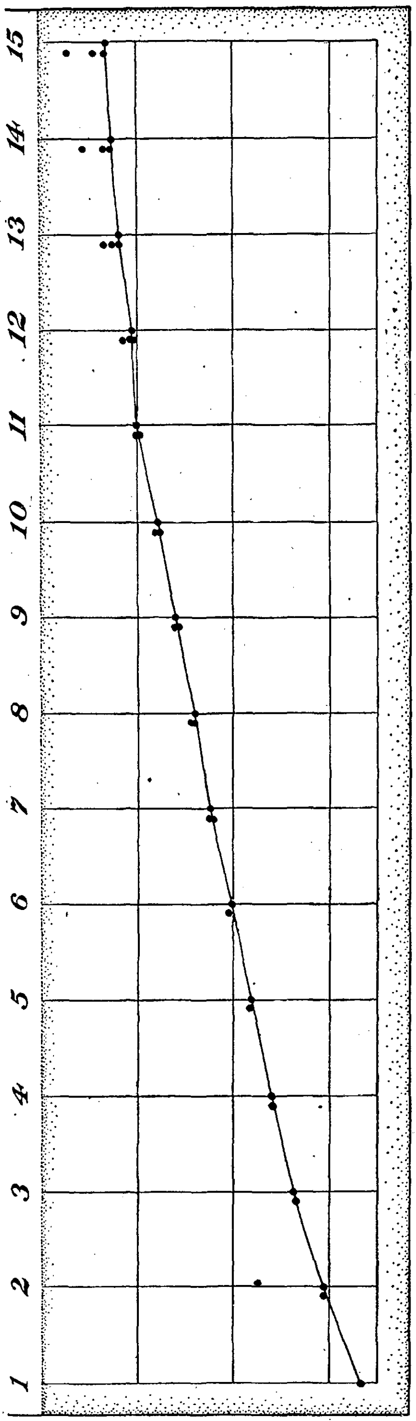


FIG. 50.—Diagram showing distribution of water pressure when the discharge is from stopcock *a* in fig. 48. Horizontal lines indicate pressure and vertical lines number of gage.

It is evident enough that were it possible to place a line of infiltration pipes in such a relation to a system of wells as is here represented, the water in the wells would begin to fall with the beginning of flow from the infiltration pipes and they would continue to do so until a new surface of equilibrium had been established at some lower level. It is very rare, however, that conditions exist which make this type of well interference at all marked, and it is the writer's judgment that too much importance has been assigned to it in the paragraph referred to.

The serious cases of well interference and natural subirrigation interference come from an actual lowering of the ground water by the withdrawal of it from the soil or sand.

The correctness of this view was established by a fifth series of measurements with the reservoir in question after the new gages had been added.

The reservoir was filled with water to the level of the surface of the sand, and then the stopcock *a* was opened and the water allowed to discharge freely; while a dam was fixed between 14 and 15, fig. 50, to prevent the water from spreading over the surface, and then the supply was turned on so as to maintain, with the aid of the overflow, a constant level of water behind the dam. After the drainage had continued until an equilibrium was reached it was found that the surface of the ground water did practically coincide with the height of the water in the pressure gages, giving the condition of things represented graphically in fig. 50, which, it will be seen, is radically different from what was found in the last experiment, fig. 49, where the surface of the area was continually kept covered with water.

If it were not true that all water capable of exerting pressure had been drawn down to the level of the curve shown by the line in the diagram it would have stood in the gages in which no pressure was shown. The observed heights of the pressure gages are given in the table below:

Table showing the level of the ground-water surface and the pressure at different levels when water is discharging at one point and entering at another.

Level.	Gage numbers and readings.				
	1.	2.	3.	4.	5.
1	0	0	0	0	0
2	0	0	0	0	0
3	0	2.940	2.658	2.418	2.188
3.5	3.344	2.950	2.637	2.410	2.190

Level.	Gage numbers and readings.				
	6.	7.	8.	9.	10.
1	0	0	0	0	0
2	1.962	1.765	1.578	1.410	1.215
3	1.968	1.788	1.613	1.425	1.246
3.5	2.000	1.776	1.618	1.410	1.231

Level.	Gage numbers and readings.				
	11.	12.	13.	14.	15.
1	0	0.870	0.665	0.455	0.294
2	1.070	.957	.766	.660	.565
3	1.082	.952	.830	.732	.672
3.5	1.078	.959	.827	.750	.690

It is clear from these gage readings that in the region of gage 1 the level of the ground-water surface had fallen below all of the gage openings except that of 3.5, which is below the level of the outlet. Even at gages 7 to 11, inclusive, where the level of the ground water is above the 2-foot level, there is very little difference shown by the gages, the readings being almost as close as they can be read. When gage 12 is passed, however, the readings begin to show a departure, but this is due to the fact that new supplies of water are continually being added at the surface, the case here becoming like that of the preceding experiment.

It appears clear, therefore, from these experiments that the lowering of the water pressure in the sands in the last series of trials is due chiefly to the fact that the water has actually been withdrawn from the sand rather than to the fact that it is in motion toward the outlet. Were the lowering of the pressure shown by the gages due chiefly to the fact that the water is not in a statical condition, the gages should respond much more quickly than they are observed to do, and they should come into a condition of equilibrium in a far shorter time than they are observed to do.

It was shown in the second experiment made with the apparatus when the water was started to flowing at 10.47 a. m. that the gages had only reached a condition of equilibrium at 1.11 p. m., after the lapse of two hours and fourteen minutes. This is ample time for the necessary loss of water from the small reach of only 14 feet of sand to bring the actual water level down to the observed level indicated by the pressure gages.

TIME REQUIRED TO LOWER THE GROUND-WATER LEVEL BY A SYSTEM OF INFILTRATION PIPES.

In another part of this paper it was shown from direct observation that the withdrawal of a comparatively small amount of water from a soil already saturated is sufficient to produce a marked change in the level of the ground water, and hence to cause marked changes in the level of water in wells and in the height of the ground water in sections where crops depend on water which is derived from the underflow by natural subirrigation.

In order to secure direct and positive data bearing upon this important question, when the water in the reservoir (fig. 48) was at rest and when the gage readings were as shown in the table below, 20 pounds of water were added to the sand and the gages were allowed to assume the new level, when the readings were again taken as given below:

Table showing the rise of the ground-water surface in coarse sand due to the addition of water.

	Gage readings.						
	1.	2.	3.	4.	5.	6.	7.
Before adding 20 pounds water.....	0.778	0.776	0.776	0.775	0.770	0.774	0.775
After adding 20 pounds water.....	.218	.218	.218	.218	.214	.215	.215
Rise in the water surface........	.560	.560	.558	.557	.556	.559	.560

Table showing the rise of the ground-water surface in coarse sand due to the addition of water—Continued.

	Gage readings.							
	8.	9.	10.	11.	12.	13.	14.	15.
Before adding 20 pounds water.....	0.778	0.775	0.772	0.772	0.775	0.772	0.772	0.770
After adding 20 pounds water.....	.215	.214	.208	.208	.214	.212	.215	.215
Rise in the water surface........	.563	.561	.564	.564	.561	.560	.557	.555

It thus appears that the 20 pounds of water added to this area raised the level of the ground water an average of 0.5587 foot; but as a part of the water added went to fill the gage tubes and two graduates which were in siphon connection with two supplementary gages, it is necessary to deduct 3.565 pounds from the 20 pounds added, thus leaving 16.435 pounds as the amount of water required to raise the level of the water 0.5587 foot in this coarse sand.

In the next experiment there was withdrawn from the same reservoir 38.3 pounds of water; and of this, 4.725 pounds came from the gages and the two graduates, thus leaving 33.575 pounds coming from the sand, lowering the level 0.7545 foot, as shown by the gages when they had come to rest after withdrawing the water.

Still a third trial was made; a single pound of water was added to the reservoir, and this had the effect of raising the ground water 0.0258 foot, or very nearly 0.31 inch. This great change in the level of the ground water, with so small an amount of water added or withdrawn, will be readily understood if reference is again made to fig. 15, where the empty space in the zone of capillary saturated soils just above the level of the ground-water surface is shown to be very small indeed, even in such coarse sands after they have stood 2.5 years in order that complete drainage should have taken place.

In a final trial with this apparatus the withdrawal of 78.7 pounds of water showed, after the gages had become stationary, a fall in the ground-water level over the whole 14.5 square feet amounting to 1.226 feet.

But 78.7 pounds of water on 14.5 square feet represents only 1.435 inches of water on the level.

It is now possible to deal definitely on a quantitative basis with such cases as those described by T. S. Van Dyke in the Irrigation Age for December, 1897, page 60.

In December, 1895, the West Los Angeles Water Company made a cut some 2,000 feet long and 18 feet deep at the upper end. A flume was laid in the bottom, from which nearly 500 inches of water have been flowing ever since and almost unaffected by the series of short years. During the two months the cut was making, and the water increasing every day, several wells on places from 1,000 to 2,000 feet upstream showed a gradual fall of their water level, which amounted in the two months to 4 feet. In June, 1896, an extension was made which took six weeks, and resulted in developing more water at about the same rate as that in the main flume. During this six weeks the water in the wells sank 16 inches.

If reference is now made to the table on page 103, where the number of inches required to raise the ground water 1, 2, 3, and 4 feet after complete drainage has occurred are given, it will be seen that for the coarsest sand in the series the withdrawal of 0.874 inch of water on the level will lower the ground water 1 foot, that 4.379 inches will lower it 2 feet, 8.55 inches 3 feet, and 12.81 inches 4 feet, while with the finest sand only a little more than 5 inches of water taken from the ground will lower the water level 4 feet.

Referring now to the map of this region (fig. 45) the position of the wells in question with reference to the completed flume will be seen. If an area larger than that covered by the map, or four blocks on a side, equal to 5,200 feet, nearly 1 square mile, be taken and the lowest rate of discharge for the completed flume which has been given by Mr. Lippincott, 6.2 second-feet, the number of days for this flume to lower the water under the whole area 4 feet may be computed, assuming the capacity of the sands of the water-bearing beds to average that given in the table referred to for the five sands. When these computations are made it appears that the time given below is required for the different sizes of sand.

	Days.
Sand No. 20	53.91
Sand No. 40	51.26
Sand No. 60	45.43
Sand No. 80	31.45
Sand No. 100	23.13

These figures, it will be seen, are fully within the observed time required for the 4 feet of change which was recorded on the well, especially when it is observed that in this short time the drainage of the soil could not be complete, and that the amount required for the mixed sands is likely to be much less than that required for the No. 20 sand, which calls for less than fifty-four days of flow for the infiltration flume to draw the water down 4 feet over an area 1 square mile in extent.

The records of discharge by this flume which we have cited from Mr. Lippincott show that its capacity decreased as, indeed would be expected and just as our own experimental flows did, but the amount of decrease was not enormously large in either case, yet the decrease has been amply large to meet reasonable expectations.

INTERFERENCE OF TWO WELLS IN SANDSTONE.

To test the principles involved in the problems of the last section an experiment was made on two wells, 1,133 feet apart, each sunk into the Potsdam sandstone to a depth of about 50 feet. One of these wells, at the residence of the writer, is 6 inches in diameter, 70 feet deep, and is cased to the rock (20 feet) with steel tubing. In the well is a double-acting pump, worked by a $2\frac{1}{2}$-horsepower gasoline engine, and capable of delivering 70 to 80 gallons of water per minute. The second well, having the same general dimensions and character, is situated on the experiment-station farm, and had recently been drilled when the experiment to be described was performed. No pump had yet been put upon this well. The normal height of the ground water in each of these wells is very nearly the same, and stands 1 or 2 feet above the surface of the indurated rock, in which the steel casings terminate.

The object of the experiment was to ascertain if at a distance of 1,133 feet the pumping of one well would sensibly disturb the level of the water in the other. To ascertain this fact a float was placed upon the water in the new well and connected with a twenty-four-hour chronograph, in which the movement of the pen is magnified threefold.

After the instrument had been connected up with the well about four hours the pump was started and run during about thirty minutes, then stopped for ten minutes, and again started and run steadily until 8 p. m., the whole period of pumping being four hours and forty minutes, at the rate of about 75 gallons per minute.

At exactly 7 a. m. the next morning the pump was started again and run for exactly ten minutes, and the record which was produced by the chronograph is represented in fig. 51. The chronograph is so

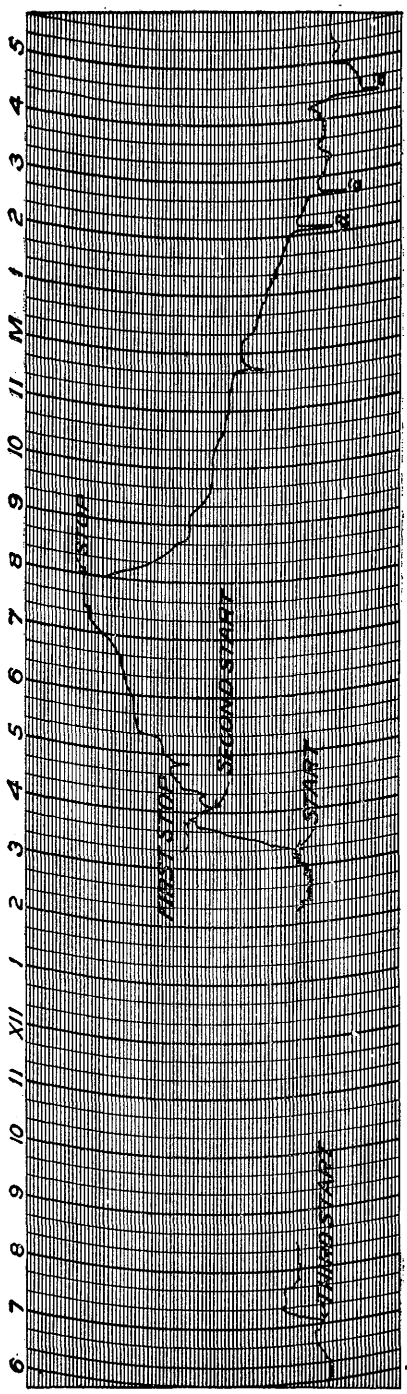


FIG. 51.—Autographic record of changes in the level of water in a well due to pumping another well 1,133 feet distant.

made that a fall of the water causes a rise of the pen. It will be noted that each time the pump was started the pen rose on the sheet faster than it had been rising before the pump was started, and that each time the pump was stopped the pen fell on the sheet faster than it had been doing, and as these coincidences occurred three consecutive times, just as would be expected if the pumping of one well affected the level of the water in the other well, there seems to be no reason to doubt that the record proves that the pumping of one well did lower the level of the water in the other well to the extent which the record shows. The total fall of the water in the well was three-fifths of an inch. It has been shown that in coarse sand, such as was used in the last experiments, 1 pound of water withdrawn from the sand in the reservoir lowered the level of the water in it 0.31 inch on the whole area, and, assuming the same rate for the circle of sandstone whose center is the well pumped, it would be necessary to pump out 8,635 cubic feet of water to produce the change in level of three-fifths of an inch which was recorded. The amount of water which was pumped out was 2,807 cubic feet.

As the water was lowered three-fifths of an inch on the circumference of the area which has been computed, it is evident that the area taken as being affected is too small, and not only this, but the amount of lowering toward the center should be some amount greater than that observed at the well, so that the amount computed would on this basis be too small. On the other hand, it must be said that the space emptied by pumping from the fine sand of the sandstone would be much smaller for the same depth than that observed for the coarse sand, certainly less than one-third of it, or less than the amount pumped out; hence it appears clear that even in this case of interference it may well be accounted for by an actual lowering of the surface of the ground water rather than by a change of pressure due simply to a change in the rate of flow, as Professor Slichter would account for it.

When the third start and stop were made in this experiment two observers set their watches together, with a view of determining how long after starting the pump it would be before the well would respond and how long after stopping before the reversal would occur. It was found that the fall of the water began about one minute and forty-five seconds after starting the pump, the time being obtained by observing the pen, watch in hand. The engine worked exactly ten minutes, but the rise of the pen, and hence fall of the water, appears to have continued nearer fifteen minutes than ten, and there was no sharp fall to fix the turning better than the curve itself shows it.

The fact that the fall of the water was so gradual and continued so long after the main pumping closed seems to indicate that an actual lowering of the ground water had taken place.

The dependent loops in the curve at *a*, *a*, *a*, are due to the passage of a railway train along the track, which always produces a rise of the water in the well equal to one-third the dimension of the loop. This rise must be due to one of two causes—either to the jarring of the soil, which destroys the capillary equilibrium and dislodges some of the capillary water, causing it to became hydrostatic, and thus raises the level of the water in the well, or else to an actual depressing of the ground, due to loading and submergence into the ground-water surface, causing it to rise. The former view appears the more likely to be true, except that it is generally true that the heavily loaded and slowly moving freight trains produce more effect than do the more swiftly moving passenger trains.

RATE OF FLOW OF WATER INTO WELLS.

One of the most important and most practical problems connected with the flow of ground water is that of the supply of water from wells. For the supply of water for stock and country homes, for the supply of water to cities, and especially for the supply of water for irrigation through wells, there is great need of a clear understanding of the laws which govern the movement of ground water and the supply of it to wells. So little are these laws understood and applied by practical men that serious and very costly mistakes in well digging are of very frequent occurrence.

When the well for the dairy building at the University of Wisconsin was dug, for example, preparatory to placing the building over it, so little attention was given to the matter that the well was permitted to be stopped in a loose sand, it being taken for granted that with 25 feet of water in the well there must be an ample supply for all the purposes of cleaning, of washing butter, and of furnishing water for a large boiler and engine, and yet the only water the authorities had reason to expect was the amount which could rise through the small circle, 6 inches in diameter, of loose, quite fine sand, into a 6-inch casing under a very low pressure. The building was erected over the well, leaving it where it can not be deepened except at great expense, and the result was the piping of lake water half a mile at great cost, when $60 at the right time would have enabled the same well to have supplied 80 gallons of cold, pure water per minute.

In another instance, at the city waterworks at Whitewater, Wisconsin, the company was at the point of asking bids for a second well, at a cost of not less than $1,200 to $1,500, the conviction being that with some new extensions they desired to make they would need a third more water than they had been taking from their well. At this juncture the writer had occasion to request permission to test the effect of lowering the level of discharge of their well on the amount of water it would supply, this being an artesian well discharging into a reservoir. To do this it was only necessary to open a gate and lower the water in the reservoir as desired. The pumps are set so as to draw both from the reservoir and from the well at the same time, and on lowering the reservoir and working their pumps the proprietors of the works were very agreeably surprised to find that their well had more than doubled the capacity they had supposed it to possess, and the digging of the second well was abandoned. These parties had been deceived by the fact that in pumping the daily supply for the city from the top of the reservoir, and near the upper limit of discharge for the well, the water was lowered quite rapidly, and so rapidly that at this rate of lowering the extra supply they contemplated could not be obtained.

In planning the laboratory for agricultural instruction there was included in it a well to be fitted up in such a manner as to permit some of the laws of the flow of water into wells to be experimentally demonstrated. This well has a depth of 140 feet, and is cased with 6-inch well tubing to and into Potsdam sandstone.

The well extends into the sandstone beyond the casing, 20.83 feet, so that there is a surface through which the water may enter the well, supposing no fissures to exist, of 32.52 square feet, instead of the 28 square inches which was expected to supply the necessary water for the dairy building referred to above.

The drillings from this well after the sandstone had been entered were saved in order to use them for experiments in determining the laws of flow of water into wells. It is usually quite expensive and often quite difficult or even impracticable to give a well a thorough test of capacity when it is being dug, and it seems to the writer that if the materials from some wells of known capacity can be examined with a view to determining the rate at which water will pass through them under stated pressures, it may be possible to devise a method of deducing the minimum capacity of a well from the dimensions of the well and the texture of the water-bearing section. It would, of course, be impossible to predict a maximum flow under given pressure, even were the sizes of the soil grains and the pore spaces known with great exactness, because in cases of greatly fissured beds, where open seams are crossed by the well, such open fissures form indeterminate percolating surfaces, through which the water may leave the rock structure and pass by the laws of flow of water in wide channels to the wells. But if it were possible to say that the flow is sure to equal a certain rate and that it is liable not to exceed that very much, such knowledge as this would be worth a great deal and would give a basis of judgment as to whether the digging may be stopped or should be pushed farther.

In the laboratory well the casing stopped at a depth of 120 feet and beyond this the well extends to 140 feet 10 inches below the surface. At the time of the drilling, when the rock had been reached and the well had been cleaned, the balance of the drill chips and sand was saved by having the bucket emptied into grain sacks, allowing the water to strain through the walls and run away. By this method of saving the material some of the finest silt was lost, as the water was not clear when it left the sacks; the per cent of material so lost would be very small indeed, but might have a measurable influence on the rate of flow through the sand.

Four groups of samples were saved with the intention of determining the flow of both water and air through them under known conditions. The aspirator trials are given in the table which follows, but time has not permitted the measurement of the flow of water.

Effective size of sand grains in the well of the physical laboratory at the University of Wisconsin.

Sample.	Pore space.	Specific gravity.	Pressure.	Time for flow of 5,000 c. c. of air.	Effective diameter of grain.
Feet.	*Per cent.*		*Cm.*	*Seconds.*	*Mm.*
120–122.5	33.80	2.65	2.81	26,215	0.05612
122.5–127.17	33.99	2.65	2.81	13,525	.07817
127.17–133.83	31.22	2.65	2.63	8,065	.1214
133.83–140.83	30.40	2.65	2.73	2,638	.2006

Several measurements have been made of the capacity of the well in question by pumping into a tank holding 162.92 cubic feet and noting the time required to fill the tank, and at the same time measuring the amount the surface of the water in the well was lowered under the rate of pumping.

To measure the changes of level in the well during the time of pumping, one-eighth inch galvanized iron pipe was coupled together, and the joints were soldered to make them permanently air-tight. This pipe was then lowered into the well between the casing and the 4-inch discharge-pipe until its lower end was some 40 feet below the level of the water in the well. To the upper end of this pipe was connected a Bourdon water gage graduated to read feet and inches of water pressure.

By means of a lever bicycle pump air is forced into the pressure tube until all the water in the pipe is forced out, at which time the gage reading becomes constant and shows the amount of water in the well above the lower end of the pressure gage. To measure the change of level of water in the well, which may occur while the pump is at work, a record is first made of the level of the water before pumping begins, and then, from time to time as the work progresses, other readings are made, which show by their differences, when compared with the first reading, the amount of lowering which has taken place.

In the first experimental test of the well the pump was worked on a 12-inch stroke and the water was discharged into a measuring reservoir, where the amount delivered was determined at the close of the trial. The pump was worked with a 2½-horsepower gas engine, whose rate of speed was very nearly constant, so that the rate of pumping may safely be computed from the time and total amount of water pumped.

In the table which follows are given the gage readings before, during, and after pumping.

Table showing the changes of level of water in well during pumping.

Time.	Pressure.		Amount of lowering.	Time.	Pressure.		Amount of lowering.
	Ft.	*In.*	*Inches.*		*Ft.*	*In.*	*Inches.*
Before start.	47	2	....	5 p.m..........	43	10	40
8.13 a.m.....	47	2	....	5.21 p.m......	43	10	Stopped.
8.14 a.m.....	44	7	31	5.21 15 p.m...	46	2	12
8.15 a.m.....	44	4	34	5.22 p.m......	46	4	10
8.16 a.m.....	44	4	34	5.23 p.m......	46	6	8
8.17 a.m.....	44	3	35	5.24 p.m......	46	8	6
8.18 a.m.....	44	3	35	5.25 p.m......	46	8	6
9 a.m........	44	2	36	5.26 p.m......	46	8	6
10 a.m.......	43	11	39	5.31 p.m......	46	9	5
11 a.m.......	43	10	40	5.37 p.m......	46	10	4
12 a.m.......	43	10	40	5.45 p.m......	46	10	4
1 p.m........	43	10	40	5.55 p.m......	46	11	3
2 p.m........	43	10	40	6 p.m.........	47	00	2
3 p.m........	43	10	40	6.10 p.m......	47	00	2
4 p.m........	43	10	40	8.45 p.m......	47	2	0

By referring to the table, it will be seen that in one minute the level of the water fell 31 inches and in four minutes 35 inches. At the end of 167 minutes the level had become constant, with a drop of 40 inches below the normal. The engine was stopped after a run of nine hours and eight minutes, and the amount of water pumped was 1,163 cubic feet, or at the mean rate of 2.122 cubic feet per minute.

The total depth of percolating surface was as follows:

Table showing thickness of water-bearing beds and effective diameter of grains of sand in sandstone.

Thickness of stone.		Effective diameter of grain.
Ft.	*In.*	*Millimeters.*
2	6	0.05612
4	8	.07817
6	8	.1214
7	0	.2006
Total. 20	10	

The total area of percolating surface will therefore be

$$0.5 \times \pi \times 20.833 + \left(\frac{.5}{2}\right)^2 \pi = 32.92 \text{ square feet.}$$

The mean rate of flow, therefore, when expressed in cubic feet per square foot of percolating surface, is

$$\frac{2.122}{32.92} = .06447 \text{ cubic feet per minute.}$$

Three other trials were made, one following the other on the same date between 11.47 a. m. and 6.31.45 p. m., the pump being driven at different speeds by changing the length of stroke.

Observed flow of well under different heads.

	9-inch stroke.	6-inch stroke.	12-inch stroke.
Water pumped ....cubic feet..	163.82	165.744	163.244
Time of pumping..............minutes..	101.	165.75	81.75
Rate of pumping per minute..cubic feet..	1.622	1.00	1.996
Extreme lowering of water.....inches..	26.5	16.	35.
Mean flow per square foot of percolating surface...cubic feet per minute..	.04921	.03038	.06063

In these trials the pumping with the 9-inch stroke was done first, and with the 12-inch stroke last.

In these three trials of pumping only those with the 9-inch and 6-inch strokes persisted long enough to bring the water in the well down to a constant level. In the first trial, however, with the 12-inch stroke, the surface had become constant after falling 40 inches. It will be interesting to observe whether, in these cases, the measured flow is proportional to the amount the water has been lowered in the well. By dividing the mean rate of pumping per minute, which is the flow, by the amount the water was lowered in each case, which is the pressure, we get

$$\text{For the 12-inch stroke } \frac{2.122}{40} = .05305.$$

$$\text{For the 9-inch stroke } \frac{1.622}{26.5} = .06121.$$

$$\text{For the 6-inch stroke } \frac{1.}{16} = .06250.$$

From these results it appears clear that the flow does not increase as rapidly as the pressure increases, pressure being understood to mean the amount the water is lowered in the well; and when the departures are expressed in percentages the amounts stand 2.06 for the 9-inch stroke and 15.12 for the 12-inch stroke too small.

In view of the practical importance of definite knowledge regarding the flow of water into wells, the writer submitted to Professor Slichter the set of problems of Series B, which are stated in the introduction, and below are given results of these computations so far as they were made.

In Problem I, Series B, a stratum of water-bearing sandstone 200 feet thick was assumed, having a pore space of 32 per cent and an effective size of grain of 0.25 mm., and it was required to find the theoretical flow into a 6-inch well extending 100 feet into the rock when the water in the well was lowered by pumping 4, 8, 12, 16, and 20 feet. The results which Professor Slichter found are given in the table below:

Problem I, Series B.

Depth of sandstone.	Amount the water is lowered in well.	Pore space of sandstone.	Capacity per minute.	Depth of well.
Feet.	*Feet.*	*Per cent.*	*Cubic feet.*	*Feet.*
200	1	32	1.8483	100
200	2	32	3.9666	100
200	4	32	7.2932	100
200	8	32	14.7864	100
200	12	32	22.1796	100
200	16	32	29.5728	100
200	20	32	36.966	100

It will be seen that the increase of flow into the well is made directly proportional to the amount the water is lowered in the well, but if the direct observations which have been cited can be relied upon, it follows that for the higher heads in the table the results are too large.

It may be that the departure from the theoretical increase which has been observed is in part due to an incorrect value assumed in equation (9), page 360, of Professor Slichter's paper, for the distance from the walls of the well at which the pressure remains undisturbed or is essentially normal and which is there taken at 600 feet. This suggestion is made in view of the fact observed as given on page 277, that the level of the water may be lowered by even moderate pumping at a distance of 1,133 feet away from the walls of the well.

The general fact that the capacity of a well is increased in a high degree the more the water is lowered in it is indicated both by observation and theory, and should be kept in mind by both well drillers and pump men. The first should see to it that he has left the bottom of his well sufficiently far below the normal level of the ground water to permit of lowering the water through considerable ranges, and the second should see that the cylinder of the pump is so placed as to make it possible to utilize the full depth of the well.

In Problem II, Series B, the object was to show the influence of the diameter of the well on the amount of water it may yield. This is important in view of the fact that the cost of a well increases rapidly with its diameter, both on account of the labor involved and the expense of curbing or casing.

With a well sunk 100 feet in 200 feet of water-bearing rock, having a pore space of 32 per cent and an effective size of grain of 0.25 mm., what will be the flow when the diameter of the well is made 2, 6, and 12 inches? Professor Slichter finds that if the size of the discharge pipe does not offer material resistance to the flow of the water the capacities of the three wells will be, in cubic feet per minute:

2-inch diameter.	6-inch diameter.	12-inch diameter.
31.90	36.94	41.45

These figures indicate that the 6-inch well discharges only 15.8 per cent more than the 2-inch well, while the 12-inch well discharges only 26.07 per cent more.

It is frequently urged that since the flow of water through pipes increases with the squares of their diameters, a 12-inch well should have a capacity equal to four 6-inch wells, but the difficulty here lies in not taking into consideration the influence of the sand itself on the rate of flow into the well.

It will readily be understood that if a given water-bearing bed can permit a flow of only 2 cubic feet per minute into a well 12 inches in diameter, a 2-inch well will easily handle nearly all the water such a rock can supply, for the 2-inch well will be able to collect 1.626 cubic feet per minute.

There are other considerations, however, which determine what the diameter of a well must be when the water must be pumped, for then such dimensions must be chosen as will permit the use of pumps of sufficient capacity to utilize the full flow of the well, and when the water is considerable distance below the surface of the ground the size of the cylinder which will deliver the water sought must fix the diameter of the well to the depth at which it must be placed.

Then, too, in the case of flowing wells, if the pressure of the well is strong, and especially if the well is deep, the friction on the walls of a small drill hole or casing becomes so large that here the diameter affects the capacity of the well in accordance with the laws which govern the discharge of water through large pipes, and a too small casing may in such cases greatly reduce the amount of really available water.

As wells of considerable diameter are sometimes dug for the convenience of placing and working irrigation pumps and to serve in part as storage reservoirs in the case of waterworks for towns, the third phase (*b*) of Problem II, Series B, was proposed. This requires the flow into a well 20 feet in diameter sunk 22 feet into the supposed water-bearing sandstone when the level of the water in the well is lowered 20 feet. The solution gives as the amount supplied 46.12 cubic feet per minute, which is 1.2485 times that of the 6-inch well when sunk to the depth of 100 feet in the same rock.

It is frequently sought to increase the capacity of such a well as the one last considered by sinking, in the bottom of the large one, one or more of small diameter, and the problem (*c*) of Problem II, Series B, was proposed to meet these cases. This problem requires the total flow into such an open well as the last, which has put down in it one, two, and three 6-inch wells extending entirely through the supposed water-bearing rock, namely, 200 feet. Solving this problem, Professor Slichter finds the following results:

	Cubic feet per minute.
Large open well alone	46.12
Large well with one 6-inch well	110.2
Large well with two 6-inch wells 5 feet apart	125.2
Large well with two 6-inch wells 10 feet apart	130.1
Large well with three 6-inch wells 5 feet apart	136.6
Large well with three 6-inch wells 10 feet apart	142.3

He concludes, further, that if the wells are placed in one straight line 10 feet apart the middle well will flow 4 per cent less than either of the end wells, and if 5 feet apart 7 per cent less.

In order to show the influence on the capacity of a well of sinking it to different depths into the water-bearing formation, Problem III, Series B, was proposed, in which the assumptions are the same as in Problem I of this series, except that the well penetrates the water-bearing bed 4, 8, 12, 16, 20, 40, 80, 100, and 200 feet. The results which he finds under an effective head of 10 feet are given in the table which follows:

	Depth of well in feet.								
	4.	8.	12.	16.	20.	40.	80.	100.	200.
Flow in cubic feet per minute	1.003	1.818	2.544	3.265	4.08	7.68	14.88	18.49	36.02

It will be seen that in this case the flow does not increase in a ratio which is proportional to the depth, but rather that the flow is relatively more rapid in the shallow wells than it is in the deeper ones. This is in part due to the fact that in the shallower wells the water has an opportunity to rise upward and approach the well from below, while in the well which penetrates the whole formation the lines of flow must all approach in parallel planes, provided the structure of the rock is homogeneous.

It is never true, however, that a water-bearing horizon is uniform in texture, and the results which have been cited from Newell's work demonstrate in a forcible and conclusive manner that generally the flow into a well along the bedding planes or planes of stratification is much more rapid than when the flow takes place across them, as must be true when the water approaches the bottom of the well from below. It will necessarily be true that where beds of coarse- and fine-grained material alternate with one another, and are penetrated by a well, the largest volumes of water will approach the well through the coarser layers, and this will be true not only because it is coarser grained but also because the reduction of pressure will be greater and farther reaching in the coarser layers; and this being true the water will necessarily flow out of the beds of finer texture into those of coarser texture and will approach the well along these planes of less resistance. It is not possible, therefore, to compute the flow of water into a well penetrating a series of beds of different textures without taking into consideration the flow which will take place from the finer beds into the coarser ones.

These considerations bring out in their true light the great importance of the beds and veins of coarse-grained materials which a well may penetrate, and show the importance of utilizing them by bringing the well into good connection with them. It will be readily seen that, when the casing of a well is carried down into a water-bearing horizon, and is not perforated throughout its entire length, it is quite possible for the end of the pipe or the perforated portion of it to be stopped in one of the finer-grained layers, thus compelling the water to leave the coarse-textured bed to pass through one of finer character before entering the well, and exactly reversing the conditions which should be sought, namely, the flow of water from the fine beds into the coarser ones, through which the approach to the well may be made.

The principle of flow to which attention is here called appears to furnish an explanation for the phenomena to which Newell refers in his paper, which has been quoted earlier in this paper. He says in his conclusions:

> These experiments and others of similar character all indicate that at constant pressure oil and water, even the purest, tend to clog up the rock through which they are passing. If this holds true for greater thicknesses and pressures, then it may be one of the causes of the diminishing flow of wells; for not only would the output slacken from lessened gas pressure (as it is shown that the flow diminishes as the pressure), but the rock becomes less able to transmit the oil.

The inference appears legitimate that whenever the pressure is reduced in a coarse textured layer of a water-bearing series, as it is by pumping, and the flow of water sets out of the finer beds into it, as a consequence, sediments are liable to be carried with it from the finer beds, which, in time, would reduce the pore space of the coarser beds, and thus diminish the flow to an appreciable extent. This tendency is intensified by the fact that in the material of finer pore the pressures are relatively higher and the velocities actually greater, and thus capable of moving materials which before the changed conditions had become stationary, and thus carry them out into the slower moving streams of the more open rock to be again deposited and to produce clogging. Then, too, in the stronger currents which concentrate in the local veins and fissures and lead into the coarser layers materials which before were stationary may, under the new conditions, be carried forward to where they may reduce the flow of the well below that at which it first discharged.

In Problem IV, Series B, the conditions are similar to those of Problem III, except that here the depth of the well remains constant while the thickness of the water-bearing beds is increased.

It is required to find the flow from a 6-inch well extending 20 feet into a sandstone when the thickness of water-bearing rock below the well is increased from 0 to 400 feet. Professor Slichter's results are as follows:

Flow of 6-inch well 20 feet deep, with varying thickness of water-bearing sandstone beneath bottom of well.

Distance from bottom of well to bottom of water-bearing rock.	Computed total flow per minute.
	Cubic feet.
0	3.60
1 foot	3.72
2 feet	3.76
4 feet	3.78
10 feet	3.83
20 feet	3.86
40 feet	3.91
80 feet	4.00
100 feet	4.05
200 feet	4.06
400 feet	4.07
600 feet	4.07

Theoretical considerations appear to indicate that the depth of sandstone below the bottom of a well may continue to increase its capacity until a depth of 400 feet is passed, when there is no further increase.

There will, of course, be limitations to problems of this sort similar to those which have been pointed out for the preceding case.

It may be said as a general conclusion that in all of those cases where indurated rock makes up the entire water-bearing series and where all of the water of the formation is known to be "sweet" there is little danger of going too far, and that the capacity will be greater the deeper the well is made.

Problem V of Series B is the only other one of those proposed for Professor Slichter's consideration which he has solved, and the results are given in full on page 367 of his paper, to which the reader is referred. The reader is also referred to his paper for such solutions as have been attempted regarding the interference of wells, and for the number of wells which may be put down in a given area of a water-bearing horizon.

CAPACITY OF WELLS UNDER DIFFERENT CONDITIONS COMPUTED FROM OBSERVED FLOWS IN THE LABORATORY WELL.

It will now be desirable to apply the theoretical conclusions presented to the data derived from experiments with the laboratory well.

It is shown on page 283 that under the highest head used on the well—40 inches—the mean flow per inch of head is 0.05305 cubic foot per minute, or 0.6366 cubic foot per foot of head. Adopting Professor Slichter's assumption that the flow increases directly as the head, we shall have, for different pressures, the following computed results:

Table showing flow under different pressures computed from observed flow under 40 inches water pressure.

Pressure.		Flow per minute.	
Pounds.	Feet.	Cubic feet.	Gallons.
0.43	1	0.6366	4.762
4.33	10	6.366	47.62
8.66	20	12.732	95.23
12.99	30	19.098	142.90
17.33	40	25.464	190.50
21.66	50	31.830	238.10
43.33	100	63.660	476.20
86.66	200	127.320	952.30
173.33	400	254.64	1,905.00

If, now, it is assumed that the capacity of this well is increased in a ratio directly proportional to depth, the following should be expected:

Table showing increase of flow with depth computed from observed flow of laboratory well.

Percolation depth.	Flow in gallons per minute under a head of—			
	1 foot.	10 feet.	20 feet.	30 feet.
′ ″				
20 10 × 1	4.762	47.62	95.24	142.86
20 10 × 2	8.8097	88.097	176.194	264.291
20 10 × 3	12.8574	128.574	257.148	385.722
20 10 × 4	16.9051	169.051	338.102	507.153

The results in this table assume that the flow which comes from the sandstone below the bottom of the well is, for each case, 10, 20, and 30 times what it is for the 1-foot pressure, and that it does not increase with the depth of the well; but in order that this may be true it must also be assumed, according to Slichter's results, that there is always a depth exceeding 400 feet of sandstone below the bottom of the well. The amount of water coming from the sandstone below the bottom of the well is taken as 15 per cent of the whole amount of flow at the observed depth of 20 feet 10 inches.

The results in these two tables appear large enough to agree with many of the observed flows from other wells under similar conditions.

The data obtained from the experiment and from the aspirator trials of the well drillings were submitted to Professor Slichter for him to compute the theoretical flow, and the results obtained by him are as follows: Assuming that the well penetrates the whole water-bearing bed, the flow is 1,673 c. c. per second, but if the lower layer of the well extends indefinitely below the bottom, the flow is increased by 299.8 c. c. per second. This would make the total flow 4.181 cubic feet per minute, which is too large by the amount

$$4.181 - 2.122 = 2.059 \text{ cubic feet,}$$

or is about double the observed flow.

In the table of theoretical flows on page 284, giving the results for Problem I, Series B, a 6-inch well 100 feet deep, in 200 feet of water-bearing sandstone, coarser than that in which the observed well is located, the computed flow in cubic feet per minute for 30 feet of pressure is given as 36.966 cubic feet per minute, while that computed from the observed flow is 56.02 cubic feet per minute.

FLOW OF WATER INTO DRIVE-WELL POINTS.

On account of the fact that drive-well points are used to a considerable extent in well construction, it appeared desirable to have some definite observations on the rate of flow through sands into these. In order to get results relating to the rate at which water may be discharged through drive-well points three pieces of apparatus were constructed, having the form shown in fig. 52.

These pieces consisted of three of the Gould well points No. 50, No. 80, and No. 90, with screens 18 inches long and with an inside diameter of 1¼ inches. Sections of 6-inch galvanized-iron pipe were provided with caps, one of which was tapped to receive the well point and discharge pipe A, a supply pipe B, and a cock for pressure gage C. The upper and lower ends of the cylinders were connected by a three-fourths-inch pipe D to introduce water at both ends, and the open ends of these pipes were covered with screens to prevent the entrance of sand.

The No. 50 apparatus was filled with a screened sand having a diameter of 0.2941 mm., No. 80 with a similar sand having a diameter of 0.1717 mm., and No. 90 with sand having a diameter of 0.09531 mm.

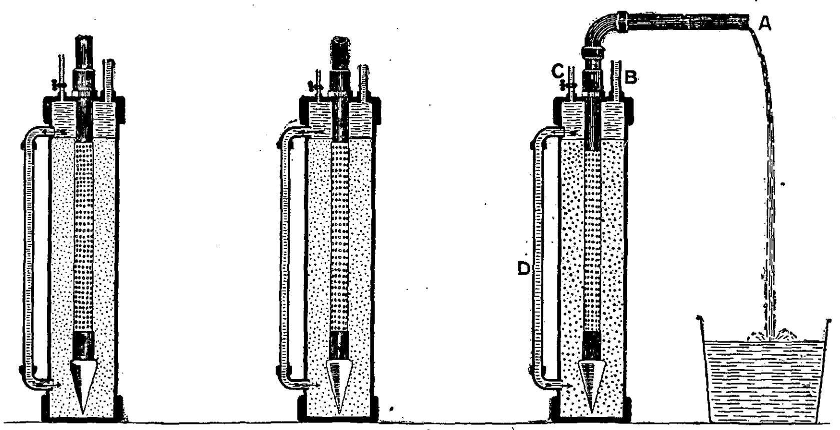


FIG. 52.—Apparatus used in demonstrating rate of discharge from drive-well points. A, discharge; B, supply; C, pressure gage.

Under these conditions the flow of water through the several pieces was measured under different pressures and the results of a portion of these trials are given in the table which follows:

Table showing the observed rate of flow of water through three drive-well points under different pressures.

Drive-well point No. 50.			Drive-well point No. 80.			Drive-well point No. 90.		
Mean pressure of water.	Mean discharge per minute.	Flow divided by pressure.	Mean pressure of water.	Mean discharge per minute.	Flow divided by pressure.	Mean pressure of water.	Mean discharge per minute.	Flow divided by pressure.
Feet.	*Pounds.*		*Feet.*	*Pounds.*		*Feet.*	*Pounds.*	
3.646	9.63	2.641	4.777	4.475	0.9369	9.256	2.67	0.2885
8.958	25.64	2.862	8.104	10.960	1.352	21.937	5.38	.2452
6.895	27.185	3.972	9.5745	12.20	1.275	21.64	6.6625	.30795
5.337	24.08	4.572	9.928	17.32	1.745	35.35	9.25	.2617
11.85	42.72	3.668	30.723	28.04	.9576	45.38	11.965	.2637
16.91	41.59	2.4655	41.735	33.22	.7960	45.45	14.005	.3083
14.945	48.645	3.275	45.366	36.346	.8016	55.14	15.305	.2775
12.69	37.07	2.969	31.96	25.97	.8125	33.86	11.34	.3349
....	....	....	....	....	....	33.60	9.81	.2940
*a*10.153	*a*32.07	*a*3.2955	*a*22.771	*a*21.066	*a*1.0846	*a*33.486	*a*9.5995	*a*.28686

a Average.

If we compare the mean flows divided by the pressures in the three cases, they stand

No. 50.		No. 80.		No. 90.
1	to	3.008	to	11.49

while the squares of the diameters of the sand grains stand

1	to	2.932	to	9.52

showing that there has been an approximation to the flow as expected from the laws of capillary tubes.

In another set of trials the following relations of flow to pressure were found, the time of flow in each case being one minute.

Table showing observed rate of flow of water through drive-well points under different pressures.

	No. 50.	No. 80.	No. 90.
	Pounds.	*Pounds.*	*Pounds.*
Flow for 30-foot pressure	56.70	27.97	10.72
Flow for 3-foot pressure	5.72	3.82	.992

If the flows observed in the first table are expressed in cubic feet per minute for a pressure of 10 feet they will stand, for No. 50, 0.5268 cubic foot; for No. 80, 0.1738 cubic foot; for No. 90, 0.04596 cubic foot.

If the length of the points were increased to 10 feet, then the flows would be for 10 feet pressure, for one minute, No. 50, 7.024 cubic feet; No. 80, 2.317 cubic feet; No. 90, 0.6128 cubic foot.

RATE OF PUMPING FROM DRIVE WELL COMPARED WITH RATE FROM OPEN WELL.

Another test was made with the No. 50 well point by connecting it with a common suction pump in the manner represented in fig. 53, so that it could be worked under more nearly normal conditions and so that the working of the pump could be compared with open-well conditions. It was found that a point of this size could not deliver water to the pump as rapidly as needed when worked with the ordinary speed for hand service. The cylinder was 2½ inches in diameter and from the open reservoir would fill an ordinary pail with 20 strokes; but when the water was drawn through the well point it required 35 strokes at the same rate to raise the same amount of water, while the labor of raising it was much more. The increased labor was due to the fact that the water came in too slowly to fill the cylinder behind the piston as rapidly as the piston was raised and as a vacuum was formed behind it.

The drive-well point, with pumps to be worked by hand, is only adapted to circumstances where small amounts of water are desired. Where water must be obtained in beds of loose sand with the larger forms of well points, having diameters sufficiently large to permit the suction pipe of the pump to be placed inside of them, the conditions become the same as those of a drilled well of similar dimensions.

It must be remembered that the best method of increasing the capacity of the point is to increase its length. Where an open well can be dug to the water and then one or two 10-foot lengths of 6-inch points sunk below this into the water-bearing beds, so that a large suction pipe can be lowered well down toward the bottom of the casing, large quantities of water may be secured if the water-bearing sands are reasonably coarse.

It is never desirable to make the well point a part of the suction pipe if considerable quantities of water are to be raised, for the reason that a heavy shock comes upon the pump with every stroke, owing to the necessity of filling the point with new water from the ground as rapidly as the piston is raised. When the point is larger and open, the water can fall outside to relieve the shock which otherwise would come and there is less chance for a shock on the back stroke in rapid pumping.

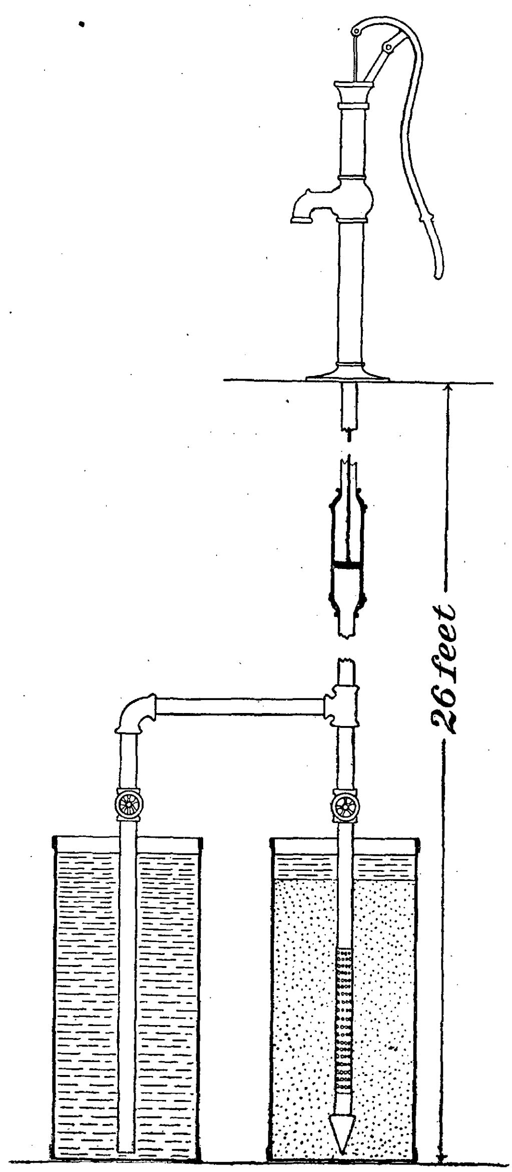


FIG. 53.—Apparatus used in comparing the rate of pumping from a drive well and from an open well.

ACKNOWLEDGMENTS.

An effort has been made to make proper acknowledgments generally in the body of this paper wherever they are required. There are certain others, however, which may best be made here.

It is desired especially to acknowledge indebtedness to Mr. A. M. Troyer and Prof. A. R. Whitson for very careful and conscientious work in securing much of the experimental data which have been presented in this paper.

It is further desired to express appreciation of the work which Professor Slichter has done, especially of that portion which he undertook, without compensation, in the earlier stages of this investigation.

THEORETICAL INVESTIGATION OF THE MOTION OF GROUND WATERS

BY

CHARLES S. SLICHTER

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THEORETICAL INVESTIGATION OF THE MOTION OF GROUND WATERS.

By Charles S. Slichter.

INTRODUCTION AND SUMMARY.

The following pages contain a theoretical investigation of the general problem of the flow of water through porous soils or rock.

In Chapter I an attempt is made to derive from purely theoretical considerations an expression for the flow of water or other fluid through a column of soil made up of grains of nearly uniform size and of approximately spherical form. For the purpose of constructing this formula, a study is made of the pores of the ideal spherical-grained soil, and the relation of porosity to the average arrangement of the grains is shown, and made a factor in the resulting formula. I derive as the formula for the quantity of water per second transmitted by a column of soil the following expression:

$$q = [1.0094] \frac{p\, d^2\, s}{\mu\, h\, \mathrm{K}} \text{ cubic centimeters per second,}$$

in which—

q is the quantity in cubic centimeters;
p is the difference in pressure at the ends of the cylinder in centimeters of water at 4° C.;
d is the mean diameter of soil grains in centimeters;
s is the area of cross section of the cylinder in square centimeters;
h is the height of the column of sand in centimeters;
μ is the coefficient of viscosity of the fluid;
K is a constant taken from Table II;
[1.0094] is the logarithm of a factor.

Measuring q in cubic feet, p in feet, h in feet, s in square feet, and d in millimeters, this formula becomes:

$$q = [9.3036-10] \frac{p\, d^2\, s}{\mu\, h\, \mathrm{K}} \text{ cubic feet per minute,}$$

and for water at 10° C. this becomes

$$q = [1.1846] \frac{p\, d^2\, s}{h\, \mathrm{K}} \text{ cubic feet per minute,}$$

in all of which the brackets inclose the logarithm of a factor.

I also attempt to derive a formula for determining the effective size of soil grains by measuring the amount of air that an aspirator will draw through a given column of the soil in a given time. The object of this work is to make possible a method for determining the capacity of a soil to transmit water, which may prove simpler and more satisfactory than the usual method of soil analysis by means of sieves of known mesh.

I derive as the formula for determining by means of an aspirator the diameter of the average-sized soil grain in a given sample:

$$d^2=\frac{Kh}{spt}\,[8.9434-10],$$

in which t is the time in minutes necessary to draw 5,000 cc. of air of temperature 20° through the soil, under an average pressure of p cm. of water at 20°. The constant K is to be taken from Table II, d and h are to be measured in centimeters, and s is to be measured in square centimeters.

The aspirator method of determining the diameter of soil grains was first suggested by Prof. F. H. King, and it was at his request that I undertook to work out the appropriate formulas. As this paper goes to press, Professor King's paper describing his method of soil analysis has just appeared. The following table, taken from his paper,[1] may be regarded as an experimental test of both the formulas above given:

Table showing observed and computed flow of water through simple sands of different diameters under a pressure of 1 cm. of water.

Grade of sand.	Diameter of grains.		Flow of water through the sample.		
	By counting and weighing.	By aspiration of air.	Observed.	Computed from aspiration diameter.	Computed from count and weight diameter.
	Mm.		*Grams.*	*Grams.*	*Grams.*
8.......	2.755	2.54	2,296	2,277	2,680
7.......	1.993	1.808	1,080	1,132	1,372
6.......	1.588	1.451	756	757	909.1
5½.......	1.345	1.217	542	522	638.6
5.......	1.157	1.095	504.6	453.2	499.6
4.......	.976	.9149	329.2	297.5	326.6
3.......	.8017	.7988	210	193	194
2.......	.6653	.7146	138.6	122	106.2
1.......	.5824	.6006	94.8	80.6	75.7
0.......	.4891	.5169	72.3	66.8	59.8

[1] F. H. King, A new method for the mechanical analysis of soils: Fifteenth Ann. Rept. Agric. Exper. Station Univ. Wisconsin, Madison, 1898, p. 123.

Professor King says further:

When it is observed that the flow of air through the sample of sand was not the identical sample through which the flow of water was measured and that it was in a different piece of apparatus, and further, that the flow of fluids through soils varies, theoretically, as the squares of the diameters, it will be conceded that, while there is not as close an agreement between the observed and the computed results as could be wished, the agreements are so close as to show that for such materials there is much more than a chance agreement. It will be seen further that in general there is a closer agreement between the observed flows and those computed from the aspirator diameters than with those computed from the count and weight diameters.

In Chapter II of the paper I investigate the general problem of the movements of water in soils and rock. I find that the problem is capable of mathematical treatment, and I show that the question is analogous to a problem in the conduction of heat or electricity, or to any other problem involving a transfer of energy. I show that there exists in the case of ground-water movements what is known as a potential function, from which we may derive, in any determinate problem, the velocity and direction of flow, and the pressure at every point of the soil or rock. The existence of the potential function is made the basis of much of the work that follows.

Chapter III contains applications of the general principles established in Chapter II to cases in which the flow of ground waters is approximately in horizontal planes. The problems worked out are mostly of use in illustrating qualitative results rather than of application to quantitative problems. It is shown in case of plane motion of ground waters that the lines of flow and lines of equal pressure always constitute an orthogonal system of curves, and a number of drawings illustrating this point are given in the text.

In Chapter IV I attempt to discuss some cases of motion of ground waters in which vertical motion takes place. In the discussion of these problems the fact appears that a change of pressure may be brought about throughout a water-bearing medium without changing the level of the water table, and the conclusion is forced upon us that an interference with wells and underground water supply may take place without much general disturbance of the water table in the immediate neighborhood of the disturbed wells and shortened underground supply.

The problem of the flow of wells is discussed in Chapter V. The formula found for the capacity of an artesian well which completely penetrates the water-bearing strata is as follows:

$$f=\frac{2\pi\ h\ (k_1 a_1+k_2 a_2+\ldots\ldots)}{\log_e (1+600/r)}\ \text{cubic feet per minute,}$$

in which h is the amount in feet that the water is lowered by pumping, r is the radius of the well in feet, and a_1, a_2, . . . are the thicknesses in feet of the various strata, and k_1, k_2, . . . are the constants depending upon the transmission capacity of the various strata. The symbol $\log_e$ calls for the natural or hyperbolic logarithm. It is also shown that the capacity of a well is not largely influenced by the size of the bore, except as the flow is controlled by pipe friction.

The flow from a well which does not completely pass through the water-bearing strata is found to be given by a formula similar to the above, but containing the additional term—

$$2.5\pi\ k_n hr,$$

in which k_n is the transmission constant for the bottom stratum.

The interference of two, three, and several wells with one another is investigated and results are given in tabular form, illustrating the conclusions reached. Diagrams of lines of flow are given for several cases, and a method is explained by which the lines of flow into any number of interfering wells, however placed, may be constructed upon the drafting board.

CHAPTER I.

LAWS OF THE RECTILINEAR FLOW OF GROUND WATER THROUGH A SOIL.

1. The rectilinear flow of a viscous fluid through a soil made up of grains of nearly uniform size and of approximately spherical form will now be investigated. It is true, of course, that few water-washed sands actually approach the condition of uniformity of size and sphericity of form that it will be necessary to hypothecate for the ideal soil which is to be made the subject of investigation in this chapter. Nevertheless, in taking account of the important elements of structure in a medium which is made up of a mass of spheres, we are probably considering in their due proportion the different factors that control the water movements in a well-sorted sand, and notwithstanding the great variety in the sizes and arrangements of contiguous grains in a natural sand, there probably exists a tendency in every such soil toward a certain average size and mean arrangement of grains which the theory of probabilities would justify us in setting up as an ideal soil to replace a given soil in the investigation of its hydraulic properties. It would probably be admitted that no matter how complex a soil may be, there exists a certain ideal soil of uniform spherical grains that will transmit under given conditions the same amount of water that would be transmitted by the complex soil. The size of the grains of this ideal soil of same transmission capacity as the complex soil we shall call the "effective size" of grain of the complex soil. How far a soil may retain its complexity and irregularity and yet be replaceable for hydraulic purposes by an ideal soil of uniform spherical grains can be determined only by experiment.

It is certain that no theoretical investigation which does not take account of the various degrees of porosity that may be shown by the same soil under different circumstances can be complete. On the other hand, I shall be amply satisfied with the results of the investigation of this chapter if it shall lead to an approximately correct expression for that factor in the formula of flow which depends alone upon the porosity of the soil.

Suppose that we have a cylinder of cross section s and of height h, filled with a soil of the kind described, and let the two ends of the cylinder be of a material (as wire gauze) permitting the free passage of water or other fluid. We shall investigate the flow through the cylinder when a given difference of pressure is maintained at the ends.

2. The fluid must pass from one end of the cylinder to the other through pores which are approximately triangular in section. The size of these pores depends both upon the size of the grains and upon the compactness of the packing of the material. In order to study the nature of the pores, we may separate out from the mass of the soil eight contiguous grains in such manner that the lines joining their centers form an equilateral parallelopiped or rhombohedron, as represented in fig. 54, in which the white rods mark the position and direc-

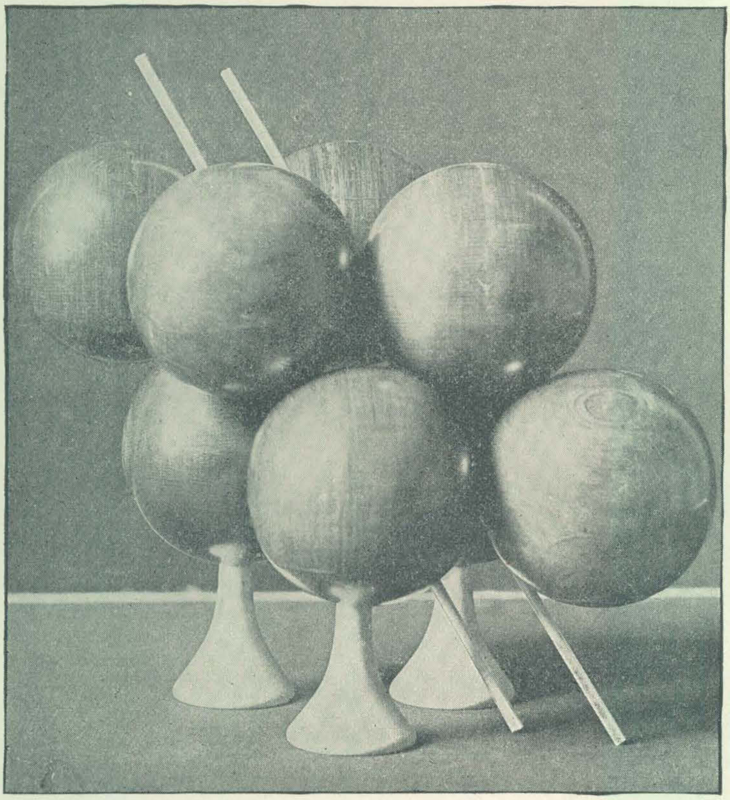

FIG. 54.—Unit element of a mass of spheres packed in the most compact manner possible. Face angles 60° and 120°.

tion of two of the pores. By studying the properties of the pores of this rhombohedron we may arrive at the properties to be assigned to the pores of the entire mass of soil, since this rhombohedron constitutes the element of volume, or the unit element, which, if repeated, will give the entire mass of soil.

If the grains of soil are arranged in the most compact manner possible, each grain will touch surrounding grains at twelve points, and the element of volume will be a rhombohedron having face angles equal to 60° and 120°. If the grains are not arranged in the most compact manner the rhombohedron will have its face angles greater than 60°, and each sphere will touch other spheres in but six points, but will nearly touch in six other points. The most open arrangement of the soil grains which is possible with the grains in contact is had when the rhombohedron is a cube.

Fig. 56 represents a section of four spheres packed in the closest manner possible, and fig. 57 represents a similar section when the packing is

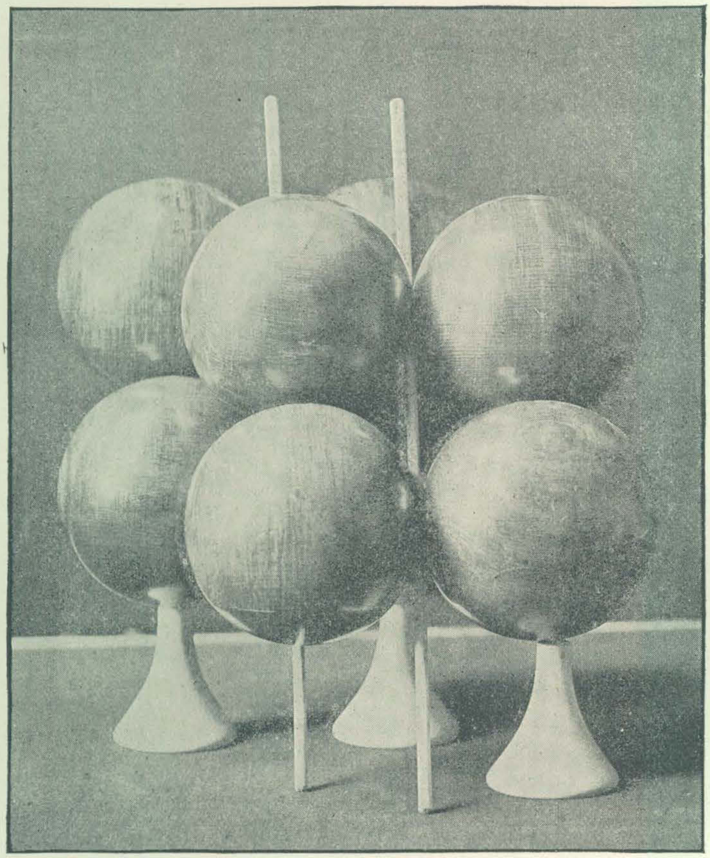

FIG. 55.—Unit element of a mass of spheres packed in the most compact manner possible. Face angles 90°, 60°, and 120°.

not so close. In fig. 56 the angle θ is 60°, and in fig. 57 θ is about 65°. Fig. 54 represents a perspective view of eight spheres, which are packed together in the closest manner possible. All eight faces of the mass shown in this diagram are alike, each face being made up of four spheres, which form a rhombus of face angles 60° and 120°. Fig. 55 shows eight spheres placed together in the most compact manner possible, in which the faces, however, are not all rhombuses, but in which two opposite faces are made up of four spheres arranged at the corners of a square, the other six faces being the same as in fig. 54. Fig. 55 is essentially the same as fig. 54, as the arrangement in fig. 55 can be made from the arrangement of fig. 54 by displacing the upper spheres one place, leaving the lower spheres unchanged. Three plane sections of the arrangement shown in fig. 54 will give a square arrangement of four spheres, two of these sections passing through diagonally opposite edges of the rhombohedron, and one section passing through the similar diagonals of a pair of opposite faces. No section of the arrangement shown in fig. 55 will give a square arrangement of spheres, these square arrangements occurring as faces in this case.

Fig. 58 shows the rhombohedron formed by joining the centers of the spheres of fig. 54. Fig. 59 shows the interior or unoccupied space

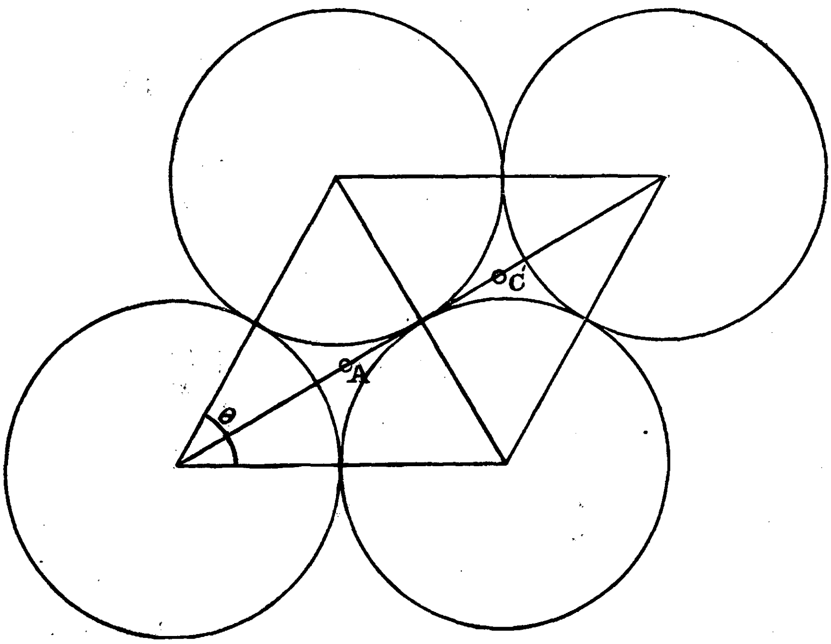

FIG. 56.—Section of four contiguous spheres in most compact packing of a mass of spheres.

of the rhombohedron of fig. 58. It is, in fact, a plaster cast of the interior of the solid shown in fig. 58. If the solid shown in this figure be repeated in all the directions of space, the continuous pores of a mass of spheres will be represented.

If we imagine a soil made up of particles arranged so that the lines joining their centers form cubes, the percentage of open space to the whole space, or the so-called porosity, can be found by dividing the difference between the volume of a sphere and the volume of the circumscribed cube by the volume of the circumscribed cube, which gives

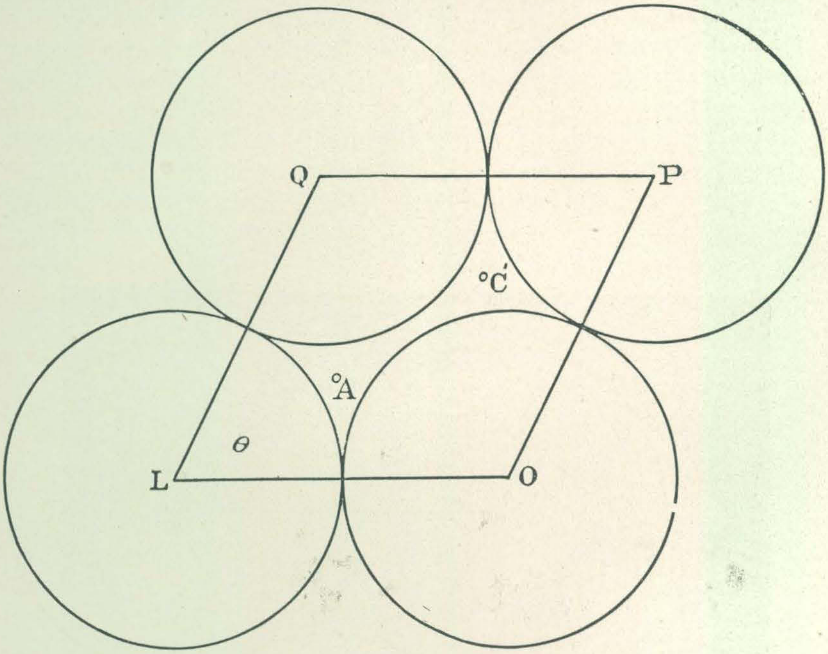

FIG. 57.—Section of four contiguous spheres in a somewhat open packing of a mass of spheres.

a porosity of 47.64 per cent. If the particles are arranged as compactly as possible, as in fig. 54, the percentage of pore space can be

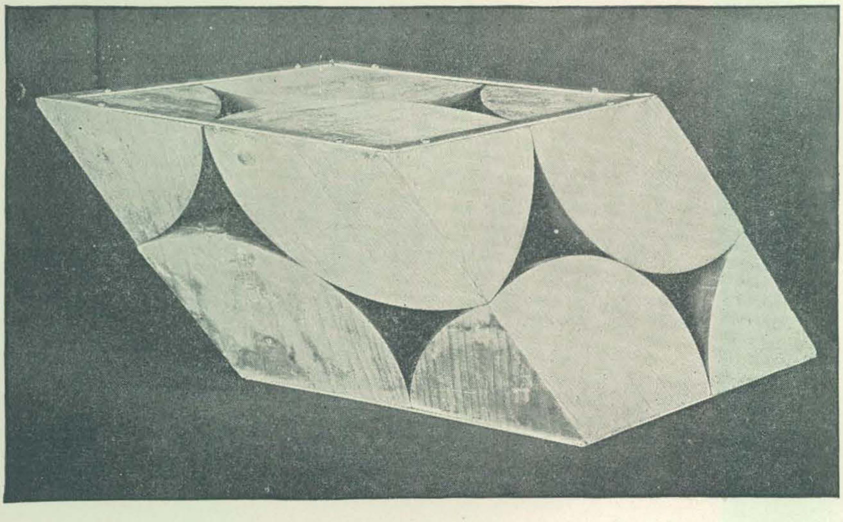

FIG. 58.—Unit rhombohedron formed by passing planes through the centers of eight contiguous spheres in the most compact packing of a mass of spheres.

found by dividing the difference between the volume of a sphere and the volume of the rhombohedron whose acute face angles are 60°, and whose edges equal the diameter of the sphere, by the volume of this rhombohedron, which gives a porosity of 25.95 per cent. This fact is shown nicely by considering that the pieces of eight different spheres which make the rhombohedron of fig. 58 can be placed together so as to make the sphere shown in fig. 60. It is plain that the eight pieces would make a complete sphere even if the face angle θ had not the value 60°, but had any other value less than 90°. If we measure the porosity of a soil composed of grains of nearly uniform size, we shall find a large variation in the results, depending largely upon the manner in which the soil was packed; but usually the porosity will lie

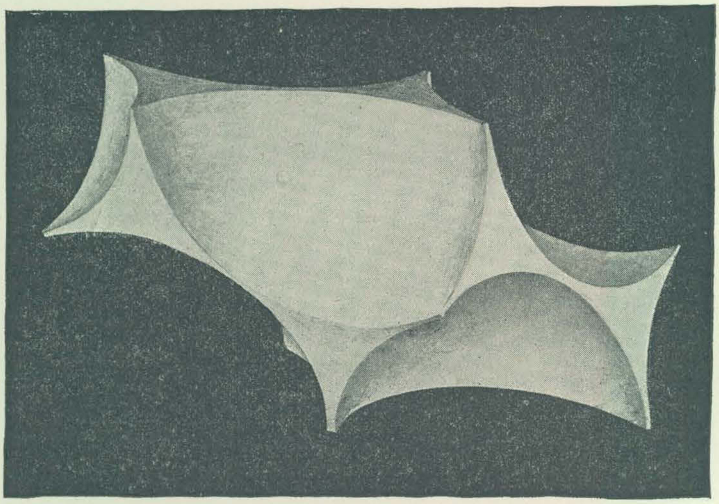

FIG. 59.—Unit element of the pore space in a mass of spheres packed in the most compact manner possible. A plaster cast of the interior of the rhombohedron of fig. 58. The spheres were not quite in contact, their surfaces being separated about one-half centimeter.

within the limits that we have pointed out. The porosity of the element of volume of the ideal soil depends upon the acute face angle of the faces of the rhombohedron. If a given soil shows, on measuring, a porosity equal to m, we may assume, by the theory of probabilities, that the element of volume which has porosity m occurs in that soil more times than an element of volume having any other porosity, and indeed we may assume that the actual soil is replaced by an ideal soil which has all of its elements of volume of constant porosity m, or what is the same thing, of a constant face angle θ.

3. It is necessary to determine the relation between the face angle θ and the porosity m.

If, in fig. 61, O H be a rhombohedron with vertices at the centers of eight contiguous spheres, each side of the spherical triangle A B D will equal θ. From the right-angled triangle A B C we may derive

$$\sin a = \frac{\sin \theta \sqrt{1 + 2 \cos \theta}}{1 + \cos \theta}, \tag{1}$$

in which a stands for the angle B O C.

Since the area of the base of the rhombohedron is $d^2 \sin \theta$, and since the altitude h equals $d \sin a$, we have the volume of the rhombohedron equal to

$$d^3 (1 - \cos \theta) \sqrt{1 + 2 \cos \theta}. \tag{2}$$

Subtracting from this the volume of a sphere of diameter d, we derive the amount of open space in the element of volume, and dividing this

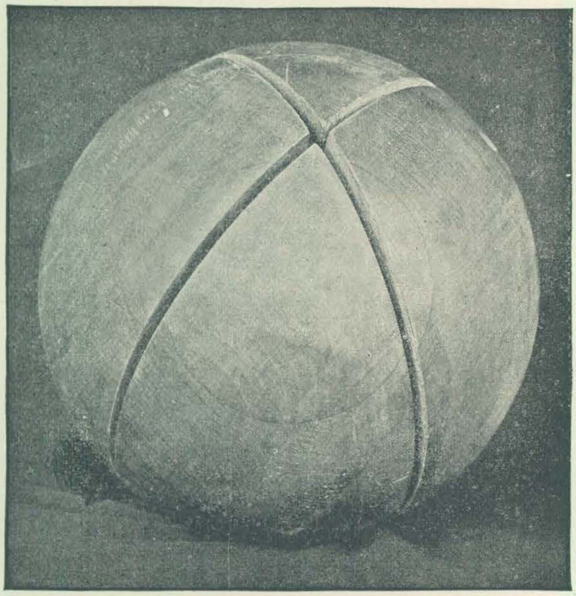

FIG. 60.—Sphere formed from the eight pieces of eight spheres which constitute the unit rhombohedron shown in fig. 58.

difference by the volume of the rhombohedron we obtain the porosity as a percentage of the whole volume. Calling this percentage m, as above, we derive

$$m = 1 - \frac{\pi/6}{(1 - \cos \theta) \sqrt{1 + 2 \cos \theta}}. \tag{3}$$

To derive θ when m is given, we must solve the cubic equation

$$2 \cos^3 \theta - 3 \cos^2 \theta + 1 - \frac{\pi^2}{36 (1 - m)^2} = 0. \tag{4}$$

The following table contains the values of θ derived from the above equation corresponding to values of m between 26 and 47 per cent.

TABLE I.—*Relation of porosity m to face angle θ.*

m	θ		m	θ	
	°	′		°	′
26	60	2	37	68	18
27	60	41	38	69	17
28	61	18	39	70	20
29	61	55	40	71	28
30	62	36	41	72	43
31	63	18	42	74	3
32	64	3	43	75	32
33	64	49	44	77	10
34	65	37	45	79	6
35	66	27	46	81	25
36	67	21	47	84	59

4. As before stated, the pores through ideal soil are capillary tubes of approximately triangular cross section. The length of these capillary

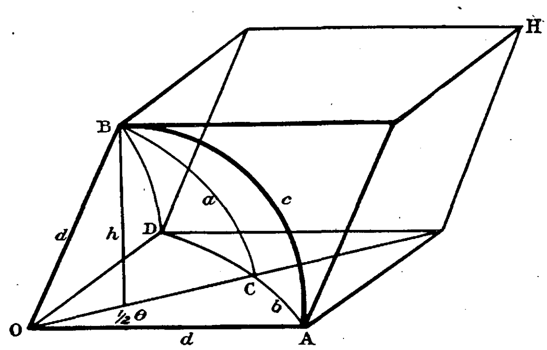

FIG. 61.—Diagram showing the metrical properties of the unit rhombohedron.

tubes is evidently greater than the length of the column of soil. In fact, if the length of the soil column be h, fig. 61 shows that the length of a pore through which a particle of fluid must pass is h sec a, or

$$\frac{h\,(1+\cos\theta)}{\sin\theta\sqrt{1+2\cos\theta}}, \qquad (5)$$

if we assume that the pore follows a straight line, as A B C in fig. 62 or 64, or the white rods in fig. 54. The central line of the triangular pore actually follows a line that is slightly curved, although following the general direction of the straight line A B C. The actual course of the central line of the pore is shown by the curved line A H B K C of fig. 64, which figure is drawn to scale for the case of the most compact pack-

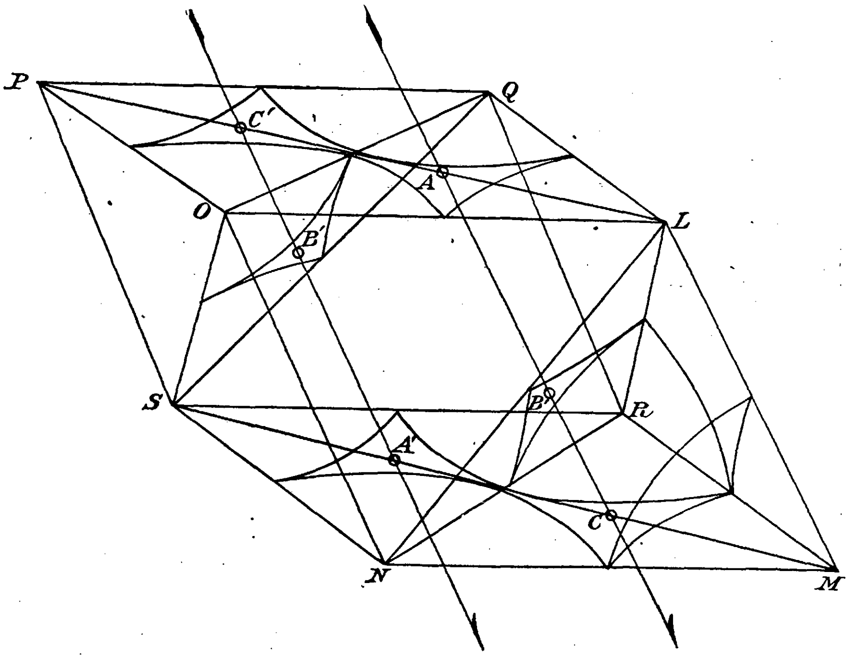

FIG. 62.—Diagram showing the course of the pores through the unit rhombohedron.

ing of the spheres, the angle A T U being about 70°. The curved line in this case is about 1.065 times the length of the straight line A B C.

Inasmuch as the maximum value of θ is $\frac{\pi}{2}$ and its minimum value is $\frac{\pi}{3}$, we may say in general that the curved line is

$$1 + \frac{.065\ (\pi/2 - \theta)}{\pi/6} \qquad (6)$$

times as long as the straight line. Reducing this last expression to the form

$$1.195 - .39\ \theta/\pi, \qquad (7)$$

and representing the length of the curved pore by l, we get

$$l = \frac{h\ (1 + \cos\theta)}{\sin\theta\sqrt{1 + 2\cos\theta}}\ (1.195 - .39\ \theta/\pi). \qquad (8)$$

5. The area of the cross section of a triangular pore can be found by subtracting the area of the circle from that of the rhombus shown in

fig. 57 and dividing the result by 2. This gives, in terms of the constants already used,

$$A_1 = \frac{(\sin \theta - \pi/4)}{2} d^2.$$

This is the area of the smallest section of the pore. The percentage of free or unoccupied area in this section of the soil is found by dividing the double of this result by the area of the rhombus shown in fig. 57.

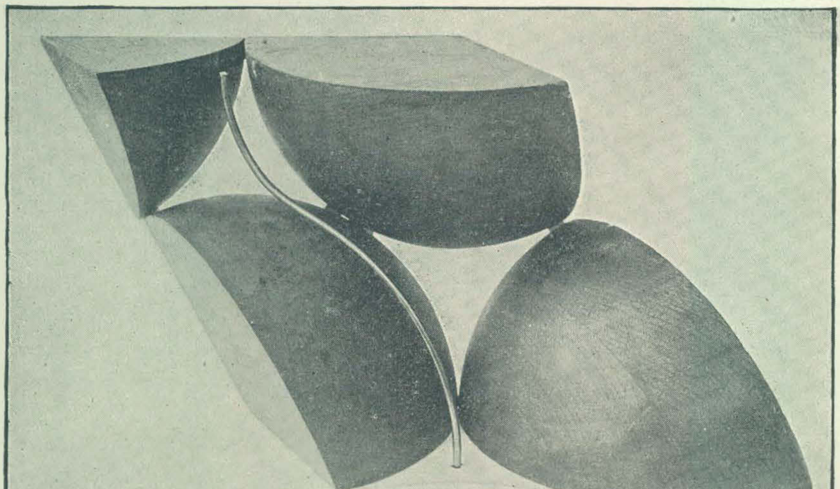

FIG. 63.—The interior of the unit rhombohedron, showing the curved axis of the triangular pore.

This gives, if n represents the per cent of unoccupied area in the section, the expression

$$n = \frac{\sin \theta - \pi/4}{\sin \theta} = 1 - \pi/4 \csc \theta. \qquad (9)$$

The pore enlarges slightly in area as it follows the surfaces of the spherical soil grains, and then diminishes again to its former value. This is shown by fig. 59. The pores between the spheres are shown in section in the planes L O P Q and M N S R of fig. 62, which figure is an attempt to represent fig. 58 diagrammatically. It is seen that each element of volume contains two pores, one following the line A B C and the other the line C′ B′ A′ in fig. 62, or following the two white rods shown in fig. 54. At A the section of the pore is a minimum, but it gradually enlarges and then diminishes again, and is again a minimum when the line A B C pierces the plane L N R at the point B. It again enlarges as we pass along B C, but diminishes again to a minimum at

C. For the arrangement of spheres shown in fig. 62, the angle[1] between the plane L N R and either the upper or lower base of the rhombohedron is about 70°, so that the pore enlarges from its minimum to its

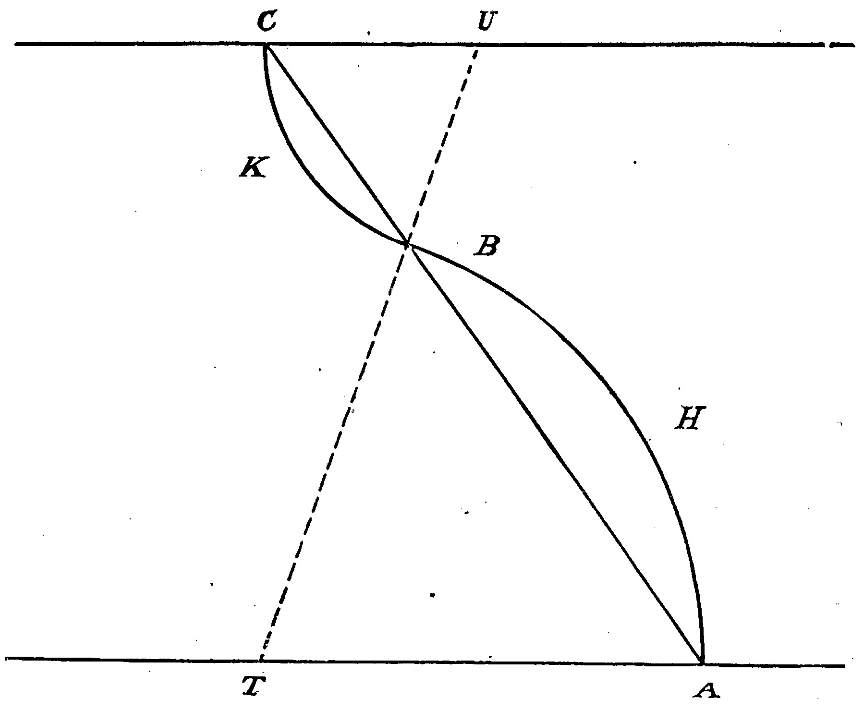

FIG. 64.—Diagram showing the metrical properties of the curved axis of a triangular pore.

maximum section while passing over about 35° of angular distance on the sphere, as is shown in fig. 66.

The mean area A_m of the triangular section shown as T S R in fig. 65 can be found by well-known methods of the calculus.[2]

Fig. 66 shows the radii of the inscribed circles of the triangles whose mean value is desired. In figs. 65 and 66:

$$A\,B = 2\,r, \qquad A\,D = r\sqrt{3},$$
$$A\,O = \tfrac{2}{3}\,r\sqrt{3}, \qquad E\,O = (\tfrac{2}{3}\sqrt{3} - 1)\,r,$$
$$A_r = \text{area of } \triangle\ R\,S\,T = 3\sqrt{3}\ \overline{O\,E}^2,$$
$$A_q = 3\sqrt{3}\ \overline{P\,Q}^2,$$

in which A_q stands for the area of the equilateral triangle which has P Q for radius of inscribed circle. From the equation of the circle

[1] This is the angle A T U of fig. 64.

[2] See Benjamin Williamson, Integral Calculus, 5th ed., New York, 1888, p. 346.

E K (which is a section of a soil grain of radius r) we derive the value of any abscissa P Q to be

$$x = \tfrac{2}{3} r \sqrt{3} - \sqrt{r^2 - y^2}. \qquad (10)$$

Hence the mean value of the area of the cross section may be found from the formula

$$\begin{aligned} A_m &= \frac{1}{b-a}\int_a^b f(y)\,dy \\ &= \frac{6\sqrt{3}}{r}\int_0^{\frac{1}{2}r} \left(\tfrac{2}{3} r\sqrt{3} - \sqrt{r^2 - y^2}\right)^2 dy \\ &= \left(\tfrac{15}{4}\sqrt{3} - 2\pi\right) r^2 \\ &= (0.2118)\, r^2. \end{aligned} \qquad (11)$$

The area of the triangle T R S is

$$A_r = (7\sqrt{3} - 12)\, r^2 = .1247\, r^2 \qquad (12)$$

and the area of the concave "spherical" triangle D F G is

$$A_F = (\sqrt{3} - \pi/2)\, r^2 = .1613\, r^2 \qquad (13)$$

The effective area of the triangular section—that is, the area in the shape of the equilateral triangle which will transmit the same amount

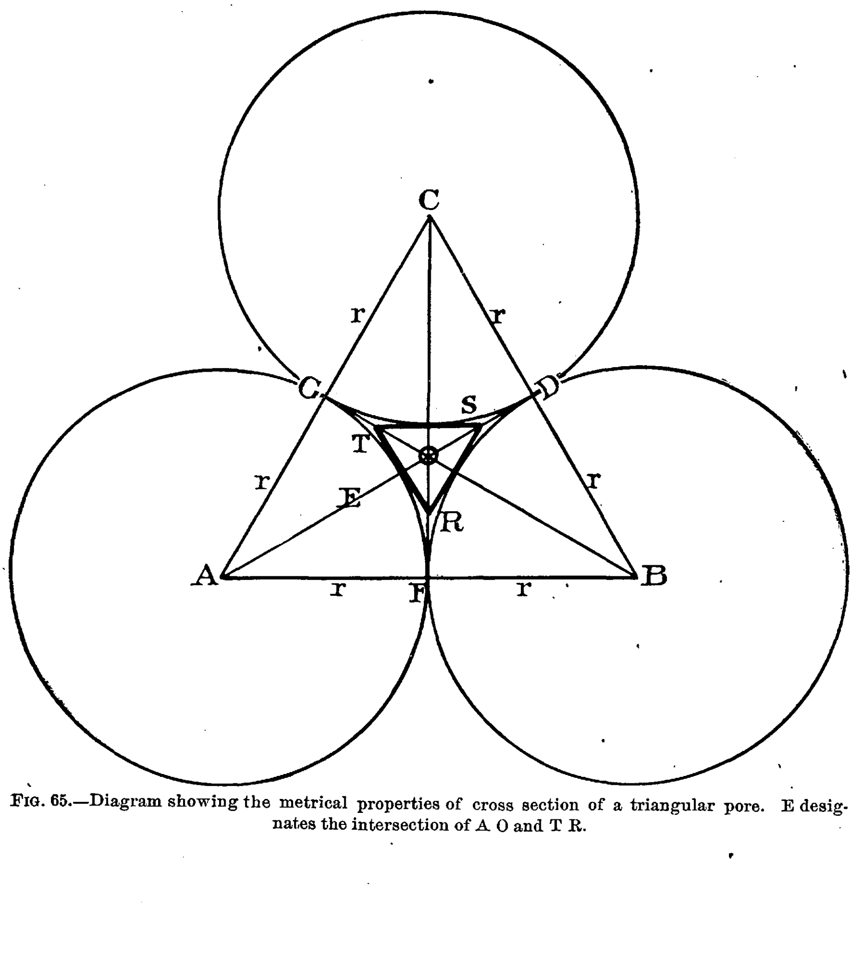

FIG. 65.—Diagram showing the metrical properties of cross section of a triangular pore. E designates the intersection of A O and T R.

of fluid that the pore of section D F G transmits—is intermediate to these two values. The difference between the two areas is .0366 r^2, and as the mean should be taken nearer to .1613 r^2 than to .1247 r^2, I have adopted .1475 r^2 as the probable value of the mean, although a slight increase or decrease in this value might be made. The area of the pore of mean section .2118 r^2 is of about 43 per cent greater area than the value .1475 r^2 just adopted as the area of the minimum section of the triangular pore.

6. Before proceeding further with the problem before us we must give attention to the flow of liquids through capillary tubes of various cross sections. The formula for the flow through a tube of circular section is

$$f = \frac{\pi a^4 p}{8 \mu l}, \tag{14}$$

in which f is the discharge in cubic centimeters per second, a is the radius of the tube, l its length, p is the difference in pressure at its ends in dynes per square centimeter, and μ is the coefficient of viscosity of the liquid. The law of flow expressed by this formula is

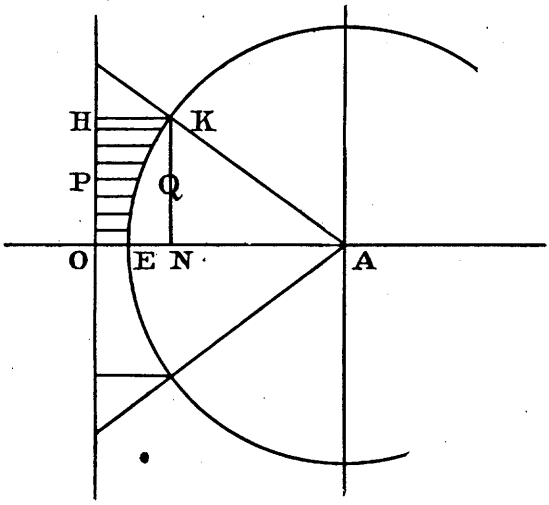

FIG. 66.—Diagram showing the variation in the cross section of a triangular pore. This figure represents a section made by passing a plane through the line A E O of fig. 65 perpendicular to the plane of the paper: A, O, and E correspond to the points designated by same letters in fig. 65. O is the center of the triangle R S T of fig. 65.

known as the Poiseuilleian law, announced as the conclusion of his experimental work by Poiseuille in 1840–1842, and afterwards derived from purely theoretical considerations, as now given in Basset's Hydrodynamics, 1888, Volume II, page 304, and in Lamb's Hydrodynamics, 1895, page 520. If A is the area of cross section, this formula may be written

$$f = \frac{A^2 p}{8 \pi \mu l}, \tag{15}$$

and the mean velocity of the fluid in the tube is given by

$$v = \frac{p A}{8 \pi \mu l} = (0.03979) \frac{p A}{\mu l}. \tag{16}$$

7. For tubes of other than circular section Greenhill[1] has shown that the expression for the velocity of a viscous liquid at any point in the cross section can be found if the motion of a frictionless liquid relative to the boundary is known for a rotating prismatic or cylindrical vessel of the same form of section. As problems of prisms of various sections rotating in a perfect liquid have been worked out by means of conjugate functions,[2] it is possible, because of this discovery of Greenhill, to write down at once solutions for problems in the flow of viscous fluids through tubes of various kinds. The method is as follows: If ψ represents the current function[3] due to the rotating cylinder, then u, the velocity parallel to the axis of the tube at any point of the cross section, is, for a viscous liquid flowing through the tube,

$$u = \psi - \tfrac{1}{2}\,\omega\,(x^2 + y^2). \tag{17}$$

If this result is not zero at the boundary of the tube a constant must be added to render it so. Throughout the result we must substitute $M = 2\,\omega$, in which $M = \frac{p}{\mu\, l}$, p being the difference in pressure at the ends, μ the coefficient of viscosity, and l the length of the tube.

These results come about from considering that ψ must satisfy

$$\frac{d^2\psi}{dx^2} + \frac{d^2\psi}{dy^2} = 0, \tag{18}$$

and that this equation is changed by substitution (17) to the form

$$\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + 2\,\omega = 0, \tag{19}$$

while the equation for the flow of a viscous fluid through a capillary tube is of the form

$$\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + M = 0. \tag{20}$$

8. For an equilateral triangular prism, having radius of inscribed circle a, we have from hydrodynamics[4]

$$\psi = -\frac{\omega}{6a}\,(x^3 - 3xy^2) \tag{21}$$

and

$$u = \frac{p}{12a\mu}\,(x - a)\,(2a + x + y\,\sqrt{3})\,(2a + x - y\,\sqrt{3}) = \frac{p}{\mu}\,\frac{\alpha\beta\gamma}{h}, \tag{22}$$

in which α, β, γ are the distances of a point from the three sides of the triangle and h is the altitude. The equations of the sides of the triangle are

$$x - a = 0,\; x + y\,\sqrt{3} + 2a = 0,\; x - y\,\sqrt{3} + 2a = 0. \tag{23}$$

[1] Proceedings London Math. Society, Vol. XIII, 1881, p. 43.
[2] Basset, Hydrodynamics, Vol. I, p. 91; Lamb, Hydrodynamics, p. 73.
[3] Basset, Hydrodynamics, Vol. I, p. 11; Lamb, Hydrodynamics, p. 70; Sampson on Stokes's Current Function; Phil. Trans. A., 1891.
[4] Lamb, Hydrodynamics, pp. 93, 523

The flux per second is

$$f = \iint u \, dx \, dy = \frac{27 \, pa^4}{20 \sqrt{3} \, \mu l} = \frac{p \, A^2}{20 \sqrt{3} \, \mu l}, \tag{24}$$

in which A is the area of the cross section of the triangular cylinder. The mean velocity is found by dividing the flux by A and gives

$$v = \frac{p \, A}{20 \sqrt{3} \, \mu l} = (0.02887) \frac{p \, A}{\mu \, l}. \tag{25}$$

The mean velocity for a circular tube of equivalent area of cross section was found above to be about 38 per cent more, or

$$(0.03979) \frac{p \, A}{\mu \, l}.$$

9. For an elliptical cylinder[1] we have

$$\psi = \tfrac{1}{2} \, \omega \frac{a^2 - b^2}{a^2 + b^2} (x^2 - y^2). \tag{26}$$

Whence

$$u = \frac{p}{2 \, \mu \, l} \left(\frac{a^2 \, b^2}{a^2 + b^2} \right) \left(1 - \frac{x^2}{a^2} - \frac{y^2}{b^2} \right). \tag{27}$$

Also

$$f = \frac{p}{4 \, \mu \, l} \, \frac{\pi \, a^3 \, b^3}{a^2 + b^2} = \frac{p}{4 \, \pi \, \mu \, l} \, \frac{A^2 \, a \, b}{a^2 + b^2}. \tag{28}$$

From this we derive the average velocity,

$$v = \frac{p}{4 \, \pi \, \mu \, l} \, \frac{A \, a \, b}{a^2 + b^2} \tag{29}$$

$$= \frac{p \, A}{4 \, \pi \, \mu \, l} \, \frac{\sqrt{1 - e^2}}{2 - e^2} \tag{30}$$

$$= \frac{p \, A}{4 \, \pi \, \mu \, l} \, \frac{\cos \theta}{1 + \cos^2 \theta},$$

in which θ is the angle of projection of the ellipse from the circle $x^2 + y^2 = a^2$, so that $\sin \theta = e$, the eccentricity.

A remarkable conclusion from this analysis is the fact that the flow through an elliptic tube is but slightly different from the flow through a circular tube of the same area of cross section, provided that the eccentricity is not too great. Even an eccentricity of 0.866 will change the flow by but 10 per cent, and an eccentricity of one-half will reduce the flow by about one-half of 1 per cent. Thus it is clear that a slight change in the shape of the cross section of a tube will change but slightly the flow through it. Analogy warrants us in extending this truth to tubes having other than elliptical sections. For example, we may conclude that the flow through a tube whose section is an oblique triangle is given approximately by the formula for a tube whose section is an equilateral triangle of the same area, even though the shape of the section of the given tube differs slightly, or even materially, from that of an equilateral triangle.

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[1] Lamb, Hydrodynamics, pp. 93, 523.

10. The velocity of flow through a tube of variable section will be less than the velocity of flow through a tube having a uniform section equal to the mean section of the first tube, because of the viscosity or internal friction of the expanding or contracting stream. We shall now determine approximately the retarding influence due to such contraction or expansion.

For a tube of uniform triangular section we may write, if a is the radius of the circle inscribed in the triangular section,

$$p / l = \frac{20 \mu v}{3 a^2}, \tag{31}$$

by expressing A, the area of cross section in equation (25), in terms of the radius of the inscribed circle. Making the supposition that the distance OH (fig. 66), through which expansion of the pore or tube takes place, is one-half the radius of the sphere, and expressing all distances in terms of OE or a, we have

$$\text{HK} = \frac{2 + \sqrt{3}}{2} a$$

and

$$\frac{v_1}{v_2} = \frac{\text{HK}^2}{\text{OE}^2} = \frac{7 + 4\sqrt{3}}{4}, \tag{32}$$

if v_1 = velocity at OE and v_2 = velocity at HK, fig. 66. Therefore, representing the increment of velocity by Δv,

$$\Delta v = v_1 - v_2 = v_1 \left(\frac{\text{HK}^2 - \text{EO}^2}{\text{HK}^2} \right) = \frac{3 + 4\sqrt{3}}{7 + 4\sqrt{3}} v_1 \doteq \frac{10}{14} v_1. \tag{33}$$

The retarding influence on any plane in a viscous liquid is μ times the variation in velocity normal to the plane.[1] The normal variation of velocity in this case is approximately

$$\frac{\Delta v}{\Delta l} = \frac{v_1 - v_2}{\frac{1}{2} r}. \tag{34}$$

Therefore the retarding influence exerted on the liquid while flowing from minimum section to minimum section is

$$2 \mu \frac{\Delta v}{\Delta l},$$

because the retardation is experienced both when the stream is contracting and when it is expanding.

Since

$$\frac{p}{l} = \frac{\Delta p}{2 \Delta l}, \tag{35}$$

we have as a corrected value of p/l (see equation (31) above),

$$\frac{p}{l} = \frac{20}{3} \frac{\mu v}{a^2} + 2 \mu \frac{\Delta v}{\Delta l}. \tag{36}$$

[1] Lamb, Hydrodynamics, p. 512.

From fig. 65,

$$\tfrac{1}{2}r \text{ or } \Delta l = \frac{3a}{2(2\sqrt{3}-3)}. \tag{37}$$

Therefore, substituting from (37) and (33) into (36),

$$\frac{p}{l} = \frac{20\mu v}{3a^2} + \frac{\mu v}{a} 4\,(59 - 34\sqrt{3}) = \frac{20\mu v}{3a^2} + \frac{\mu v}{a}\,(0.4340). \tag{38}$$

From this we find that

$$v = \frac{3}{20}\,\frac{pa^2}{\mu l(1+0.0651a)}. \tag{39}$$

As this differs little from

$$\frac{3}{20}\,\frac{pa^2}{\mu l},$$

which is the value of v written in (31) above, the retardation is negligible.

11. We now have sufficient data to enable us to determine the flux and the mean velocity of flow of a fluid through a mass of soil. In section 5 we found the mean cross section of a pore to be about 43.5 per cent greater than the minimum cross section. We also noted in section 8 that the flow through a circular tube is greater than the flow through a triangular tube of same area of cross section by about 38 per cent. By converting the triangular pore into a uniform circular pore of the same area as the minimum section of the triangular pore, we should fall short about 5.5 per cent of making the true correction. However, by considering the pore to be straight instead of curved, as shown in fig. 63, we have made another error of almost exactly the same amount but in the opposite direction. Therefore by converting the area of the minimum section into a circular section and dropping the correction to the length of a pore previously determined (equation 6), we may permit the two errors to neutralize each other, and simplify the resulting formula. The area of minimum section we have found to be (see section 5)

$$\frac{(\sin\,\theta - \pi/4)d^2}{2}.$$

Calling this the area of a circular pore, we have as the mean velocity from section 6,

$$v = \frac{p}{8\pi l\mu}\left(\frac{\sin\,\theta - \pi/4}{2}\right)d^2. \tag{40}$$

In section 4 we found the length of the pore, if considered to be straight, to equal

$$l = \frac{h(1+\cos\theta)}{\sin\,\theta\sqrt{1+2\cos\theta}}.$$

Therefore equation (40) becomes

$$v=\frac{pd^2}{16\pi\mu h}\left(\frac{\sin\theta\sqrt{1+2\cos\theta}(\sin\theta-\pi/4)}{1+\cos\theta}\right). \qquad (41)$$

If the section of the cylinder containing the soil be s, we have the percentage of open space in a cross section, from equation (7) above,

$$ns=\frac{(\sin\theta-\pi/4)s}{\sin\theta}.$$

Multiplying v by ns, we derive for the flux per second

$$f=\frac{pd^2s}{16\pi\mu h}\left(\frac{\sqrt{1+2\cos\theta}\,(\sin\theta-\pi/4)^2}{1+\cos\theta}\right)$$

$$=\frac{pd^2s}{16\pi\mu h}\left(\frac{\sqrt{1+2\cos\theta}(1-\cos\theta)\,(\sin\theta-\pi/4)^2}{\sin^2\theta}\right). \qquad (42)$$

Substituting the value of $(1-\cos\theta)\sqrt{1+2\cos\theta}$ from (3) and placing B for $1/(1-\pi/4\csc\theta)^2$, we get

$$f=\frac{pd^2s}{96\mu hB(1-m)}. \qquad (43)$$

Taking g equal to 981 dynes and measuring the pressure p in terms of centimeters of water at 4° C., we have the formula

$$q=[1.0094]\frac{pd^2s}{\mu hK} \text{ cubic centimeters per second,} \qquad (44)$$

in which the brackets [1.0094] indicate the logarithm of a factor, and in which $K=B(1-m)$. The logarithm of the constant multiplier K has been computed for various values of m and placed in Table II.

If we measure p in feet of water at 4° C., s in square feet, h in feet, and d in millimeters, and use the minute for the unit of time, the above formula may be written

$$q=[9.3036-10]\frac{pd^2s}{\mu hK} \text{ cubic feet per minute.} \qquad (45)$$

The coefficient of viscosity for water for various temperatures will be found given in Table III. If we substitute the value of $\mu_{10}=0.01315$ for 10° C., we obtain the formula

$$q=[1.1846]\frac{pd^2s}{hK} \text{ cubic feet per minute.} \qquad (46)$$

Part of the expression on the right side of this equation depends only upon the character of the soil through which the water is passing. Representing this by k, we have

$$k=[1.1846]\frac{d^2}{K}. \qquad (47)$$

The constant k is the quantity of water that would be transmitted in unit time through a cylinder of the soil of unit length and unit cross section under unit difference in head at the ends.

We shall frequently refer to k as the transmission constant, or merely as the constant of a soil. The constant K is the factor in the formula which depends only upon the value of the porosity of the soil. When the porosity of a soil has been measured, the value of K, or rather the value of its logarithm, can be found from Table II. From that table it appears that if two samples of the same sand are packed, one sample so that its porosity is 26 per cent and the other sample so that its porosity is 47 per cent, the flow through the latter sample will be more than seven times the flow through the former sample. If the two samples of the same sand had been packed so that their porosities had been 30 per cent and 40 per cent, respectively, the flow through the latter sample would have been about 2.6 times the flow through the former sample. These facts should make clear the enormous influence of porosity on flow, and the inadequacy of a formula of flow which does not take it into account.

APPLICATION AND ILLUSTRATION OF THE FORMULAS OBTAINED ABOVE.

12. We shall now propose several problems that illustrate the formulas obtained in the preceding theoretical work.

First let us consider the following:

A layer of sandstone 100 feet thick and 100 miles wide has a dip from north to south of 5 feet per mile, and is underlain and overlain by impervious material. If there is a catchment area at the upper end, and if the ground water has free means of escape at a cliff or cut at the lower end, let us determine what is the delivery of water in cubic feet per minute for each linear foot of section at right angles to the dip. First, suppose the stone has a mean size of grain of 0.15 mm. and a porosity of 30 per cent. These values substituted in (46) give

$$q = [7.8169-10]\frac{ps}{h} \text{ cubic feet per minute.} \qquad (48)$$

The cause of the flow of ground water is supposed to be the difference of head of 5 feet per mile. Substituting, therefore, $p=5$, $h=5{,}280$, and $s=100$, we obtain

$$q = .0006213 \text{ cubic foot per minute,}$$
$$= .8946 \text{ cubic foot per day,}$$

for each linear foot of the cliff or cut.

If the stratum of sandstone serves as an artesian water supply we may readily estimate to what extent the natural supply transmitted by the water-bearing stratum is drawn upon by a given well. Suppose, for example, that 5,000 cubic feet per day are drawn from a well. This is equivalent to the ordinary supply transmitted by a strip of the sandstone a mile in width, so that if the artesian area is 100 miles square, only 100 wells of the capacity named could be supplied by the sandstone without permanently lowering the water table, granting, of course, the absence of open cracks and fissures in the stone.

This limited capacity of a sandstone to transmit water is still apparent if we suppose the size of grains and the porosity to be largely increased. For example, if the size of grain in the above problem had been given as 0.25 mm. and the porosity as 32 per cent, the flux would have been

$$q = [8.3537 - 10] \frac{ps}{h} \text{ cubic feet per minute,} \tag{49}$$

which reduces to

$$q = .00214 \text{ cubic foot per minute,}$$
$$= 3.08 \text{ cubic feet per day;}$$

for $p = 5$, $h = 5,280$, and $s = 100$. If 5,000 cubic feet per day are drawn from a well, the ordinary natural supply from a strip of the sandstone 1,500 feet wide would be exhausted in supplying the well.

If the size of grain be taken as 0.5 mm. and the porosity as 32 per cent, the flux for each linear foot of section of stone would be

$$q = .00856 \text{ cubic foot per minute,}$$
$$= 12.32 \text{ cubic feet per day.}$$

The well furnishing 5,000 cubic feet per day would in this case represent the natural supply from a strip of the sandstone about 400 feet wide.

The hypothesis of fissures, either in the sandstone itself or in the underlying or overlying strata, will, of course, radically modify the above figures. The limited quantity of the artesian supply will usually appear, however, from other considerations. As an illustration, suppose that the catchment area is equal to the artesian area and that the rainfall on the catchment area is 36 inches per year, one-third of which finds its way, we will suppose, into the catchment rock, two-thirds either running off in surface streams or supplying the evaporation. Then, if no allowance be made for loss from leakage or the supply of springs, etc., a well in the artesian area using 5,000 cubic feet per day represents the available rainfall that is collected on a square 1,350 feet on a side. Thus, even if perfect means of communication by means of fissures existed between the catchment and the artesian areas, wells of the capacity named could not be placed, on the average, any nearer to each other than 1,350 feet.

13. It is not unreasonable to suppose that the effective size of soil grains can be determined by measuring the time required to pass a given quantity of air under a given difference of pressure through a

cylinder filled with the soil. This method was first proposed by Prof. F. H. King, and is based on the assumption that formula (44) holds for air as well as water. It was at the suggestion of Professor King that formula (44) was produced in the first instance. For computing the value of d, it is convenient to rewrite the formula as follows, substituting the value of the coefficient of viscosity of air, and substituting 5,000 c. c. for q,

$$d^2 = k\frac{h}{s\,p\,t}[8.9434-10]. \tag{50}$$

In the formula, t is the time necessary to draw 5,000 c. c. of air at temperature 20° C. through a cylinder of soil having a cross section of s square centimeters and a length of h centimeters. K is to be taken from Table II and [8.9438 — 10] is the logarithm of a factor. The pressure at which the volume of the air passed through the soil is measured must be the *mean* of the pressures at the ends of the column. Meyer[1] has shown that the law of flow through capillary tubes holds for gases if the volume of gas be measured at the mean pressure.[2]

The coefficient of viscosity of air at 20° C. used in this formula is that due to Obermayer[3] and is equal to 0.000179.

Obermayer's formula for μ for air is

$$\mu = \mu_0\,(1 + .0038585\,\theta - .00000105\,\theta^2),$$

in which

$$\mu_0 = .0001705,$$

and in which θ stands for temperature centigrade.

The following formula[4] may be used to determine μ for water:

$$\mu = \frac{.0178}{1 + .0337\,\theta + .000221\,\theta^2}.$$

This formula is due to Helmholtz.

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[1] O. E. Meyer, Ueber die Strömung der Gäse durch Capillarröhren, Poggendorff's Annalen, Vol. CXXVII, pp. 269, 270.

[2] See introduction to this paper for experimental results published by Prof. F. H. King while this paper was in press.

[3] See Basset, Hydrodynamics, Vol. II, p. 250.

[4] Lamb's Hydrodynamics, p. 513.

TABLE II.—*Constants for various porosities of an ideal soil.*

[*m* is the porosity expressed as a percentage.]

m.	*n.*	Log K.	*d.*	Colog K.
26	9.37	1.9258	563	8.0742
27	9.93	1.8695	504	8.1305
28	10.45	1.8191	490	8.1809
29	10.98	1.7701	502	8.2299
30	11.55	1.7199	467	8.2801
31	12.10	1.6732	455	8.3268
32	12.66	1.6277	430	8.3723
33	13.22	1.5847	438	8.4152
34	13.78	1.5409	410	8.4591
35	14.34	1.4999	407	8.5001
36	14.91	1.4592	400	8.5408
37	15.49	1.4193	377	8.5807
38	16.05	1.3816	371	8.6184
39	16.61	1.3445	367	8.6555
40	17.19	1.3078	353	8.6922
41	17.75	1.2725	351	8.7275
42	18.32	1.2374	345	8.7626
43	18.90	1.2029	339	8.7971
44	19.46	1.1690	320	8.8310
45	20.03	1.1370	312	8.8630
46	20.57	1.1058	329	8.8942
47	21.17	1.0729	....	8.9271

Proportional parts.

	563	504	502	490	467	455	438
1	56.3	50.4	50.2	49.0	46.7	45.5	43.8
2	112.6	100.8	100.4	98.0	93.4	91.0	87.6
3	168.9	151.2	150.6	147.0	140.1	136.5	131.4
4	225.2	201.6	200.8	196.0	186.8	182.0	175.2
5	281.5	252.0	251.0	245.0	233.5	227.5	219.0
6	337.8	302.4	301.2	294.0	280.2	273.0	262.8
7	394.1	352.8	351.4	343.0	326.9	318.5	306.6
8	450.4	403.2	401.6	392.0	373.6	364.0	350.4
9	506.7	453.6	451.8	441.0	420.3	409.5	394.2
	430	**410**	**409**	**407**	**377**	**371**	**367**
1	43.0	41.0	40.9	40.7	37.7	37.1	36.7
2	86.0	82.0	81.8	81.4	75.4	74.2	73.4
3	129.0	123.0	122.7	122.1	113.1	111.3	110.1
4	172.0	164.0	163.6	162.8	150.8	148.4	146.8
5	215.0	205.0	204.5	203.5	188.5	185.5	183.5
6	258.0	246.0	245.4	244.2	226.2	222.6	220.2
7	301.0	287.0	286.3	284.9	263.9	259.7	256.9
8	344.0	328.0	327.2	325.6	301.6	296.8	293.6
9	387.0	369.0	368.1	366.3	339.3	333.9	330.3
	353	**351**	**345**	**339**	**329**	**320**	**312**
1	35.3	35.1	34.5	33.9	32.9	32.0	31.2
2	70.6	70.2	69.0	67.8	65.8	64.0	62.4
3	105.9	105.3	103.5	101.7	98.7	96.0	93.6
4	141.2	140.4	138.0	135.6	131.6	128.0	124.8
5	176.5	175.5	172.5	169.5	164.5	160.0	156.0
6	211.8	210.6	207.0	203.4	197.4	192.0	187.2
7	247.1	245.7	241.5	237.3	230.3	224.0	218.4
8	282.4	280.8	276.0	271.2	263.2	256.0	249.6
9	317.7	315.9	310.5	305.1	296.1	288.0	280.8

TABLE III.—*Coefficients of viscosity for water for various temperatures centigrade.*

θ=temperature centigrade.	μ=coefficient of viscosity.	θ=temperature centigrade.	μ=coefficient of viscosity.
0	0.0178	10	0.0131
1	0.0172	11	0.0128
2	0.0166	12	0.0124
3	0.0161	13	0.0120
4	0.0156	14	0.0117
5	0.0152	15	0.0114
6	0.0147	16	0.0111
7	0.0143	17	0.0109
8	0.0138	18	0.0106
9	0.0135	19	0.0103
10	0.0131	20	0.0101

CHAPTER II.

GENERAL LAWS OF THE FLOW OF GROUND WATERS.

1. Experimenters have usually claimed that the velocity of the flow of a liquid in a given direction through a column of soil is proportional to the difference in pressure at the ends of the column and inversely proportional to the length of the column. This law is often referred to as "Darcy's law,"[1] and may be expressed by a formula, as follows:

$$v = k\frac{p}{h}, \tag{1}$$

in which v is the velocity, p is the difference in pressure at the ends of the column of soil, and h is the length of the column. The pressure at the ends of the column must be taken just inside of the soil itself, and not in the liquid outside of the surface of the soil. There appears to be a sudden reduction in pressure as the liquid enters the soil, just as there is a loss of head due to the orifice of influx in case of water entering an ordinary water main.[2] The constant k depends upon the size of the soil grains, the porosity of the soil, and the viscosity of the liquid. The form of this constant was investigated from a theoretical standpoint in Chapter I. (See Chapter I, equation (47).) Darcy and others have determined its value experimentally for different soils, and have suggested various forms of experimental filters suited for this purpose.[3]

Darcy's law is entirely analogous to the well-known law of Poiseuille for the flow of a liquid through a capillary tube,[4] and, like this latter law, it fails to hold for high pressure gradients; for example, the law may be true for a pressure variation not exceeding 1 gram per length of 10 centimeters, but may fail to hold for a pressure variation of 10 grams per length of 1 centimeter. The limits within which the law holds, and the modifications which a second approximation require, can be determined only by exhaustive experiments on a wide range of materials.

[1] H. Darcy, Les fontaines publiques de la ville de Dijon, Paris, 1856. Darcy-Bazin, Recherches hydrauliques, Paris, 1865.

[2] Allen Hazen, Some physical properties of sands and gravels: Report Mass. State Board of Health, 1892, p. 541. Consult also bibliography in the appendix.

[3] Hazen, loc. cit., and Otto Lueger, Wasserversorgung der Städte, Stuttgart, p. 125.

[4] The most important memoirs on the flow of liquids and gases through capillary tubes are the following: Poiseuille, Recherches sur le mouvement des liquids dans les tubes de très-petits diamètres: Acad. Sciences, Savants estrangers, 1842, Vol. IX, p. 433. Graham, On the motions of gases: Phil. Trans. Royal Soc. London, 1846, p. 573; 1849, p. 349. O. E. Meyer, Ueber die innere Reibung der Gase: Pogg. Annalen, Vol. CXXVII, 1866, p. 253; Vol. CXLVIII, 1873, p. 1. M. Couette, Étude sur le Frottement des liquids.

Equation (1) may also be written

$$v = k\frac{\partial p}{\partial h}.$$

2. If a fluid in a porous medium is not required to move in a single direction, but has liberty to move in any direction, then if at a given point, P, the motion is in direction s we may write

$$v = k\,\frac{\partial p}{\partial s}, \tag{2}$$

in case the motion is steady, using the term "steady motion" in its usual sense in hydrodynamics, as descriptive of motion which does not vary with the lapse of time. The pores of a soil are arranged in such a haphazard manner that we are at liberty to suppose that at any particular point the fluid is free to move in any desired direction. The flow of a fluid in a soil, then, is not different from the flow of a hypothetical fluid which we may suppose to replace both the fluid in the soil and the soil itself, which hypothetical fluid has the law of flow for steady motion given by the equation

$$v = k\,\frac{\partial p}{\partial s}.$$

In case no external attractive forces are acting, the equations of motion in three dimensions of the hypothetical fluid are

$$\begin{aligned} u &= \frac{dx}{dt} = k\,\frac{\partial p}{\partial x}, \\ v &= \frac{dy}{dt} = k\,\frac{\partial p}{\partial y}, \\ w &= \frac{dz}{dt} = k\,\frac{\partial p}{\partial z}. \end{aligned} \tag{3}$$

The equation of continuity is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{4}$$

the same as in the case of ordinary liquids. The equation of continuity holds for both perfect and viscous liquids, and is simply the mathematical statement that a given mass of the liquid does not change its volume during the given motion—that is, that the liquid is incompressible. If we substitute from (3) into (4) we obtain

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0. \tag{5}$$

3. This equation (equation 5) is the familiar equation occurring in nearly all branches of applied mathematics, known as Laplace's equation. The function p, which satisfies this differential equation, is called

a *potential function*, and from equations (2) and (3) it is observed that the velocity in any direction is the differential coefficient of the potential function with respect to that direction. In the hydrodynamics of perfect fluids the function that possesses this property is called the "velocity potential," but in the hydrodynamics of the hypothetical fluid now under consideration the velocity potential (omitting the constant k) is identical with the pressure function. The coincidence of the pressure function with the potential function is a matter of great interest and importance, and presents a striking analogy with the mathematics of electrical action.

If, as some claim, the velocity of ground water is not directly proportional to pressure, but varies in an arithmetical progression of the form

$$v = kp + c,$$

then equations (3) above must be modified by the addition of a constant, but equation (5) will be unaltered. Thus Laplace's equation is satisfied in either case.

It seems remarkable that the fact that the solution of any problem in the motion of ground waters depends upon the solution of the differential equation (5) has not been pointed out before. The existence of this function is made the basis of nearly all the work in the following pages.

4. If we assume that an external impressed force, as gravity, acts upon the liquid in the z direction with constant intensity g, and if the density of the fluid be ρ, then the expression for w becomes

$$w = k\left(\frac{\partial p}{\partial z} + \frac{\rho g\, dz}{dz}\right). \tag{6}$$

Therefore the equations of motion with gravity acting are

$$\begin{aligned} u &= \frac{dx}{dt} = k\frac{\partial p}{\partial x}, \\ v &= \frac{dy}{dt} = k\frac{\partial p}{\partial y}, \\ w &= \frac{dz}{dt} = k\frac{\partial p}{\partial z} + k\rho g. \end{aligned} \tag{7}$$

These hold, of course, only for the case of steady motion. Equations (4) and (5) are unchanged by the new hypothesis.

5. We have, therefore, shown that a problem in the steady motion of ground waters is mathematically analogous to a problem in the steady flow of heat or electricity, or to a problem in the steady motion of a perfect fluid. The unknown function p must be determined from the partial differential equation (5), subject to the boundary conditions present in each particular problem undertaken. The function p is

necessarily finite, continuous, and single valued at all points of the hypothetical liquid, and the general methods usual in potential theory apply. In a determinate problem the value of p must be given over a closed boundary, or along a given axis in space, from which we shall be able to derive the value of p at every point of the region expressed as a function of x, y, and z. After p has been determined by the appropriate solution of (5) for a given problem, the equation $p=c$ will give, for different values of c, a series of surfaces upon each one of which the pressure has the constant value assigned. These are the *equipotential or equipressural surfaces.* Orthogonal to this series of surfaces there exists a series of lines in space, along which the particles of liquid actually move. These lines are the *lines of flow.*

Equations (7) introduce an interesting series of problems, in which, however, the boundary conditions are somewhat more difficult to handle than in the case of equations (3).

The equations above written involve the assumption that the medium in which the flow is taking place is everywhere of the same structure—as, for example, a soil or rock which does not essentially change, from place to place, the size or character of its pores. Such is usually the case within the same geological formation, but in stratified material the constant k is apt to be different for vertical motion from what it is for horizontal motion.

CHAPTER III.

MOTION OF GROUND WATER IN HORIZONTAL PLANES.

1. If steady motion of ground water is taking place in two dimensions, as, for example, in a horizontal stratum of porous rock underlain and overlain by impervious material, the equations of motion become, in their simplified form,

$$
\begin{aligned}
u &= \frac{dx}{dt} = k\,\frac{\partial p}{\partial x}, \\
v &= \frac{dy}{dt} = k\,\frac{\partial p}{\partial y},
\end{aligned}
\tag{1}
$$

and the equation for determining p becomes

$$
\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = 0. \tag{2}
$$

(See Chapter II, section 2.)

If the value of p is given along a straight line or along two parallel lines, or around a rectangular boundary, we may solve equation (2) by means of Fourier's series or Fourier's integral. If the value of p is given around any other boundary we must rely chiefly upon the method of conjugate functions or upon the method of images.

In respect to the method of conjugate functions, it must be remembered that it is not in general possible by known mathematical methods to solve Laplace's equation so as to fulfill given boundary conditions, but we must be content in most cases to solve the inverse problem of assigning a value to the potential or pressural function p, determining in each case the boundary conditions which will render the proposed function the true solution. In fact, a large number of the problems which have been solved in mathematical physics have been attacked by this inverse process. It is important for this reason that we should have before us the solution of as many problems as possible, since the most likely method by which we shall be able to solve a new problem is by reducing it to one of the cases in which a similar problem has been constructed by the inverse process. Indeed, one must often be content to secure an approximate solution in a given case by searching among problems already solved for one whose equipotential lines or surfaces have a form somewhat resembling the given boundary, and then so to modify the problem by tentative methods as to produce conditions more nearly corresponding to those of the given problem. For this reason it is desirable to solve all possible kinds of problems in the motion of ground waters, whether they seem to be "practical" or not. Moreover, the drafting board should be freely used to construct lines of flow and lines of pressure, in the expectation that light will be thrown on other problems whose solution may be desired. With this material at hand, a new problem will likely have analogies to those already constructed, and at least a partial solution of the new problem will be possible.

2. There exists in every case of plane motion of ground waters a function, $\psi (x, y)$, from which the lines of flow may be determined. The equation of continuity for plane motion is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \tag{3}$$

This is the analytical condition that $u\,d\,y - v\,d\,x$ should be an exact differential. Let, therefore,

$$u\,d\,y - v\,d\,x = d\,\psi. \tag{4}$$

Hence

$$u = \frac{\partial \psi}{\partial y};\ v = -\frac{\partial \psi}{\partial x}. \tag{5}$$

We may write equation (4) in the form

$$d\psi = \left(u\frac{dy}{ds} - v\frac{dx}{ds} \right) ds, \tag{6}$$

in which ds is the element of any path in the plane xy. But $\frac{dy}{ds}$ and $-\frac{dx}{ds}$ are the direction cosines, l, m, of the inwardly drawn normal to ds. Whence we write

$$\psi = \int_{A}^{P} (lu + mv)\,ds, \tag{7}$$

in which A and P are any two points on the path S. It is plain that the right side of (7) is the expression of the flow from right to left across the path AP. Therefore, if P moves so that ψ does not change in value, no flow is taking place across AP, and P must describe a line of flow. That is

$$\psi = c \tag{8}$$

is an equation of a line of flow, and ψ may be called the *current function.* Since p is the velocity potential, we have the relation

$$\frac{\partial p}{\partial x} = \frac{\partial \psi}{\partial y};\ \frac{\partial p}{\partial y} = -\frac{\partial \psi}{\partial x}. \tag{9}$$

These are the conditions that $p + i\psi$ should be a function of the complex variable $x + iy$;[1] that is

$$p + i\psi = f\,(x + iy). \tag{10}$$

The curves $p =$ constant are the curves of equivelocity potential, and are, of course, also curves of equal pressure; the curves $\psi =$ constant are, as above stated, the lines of flow, or the actual paths traced by the particles of fluid.

Equations (9) give, by multiplying by $\frac{\partial\psi}{\partial x}$ and $\frac{\partial\psi}{\partial y}$, respectively, and adding, the equation

$$\frac{\partial p}{\partial x}\frac{\partial\psi}{\partial x} + \frac{\partial p}{\partial y}\frac{\partial\psi}{\partial y} = 0, \tag{11}$$

which shows that the two systems of curves cut one another at right angles. It is also evident that we may look upon the curves $\psi =$ constant as the curves of equal pressure, and the curves $p =$ constant as the lines of flow; that is, from every problem solved we may construct the solution of a new problem in which the lines of flow of the first problem become the lines of pressure in the second problem, and vice versa.

3. Let there be any arbitrary distribution of pressure along the line X X′ in fig. 67. Let this pressure be represented by $p = f\,(x)$. Then, if

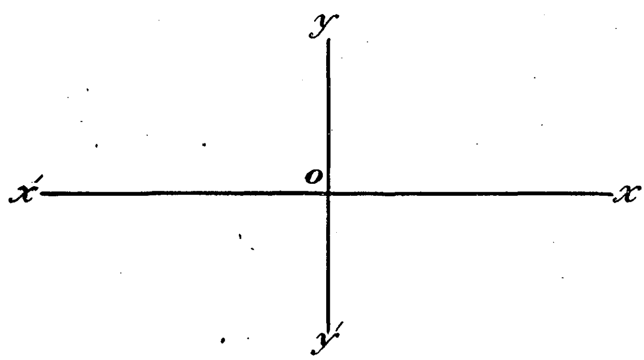


FIG. 67.—Coordinate axes.

we suppose that the pressure is zero at an infinite distance from X X′, we must solve the equation

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = 0$$

subject to the boundary conditions

$$\left.\begin{array}{ll} p = f(x) & \text{when } y = 0 \\ p = 0 & \text{when } y = \infty \end{array}\right\}. \tag{12}$$

[1] A. B. Basset, Treatise on Hydrodynamics, Cambridge, 1888, Vol. I, Chap. V. Horace Lamb, Hydrodynamics, Cambridge, 1895, Chap. IV. Clerk Maxwell, Treatise on Electricity and Magnetism, 3d ed., Oxford, 1892, Vol. I, Chap. XII. W. E. Byerly, Integral Calculus, 2d ed., Boston, 1892, p. 272.

Using the usual method[1] for determining the value of the Fourier's integral which satisfies equations (12), we obtain

$$p=\frac{1}{\pi}\int_0^\infty\int_{-\infty}^\infty e^{-\alpha y} f(\beta)\cos\alpha(\beta-x)\,d\alpha d\beta. \tag{13}$$

This gives, performing the α integration,

$$p=\frac{1}{\pi}\int_{-\infty}^\infty \frac{yf(\beta)\,d\beta}{y^2+(\beta-x)^2}. \tag{14}$$

If $f(\beta)$ is an even function, we obtain

$$p=\frac{1}{\pi}\int_0^\infty yf(\beta)\left[\frac{1}{y^2+(\beta-x)^2}+\frac{1}{y^2+(\beta+x)^2}\right]d\beta; \tag{15}$$

and if $f(\beta)$ is odd,

$$p=\frac{1}{\pi}\int_0^\infty yf(\beta)\left[\frac{1}{y^2+(\beta-x)^2}-\frac{1}{y^2+(\beta+x)^2}\right]d\beta. \tag{16}$$

4. Suppose that a pressure equal to unity is maintained at all points of X X′ to the right of the origin O, and that the pressure is zero at all points of X X′ to the left of the origin, as in fig. 68. As an approxi-

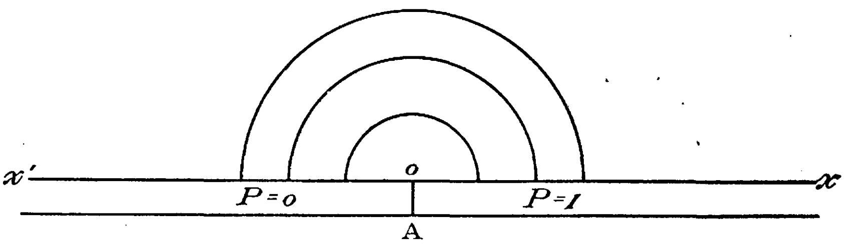


FIG. 68.—Diagram illustrating the problems discussed in sections 4 and 5, Chapter III.

mate illustration, we may suppose that there is a long ditch dug in a level region to the depth of the surface of the ground water, and divided by a dam O A. Water is maintained at a given height in the part O X, but the water is pumped out of the part O X′, so that its level is reduced to the normal level of the ground water. The problem is to determine the flow from one ditch to the other through the surrounding soil.

From the equation (14) above we derive

$$p=1-\frac{1}{\pi}\tan^{-1}\frac{y}{x}. \tag{17}$$

[1] See W. E. Byerly, Fourier's Series and Spherical Harmonics, Boston, 1893, pp. 70 and 73. Nearly all of the integrals that occur in the following sections will be found in Chapter IV of Byerly's excellent treatise.

The expression for ψ, the function conjugate to the above, is

$$\psi = \frac{1}{2\pi} \log_e (x^2 + y^2) = \frac{1}{\pi} \log_e r, \tag{18}$$

which can be found from (17) by the relations given by (9) above.[1]

Equations (17) and (18) may be written in the form

$$y = -x \tan c_1 \pi, \tag{19}$$

$$x^2 + y^2 = e^{-2\pi c_2}. \tag{20}$$

If we assign to c_1 and c_2 a series of values differing by a constant amount, we get from (19) and (20) the series of orthogonal lines and cir-

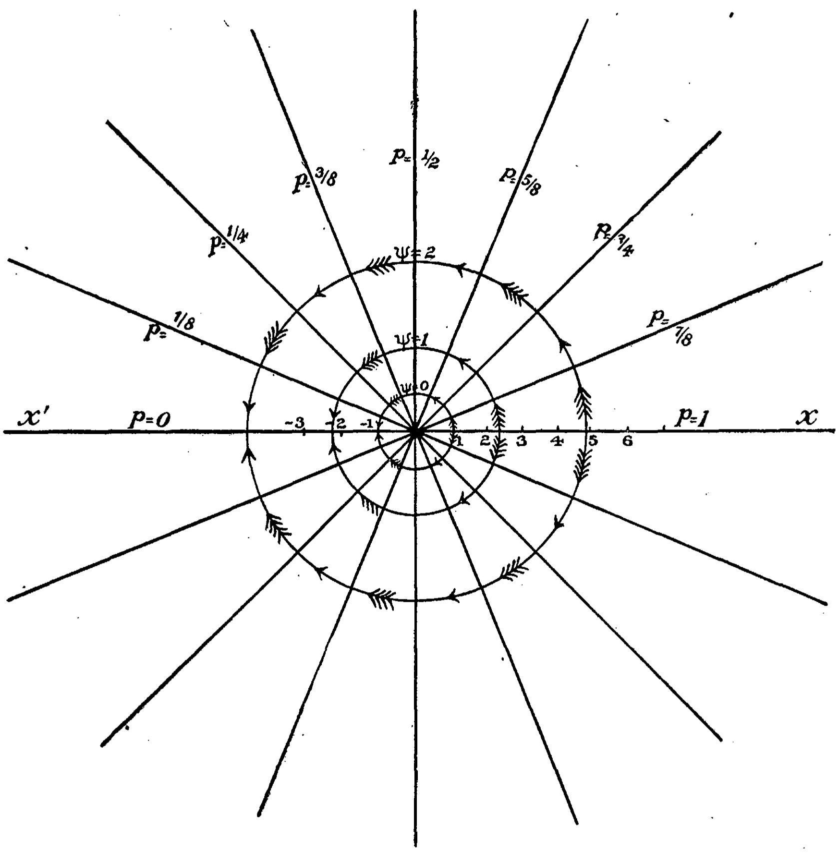


FIG. 69.—Lines of flow and lines of equal pressure for the problems discussed in sections 4 and 5, Chapter III.

cles represented in fig. 69. The straight lines are equipressural lines and the circles are lines of flow. The velocity of outflow perpendicular to O X at a distance x from O is

$$k \left. \frac{\partial p}{\partial y} \right]_{y=0} = \frac{k}{\pi x}. \tag{21}$$

[1] See W. E. Byerly, Fourier's Series and Spherical Harmonics, p. 74, footnote.

The flux across O X from $x = a$ to $x = x$ is

$$f = \int_a^x \frac{k\,dx}{\pi x} = \frac{k}{\pi} \log_e \frac{x}{a}. \tag{22}$$

5. The meaning of the equations just obtained can best be illustrated by considering a particular case. Suppose that the ditch A X, fig. 68, is 5 feet deep and that the dam O A is 2 feet thick. If the bottom of the ditch and the dam are both impervious to water, we desire to know how much water escapes from 100 feet of the ditch immediately to the right of the dam if the soil has an effective size of grain of 0.15 mm and a porosity of 30 per cent, and provided that the water is 1 foot lower in the ditch A X′ than in A X.

In this case we have

$$f = \frac{2 \times 5\,[7.8169 - 10]}{\pi} \log_e 100, \text{ cubic feet per minute,}$$

in which the bracket incloses the logarithm of k for the kind of soil mentioned, as previously determined in Chapter I, equation (48). The factor 2 is placed in the result in order to include the flow of water from both sides of the ditch. Performing the computation, we obtain $f = .09616$ cubic foot per minute, or about 5.8 cubic feet per hour.

If we interchange the functions p and ψ above, we produce an interesting problem which is the inverse of the given problem. In this case the straight lines converging toward O (fig. 69) become the lines of flow and the circles become the lines of equal pressure. In this case we may imagine that the ground water is being "created" or "annihilated" at the point O, which point is then designated as a "source" or "sink." As a concrete case, we may suppose that there is a well at the point O in which the water is being kept permanently at a constant level below the normal water table, so that the water flows into the well along the straight lines converging at O. The lines of equal pressure are the circles with centers on the axis of the well. The well, of course, corresponds to a "sink."

An extended account of the well problem will be found in Chapter V.

6. Let the following distribution of pressure be given along the line XX′:

$p = 0$ if $x < -1$ or $x > +1$, and $p = 1$ if x is between -1 and $+1$. (See fig. 70.)

We may easily determine the form of p by means of equation (15):

$$p = \frac{1}{\pi}\left(\tan^{-1}\frac{1+x}{y} + \tan^{-1}\frac{1-x}{y}\right). \tag{23}$$

The conjugate function is

$$\psi = \frac{1}{2\pi} \log_e \frac{(1-x)^2 + y^2}{(1+x)^2 + y^2}. \tag{24}$$

From (23) we derive the equipressural lines,

$$x^2 + (y - \cot c_1 \pi)^2 = \csc^2 c_1 \pi, \tag{25}$$

and from (24) we derive the lines of flow

$$(x + \coth c_2 \pi)^2 + y^2 = \operatorname{csch}^2 c_2 \pi. \tag{26}$$

This system of orthogonal curves consists of the two series of circles represented in fig. 71 and is the well-known "dipolar" system of circles. The velocity normal to O X at any point of O A is equal to

$$k \frac{\partial p}{\partial y}\Big]_{y=0} = \frac{2}{\pi} \frac{k}{1 - x^2}. \tag{27}$$

The flux normal to O A for any region between $x = 0$ and $x = x$ is given by

$$f = \int_0^x u\, dx = \frac{2\,k}{\pi} \int_0^x \frac{dx}{1 - x^2} = \frac{2\,k}{\pi} \tanh^{-1} x$$

$$= \frac{k}{\pi} \log_e \frac{1 + x}{1 - x}. \tag{28}$$

This expression gives the amount of water which percolates through each side of the ditch for each foot in depth of percolating surface.

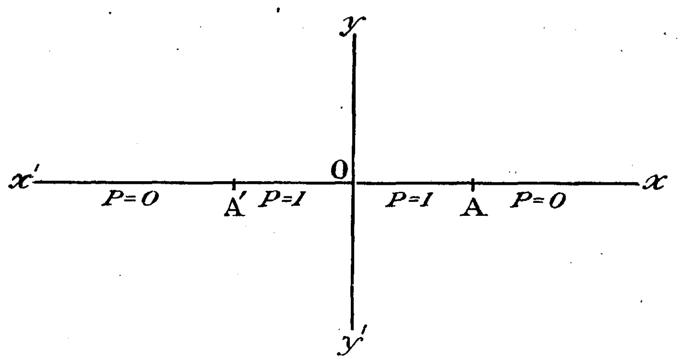


FIG. 70.—Boundary conditions for the problems discussed in sections 6 and 7, Chapter III.

The inverse problem to this is the case of a source at A and a sink at A′, or vice versa. The line of flow from A to A′ are shown in the diagram by the lines joining A and A′. The other lines are of equal pressure.

7. The significance of the above discussion is best shown by a particular example. Suppose that the ditch A A′ is 200 feet long, and that it contains 5 feet of water. Let the water be 2 feet lower in the ditches A X and A′ X′, and let the dams at A and A′ be 1 foot thick. The percolating surface O A is then 5 feet deep by 99 feet long. The difference of head under which the water flows is 2 feet, so that the flux from O A is

$$f = \frac{2 \times 5}{\pi} k \log_e \frac{1.99}{.01}.$$

This result must be doubled to give the flow from A′ A, and must be doubled again in order to account for the flow from both sides of the ditch. The number $\frac{99}{100}$ appears for x because O A was taken equal to unity in the work from which equation (28) was derived. The constant k depends upon the character of the soil. If we suppose that the soil grains have an effective size of 0.15 mm. and that the porosity is 30 per cent, the value of k will be that used in section 5 above, and designated by the logarithm (7.8169—10). The natural logarithm of 199 is 5.2833 and the total flowage is easily computed to be

0.5556 cubic foot per minute.

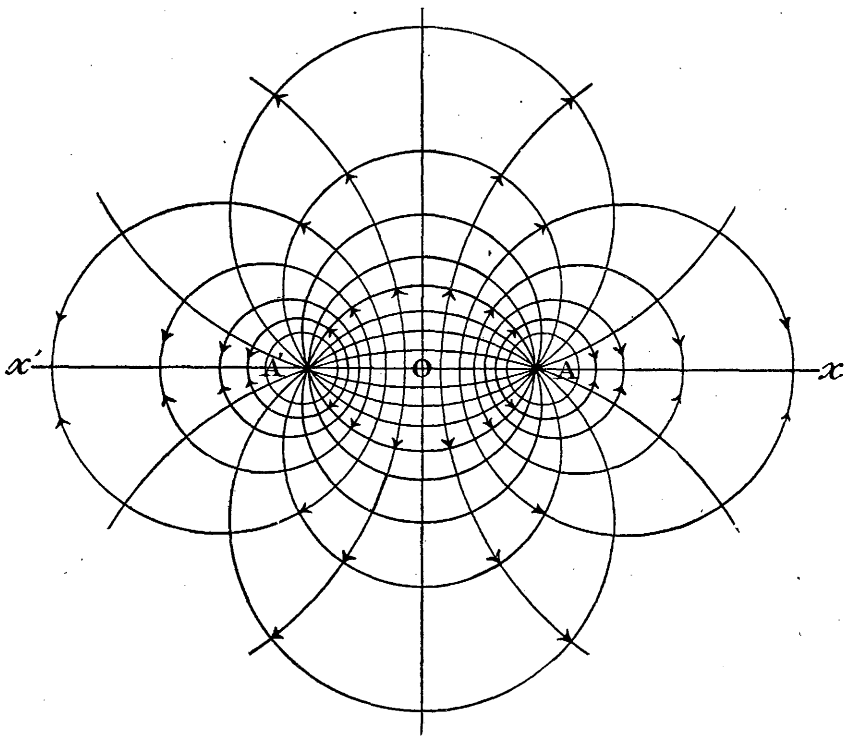


FIG. 71.—Lines of flow and lines of equal pressure for the problems discussed in sections 6 and 7, Chapter III. Lines of flow are indicated by arrowheads.

Inasmuch as we are not at present taking account of vertical flow, but are merely considering the horizontal motion of ground waters, we must suppose that the bottom of the ditch reaches a level impervious stratum, so that no percolation takes place through the bottom.

8. Let the following distribution of pressure be given along X X′: $p = -1$ if $x < -1$, $p = 0$ if $-1 < x < 1$, $p = 1$ if $x > 1$, as shown in fig. 72.

The form of p is easily determined from equation (16) above.

$$p = \frac{1}{\pi}\left[\tan^{-1}\frac{1+x}{y} - \tan^{-1}\frac{1-x}{y}\right]. \tag{29}$$

The conjugate function is

$$\psi = \frac{1}{2\pi}\log_e[(1-x)^2+y^2][(1+x)^2+y^2]. \tag{30}$$

The equation of the equipressural lines is, therefore,

$$x^2 + 2xy\cot c_1\pi - y^2 = 1, \tag{31}$$

and the equation of the lines of flow is

$$[(1-x)^2+y^2][(1+x)^2+y^2] = e^{2c_2\pi}. \tag{32}$$

The orthogonal system of curves consists of the system of rectangular hyperbolas and Cassinian ovals shown in fig. 73.

To illustrate approximately this case of motion, imagine X X′ to be a ditch in a soil in a region where the ground water is level. Suppose the ditch to be dammed at A and B and the pressure of water maintained in the portions of the ditch X′ B, B A, A X in the scale of the numbers 1, 2, 3. The water in A X will finally find itself in the ditch B X′, the water in the ditch to the right of K moving into B X′ without first passing into A B, and the water in the ditch between A and K moving into B X′ by first passing into the portion O A and out again through the walls of O B.

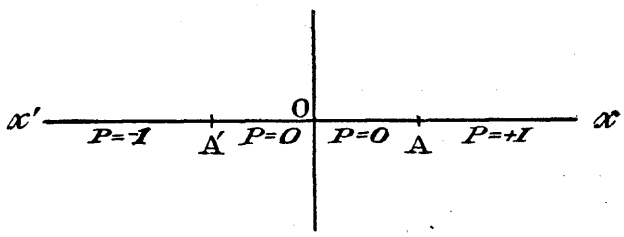


FIG. 72.—Boundary conditions for the problem discussed in section 8, Chapter III.

If we interchange p and ψ, we shall have the solution of the problem in which we have either two sources or two sinks at A and B, respectively. We may suppose, for example, that a level water-bearing stratum is pierced at A and B by two artesian wells which are being pumped simultaneously under the same loss of head, or which are flowing under the same head. Then the hyperbolas in the diagram represent the lines of flow into the well and the ovals represent curves of equal pressure.

A discussion of the mutual interference of the two wells presented by this problem is discussed in Chapter V, section 16.

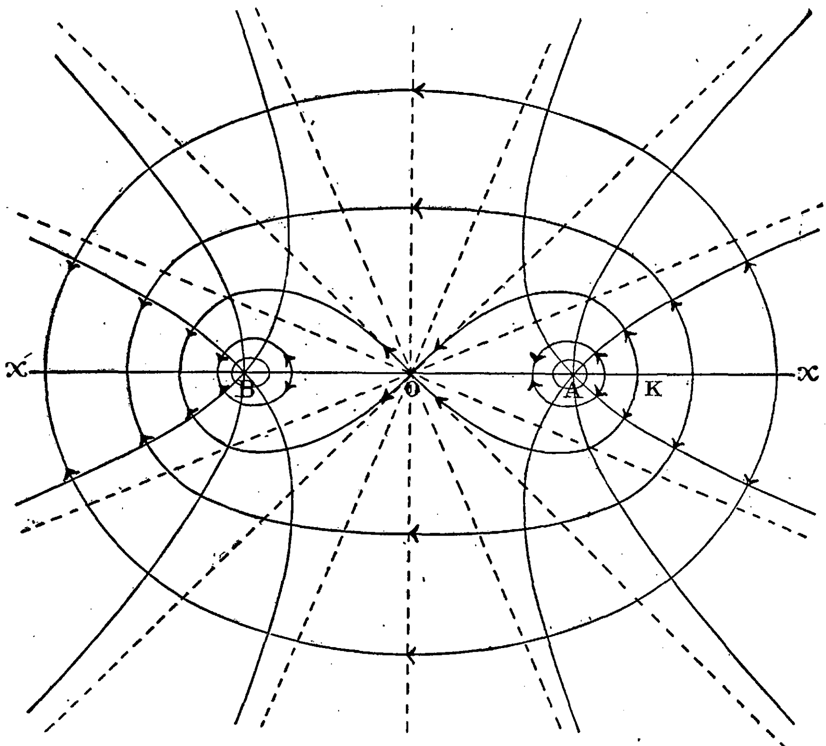


FIG. 73.—Lines of flow and lines of equal pressure for the problem discussed in section 8, Chapter III. Lines of flow are indicated by arrowheads. The dotted lines are the asymptotes to the hyperbolas. The point K is at the right-hand end of the lemniscate.

9. In general, if we have given any distribution of pressure, $f_x(x)$, along X X′ and any distribution, $f_y(y)$, along YY′, we obtain the following solution:

$$p = \frac{1}{\pi}\int_0^{\infty}\Big[f_x(\beta)\left(\frac{y}{y^2+(\beta-x)^2}-\frac{y}{y^2+(\beta+x)^2}\right)$$

$$+f_y(\beta)\left(\frac{x}{x^2+(\beta-y)^2}-\frac{x}{x^2+(\beta+y)^2}\right)\Big]d\beta. \tag{33}$$

If $f_x(x) = a$ and $f_y(y) = b$, we obtain

$$p = a + \frac{2}{\pi}(b-a)\tan^{-1}\frac{y}{x}, \tag{34}$$

$$\psi = \frac{2}{\pi}(b-a)\log_e(x^2+y^2). \tag{35}$$

10. If we have given a distribution of pressure along two parallel lines, say

$$p = f_x(x) \text{ when } y = 0$$

and

$$p = F_x(x) \text{ when } y = b,$$

we obtain the following solution:

$$p = \frac{1}{2b} \sin \frac{\pi y}{b} \int_{-\infty}^{\infty} \left[\frac{f_x(\beta)}{\cosh \frac{\pi}{b}(\beta - x) - \cos \frac{\pi y}{b}} + \frac{F_x(\beta)}{\cosh \frac{\pi}{b}(\beta - x) + \cos \frac{\pi y}{b}} \right] d\beta. \qquad (36)$$

11. If we have given a distribution of pressure around the edges of a rectangle, we may express the value of p at any point of the plane in terms of four Fourier's series. If the boundary conditions are

$$p = f_x(x) \text{ when } y = 0,$$
$$p = F_x(x) \text{ when } y = b,$$
$$p = f_y(y) \text{ when } x = 0,$$
$$p = F_y(y) \text{ when } x = a,$$

we obtain

$$p = \frac{2}{a} \sum_{n=1}^{n=\infty} \left[\sin \frac{n\pi x}{a} \left(\frac{\sinh \frac{n\pi}{a}(b-y)}{\sinh \frac{n\pi b}{a}} \int_0^a f_x(\beta) \sinh \frac{n\pi\beta}{a} d\beta + \frac{\sinh \frac{n\pi y}{a}}{\sinh \frac{n\pi b}{a}} \int_0^a F_x(\beta) \sin \frac{n\pi\beta}{a} d\beta \right) \right]$$

$$+ \frac{2}{b} \sum_{n=1}^{n=\infty} \left[\sin \frac{n\pi y}{b} \left(\frac{\sinh \frac{n\pi}{b}(a-x)}{\sinh \frac{n\pi a}{b}} \int_0^b f_y(\beta) \sin \frac{n\pi\beta}{b} d\beta + \frac{\sinh \frac{n\pi x}{b}}{\sinh \frac{n\pi a}{b}} \int_0^b F_y(\beta) \sin \frac{n\pi\beta}{b} d\beta \right) \right]. \qquad (37)$$

If the pressure on each of the four sides of the rectangle is h this reduces to

$$p = \frac{4}{\pi} \sum_{n=1}^{n=\infty} \frac{h}{n} \left(\frac{\sinh \frac{n\pi}{a}(b-y) + \sinh \frac{n\pi y}{a}}{\sinh \frac{n\pi b}{a}} \right) \sin \frac{n\pi x}{a}$$

$$+ \frac{4}{\pi} \sum_{n=1}^{n=\infty} \frac{h}{n} \left(\frac{\sinh \frac{n\pi}{b}(a-x) + \sinh \frac{n\pi x}{b}}{\sinh \frac{n\pi a}{b}} \right) \sin \frac{n\pi y}{b}. \qquad (38)$$

If $a = b$, this becomes

$$p = \frac{4}{\pi} \sum_{n=1}^{n=\infty} \frac{h}{n} \left(\frac{\sinh \frac{n\pi(a-y)}{a} + \sinh \frac{n\pi y}{a}}{\sinh n\pi} \right) \sin \frac{n\pi x}{a}$$

$$+ \frac{4}{\pi} \sum_{n=1}^{n=\infty} \frac{h}{n} \left(\frac{\sinh \frac{n\pi}{a}(a-x) + \sinh \frac{n\pi x}{a}}{\sinh n\pi} \right) \sin \frac{n\pi y}{a}. \qquad (39)$$

METHOD OF CONJUGATE FUNCTIONS OR CONFORMAL TRANSFORMATION.

12. As previously stated, many important problems in two-dimensional potential can be solved by the method of conjugate functions. For the complete theory and the details of the method the reader must be referred to special treatises, such as the chapters of Bassett, Lamb, and Clerk Maxwell, referred to in section 2, or to A. G. Webster's Theory of Electricity and Magnetism (New York, 1897), pages 79–90 and 307–324, but especially to Gustav Holzmüller's Einführung in die Theorie der isogonalen Verwandtschaften (Leipsig, 1882).

Briefly stated, the method of conjugate functions depends upon the fact that if a finite single-valued and continuous function of a complex variable, as, for example,

$$f(x + yi),$$

be broken up into its real and imaginary parts, say p and ψi, so that

$$f(x + yi) = p + \psi i,$$

then p and ψ are each functions of x and y, which satisfy Laplace's equation. Also the equations

$$p = c_1,$$
$$\psi = c_2,$$

when represented geometrically for arbitrary values of c_1, and c_2, give a system of orthogonal curves, one set of which are the equipotential or equipressural lines, while the other set are the lines of flow.

Stated geometrically, the process consists in transforming the system of orthogonal straight lines

$$x = c',$$
$$y = c'',$$

by means of the function or operator f, into a system of orthogonal curves

$$p = c_1,$$
$$\psi = c_2,$$

which curves, like the system of straight lines, will constitute a new and possible scheme of equipotential lines and lines of flow. When looked at from this point of view, the process is called "conformal transformation," or "conformal representation."

The form of the function f may be selected in an unlimited number of ways, and the orthogonal curves may be determined for an unlimited number of problems, but it is usually inadvisable to attempt to assign in advance the form that must be given to f in order to produce curves of a given kind. The usual process is tentative and indirect, and consists in assigning the form of f. An interesting solution of the problem of section 13, below, by a direct method, may be found in Webster's Treatise on Electricity and Magnetism, page 315.

In the following paragraphs we shall uniformly employ the notations

$$z = x + iy \tag{40}$$

and

$$w = f(z) = f(x + iy) = p + i\psi. \tag{41}$$

13. Let us perform the transformation

$$w = \cosh^{-1}\frac{z}{c},$$

or, what is the same thing, the transformation

$$z = c \cosh w; \tag{42}$$

that is

$$x + iy = c \cosh (p + i\psi) \tag{43}$$

$$= c\,(\cosh p \cos\psi + i \sinh p \sin\psi). \tag{44}$$

Therefore

$$x = c \cosh p \cos\psi, \tag{45}$$
$$y = c \sinh p \sin\psi,$$

and eliminating p and ψ in turn,

$$\frac{x^2}{c^2 \cosh^2 p} + \frac{y^2}{c^2 \sinh^2 p} = 1, \tag{46}$$

$$\frac{x^2}{c^2 \cos^2 \psi} - \frac{y^2}{c^2 \sin^2 \psi} = 1. \tag{47}$$

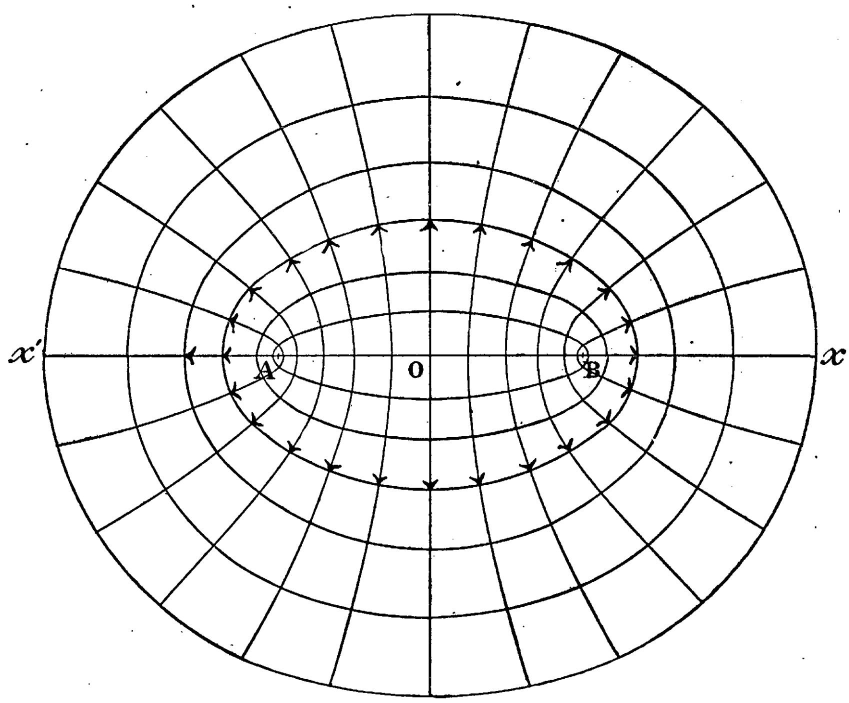


FIG. 74.—Lines of flow and lines of equal pressure for the problem discussed in section 13, Chapter III. Lines of flow are indicated by arrowheads.

These equations represent a system of confocal ellipses and hyperbolas, as shown in fig. 74. Solving (46) for p and (47) for ψ, we obtain

$$\begin{aligned} p &= \cosh^{-1} H, \\ \psi &= \cos^{-1} H, \end{aligned} \tag{48}$$

in which

$$H = \left[\frac{x^2 + y^2 + c^2 \pm \sqrt{(x^2+y^2+c^2)^2 - 4\,c^2x^2}}{2c^2}\right]^{\frac{1}{2}}. \tag{49}$$

For the values of p and ψ along XX′ these reduce to

$$p = \cosh^{-1}\frac{x}{c} \text{ for } x > +c \text{ and } < -c, \tag{50}$$

$$p = 0 \qquad \text{for } x < +c \text{ and } > -c, \tag{51}$$

$$\psi = \cos^{-1}\frac{x}{c} \text{ for } x < +c \text{ and } > -c, \tag{52}$$

$$\psi = 0 \qquad \text{for } x > +c, \tag{53}$$

$$\psi = \pi \qquad \text{for } x < -c. \tag{54}$$

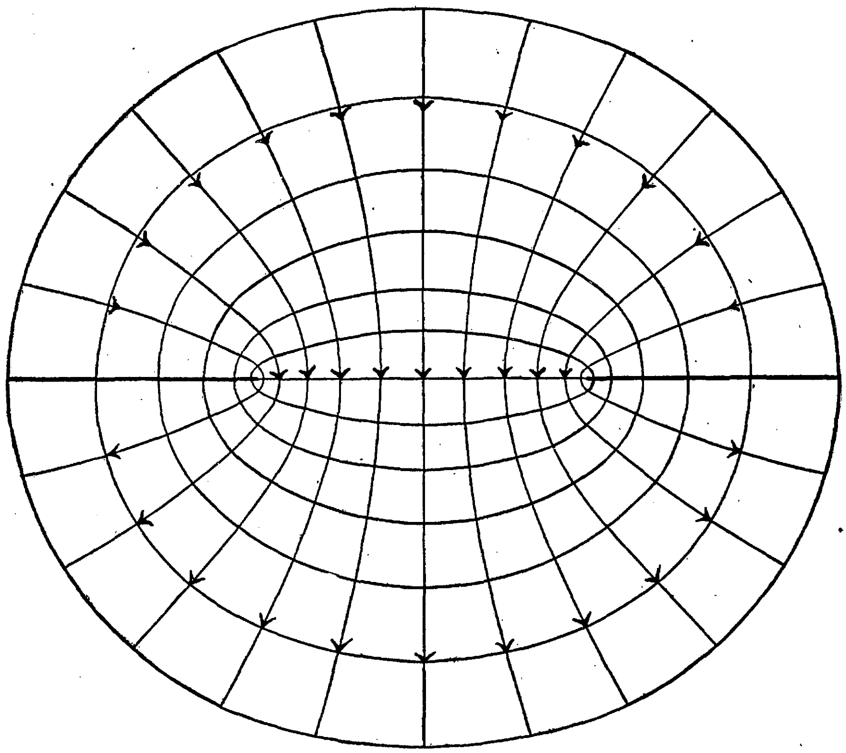


FIG. 75.—Lines of flow and lines of equal pressure for a modification of the problem discussed in section 13, Chapter III. Lines of flow are indicated by arrowheads.

This problem admits of several interesting modifications. If we maintain a pressure 0 along the line AB, and a constant pressure along any one of the ellipses, then the hyperbolas are lines of flow as represented in fig 74. If the pressure is maintained equal to $-k$ along the upper half of one of the ellipses and equal to $+k$ along the lower half of the same ellipse, and if A X′ and B X are impervious partitions, then the lines of flow are represented by the hyperbolas as marked in fig. 75. If the signs of k be reversed in both instances mentioned, the arrowheads will point in the reverse directions. If, however, pressure is maintained equal to 0 along A X′ and equal to π along B X, then the ellipses become the lines of flow as marked in fig. 76. Thus we may say that fig. 74 represents the lines of flow and the lines of pressure when ground water is flowing into the ditch A B, or, in the case of fig. 76, we have the case of ground water flowing from the ditch B X into the ditch A X′ through the surrounding soil, the water being 3.1416 feet higher in B X than in A X′.

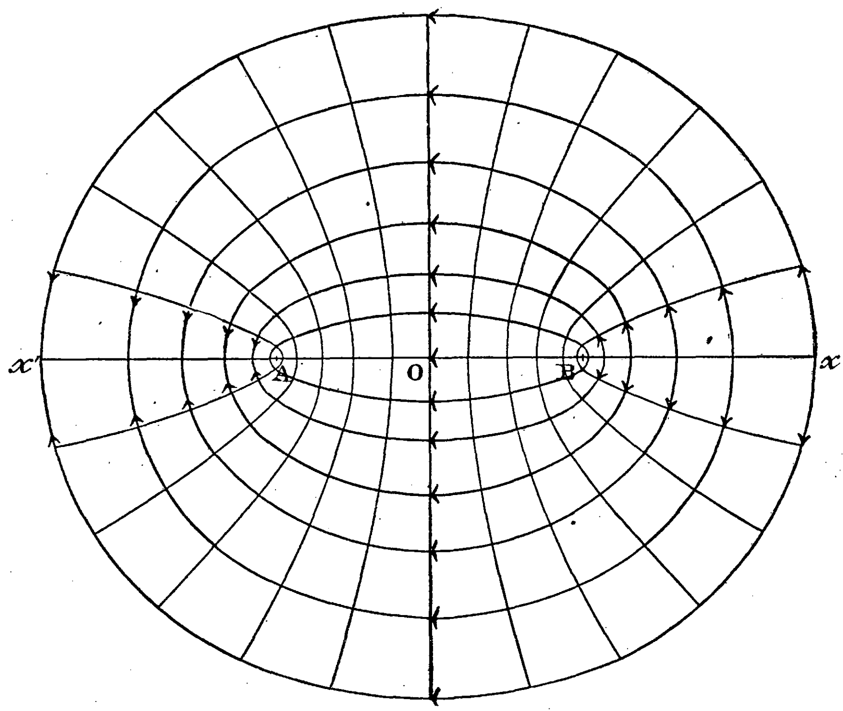


FIG. 76.—Lines of flow and lines of equal pressure for a second modification of the problem discussed in section 13, Chapter III. Lines of flow are indicated by arrowheads.

The chief value in the results of a problem of the kind just mentioned is qualitative rather than quantitative. To appreciate fully all the qualitative results that follow from the discussion we must remember that any pair of ellipses or any pair of hyperbolas may be taken as the boundaries along which a constant pressure is maintained; the included parts of the orthogonal curves will then represent the lines of flow.

An interesting modification of the present problem is brought about by increasing the distance AB indefinitely. In this case the ellipses and hyperbolas become an orthogonal system of parabolas as represented in fig. 77. The equations to these are

$$y^2 = 4p\ (x + p),$$
$$y^2 = 4\psi\ (x - \psi).$$

14. Another interesting transformation is furnished by the substitution

$$z = w + e^w,$$

or

$$x + iy = p + i\psi + e^{p+i\psi}.$$

Therefore

$$x = p + e^p \cos \psi,$$
$$y = x + e^p \sin \psi.$$

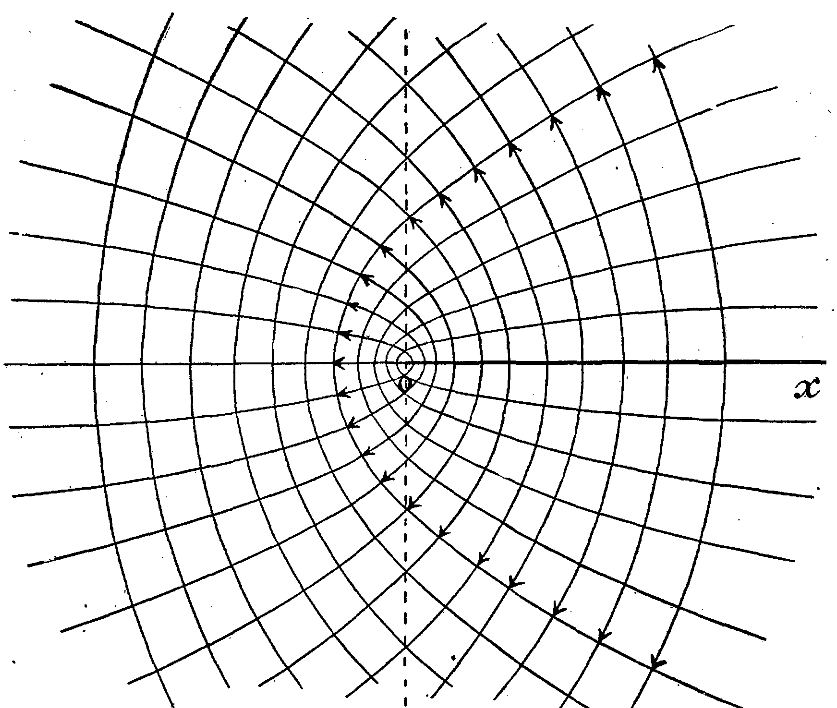


FIG. 77.—Lines of flow and lines of equal pressure for the problem discussed in section 13, Chapter III, as they exist after increasing indefinitely the length of A B, fig. 74. Lines of flow are indicated by arrowheads.

The lines of flow and lines of equal pressure are shown in fig. 78. It is the case of flow into a porous medium from the canal BB′AA′ with the impervious walls AB and A′B′. If the lines connecting AB with

A′B′ are taken as the lines of flow, then we must have a constant pressure maintained along BA and B′A′ and a pressure zero along XX′,

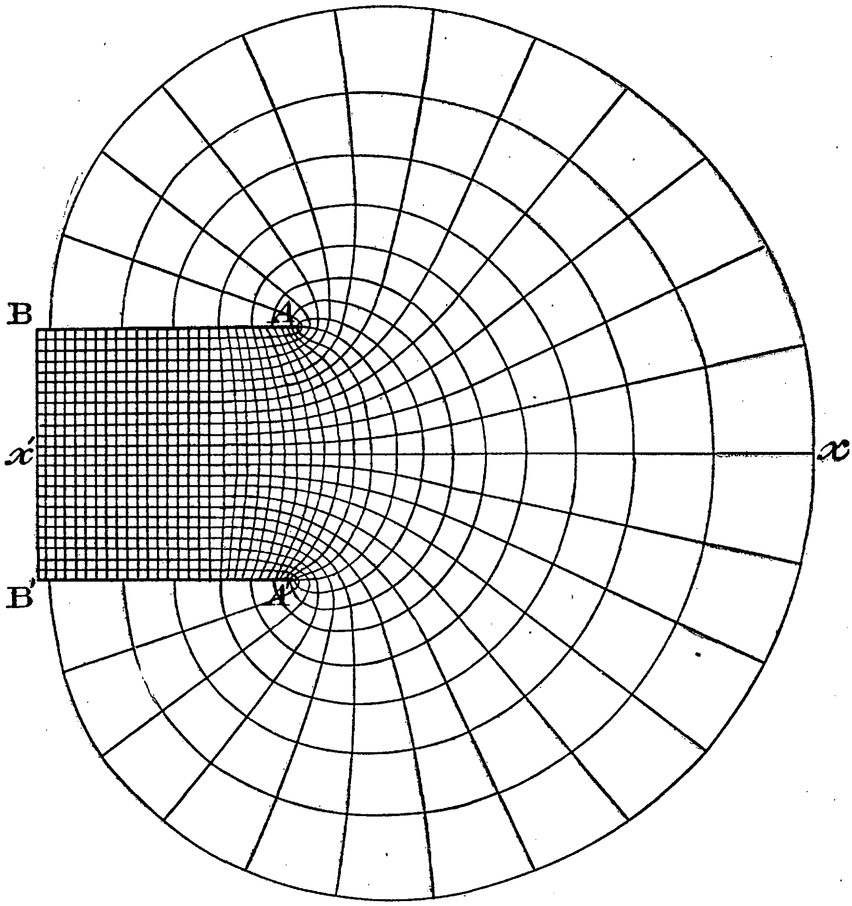


FIG. 78.—Lines of flow and lines of equal pressure for the problems discussed in section 14, Chapter III. (After Helmholtz and Clerk Maxwell.)

or a constant pressure maintained along BA, with a constant lower pressure along B′A′, or vice versa[1].

[1] See H. von Helmholtz, Wissenschaftliche Abhandhengen, Vol. I, p. 154.

CHAPTER IV.

MOTION OF GROUND WATER IN VERTICAL PLANES.

1. The important distinction between motion of ground water in horizontal and the motion of ground water in vertical planes has already been pointed out.[1] This distinction is necessitated, of course, by the important control of gravity upon the motion of anything that has vertical freedom of motion, which control becomes nil in case vertical freedom vanishes.

The equations of motion for the vertical plane xz, as determined in Chapter II, section 4, are:

$$u = k\frac{\partial p}{\partial x}, \tag{1}$$

$$w = k\frac{\partial p}{\partial z} + k\rho g, \tag{2}$$

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial z^2} = 0. \tag{3}$$

Laplace's equation for the determining of p is the same as in the case of horizontal motion, but the boundary conditions are, of course, of quite a different character from those occurring in the class of problems already discussed. The effect of gravity is shown by the presence of the additional term $k\rho g$ in the expression for the vertical component of velocity, w.

2. Let the following diagram, fig. 79, represent a vertical section of a rectangular tank filled with sand, having an impervious bottom, but with the portions O B and A C of the ends made of pervious material, such as wire gauze, and so constructed as to permit the free escape of the water. Let the distances O B and A C be represented by b and let a given head of water, h, be maintained above the surface of the soil B C. If the distance O A is $2a$, we require the lines of flow and lines of pressure throughout the soil in the tank, and the quantity of water escaping at the ends.

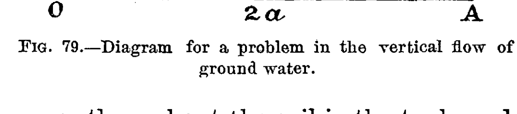


FIG. 79.—Diagram for a problem in the vertical flow of ground water.

[1] See Chapter II, section 4.

The boundary conditions are

$$p = 0 \text{ when } x = 0, \tag{4}$$
$$p = 0 \text{ when } x = 2a, \tag{5}$$
$$p = h \text{ when } z = b, \tag{6}$$
$$w = 0 \text{ when } z = 0. \tag{7}$$

This last condition may be written

$$\frac{\partial p}{\partial z} = -g\rho \text{ when } z = 0. \tag{8}$$

Following the usual method for the expression of the solution of Laplace's equation in a Fourier's series satisfying the boundary conditions, we obtain

$$p = \frac{4h}{\pi}\sum_{n=1}^{n=\infty}\frac{1}{n}\frac{\cosh\frac{n\pi z}{2a}}{\cosh\frac{n\pi b}{2a}}\sin\frac{n\pi x}{2a}$$

$$+\frac{4g\rho}{\pi}\cdot\frac{2a}{\pi}\sum_{n=1}^{n=\infty}\frac{\sinh\frac{n\pi(b-z)}{2a}}{n^2\cosh\frac{n\pi b}{2a}}\sin\frac{n\pi x}{2a}. \tag{9}$$

In this series n is to take on the values of successive odd numbers only.

From this equation we easily determine by differentiation the expressions for the velocities:

$$u = \frac{2hk}{a}\sum_{n=1}^{n=\infty}\frac{\cosh\frac{n\pi z}{2a}}{\cosh\frac{n\pi b}{2a}}\cos\frac{n\pi x}{2a}$$

$$+\frac{4g\rho k}{\pi}\sum_{n=1}^{n=\infty}\frac{1}{n}\frac{\sinh\frac{n\pi(b-z)}{2a}}{\cosh\frac{n\pi b}{2a}}\cos\frac{n\pi x}{2a}, \tag{10}$$

$$w = \frac{2hk}{a}\sum_{n=1}^{n=\infty}\frac{\sinh\frac{n\pi z}{2a}}{\cosh\frac{n\pi b}{2a}}\sin\frac{n\pi x}{2a}$$

$$-\frac{4g\rho k}{\pi}\sum_{n=1}^{n=\infty}\frac{1}{n}\frac{\cosh\frac{n\pi(b-z)}{2a}}{\cosh\frac{n\pi b}{2a}}\sin\frac{n\pi x}{2a}+g\rho k. \tag{11}$$

3. The amount of the fluid flowing out of one end is

$$f = \int_0^b u \, dz. \tag{12}$$

If h be taken equal to zero, the integration of (12) gives

$$f = \frac{8a}{\pi^2} g \rho k \sum_{n=1}^{n=\infty} \left[\frac{1}{n^2} - \frac{1}{n^2 \cosh \frac{n \pi b}{2 a}} \right]$$

$$= \frac{8 a}{\pi^2} g \rho k \left[\frac{\pi^2}{8} - \sum_{n=1}^{n=\infty} \frac{1}{n^2 \cosh \frac{n b \pi}{2 a}} \right], \tag{13}$$

in which n is an odd number. If we take in turn $a = b$, $2b$, and $4b$, we obtain the following results:

Value of a.	Flux.
b	(.674) $g \rho k b$
$2 b$	(.737) $g \rho k b$
$4 b$	(.739) $g \rho k b$

In converting these results into cubic feet per minute we must substitute the value of k used in our previous work for $g k$ in this formula, since we have agreed to measure pressure in terms of water height and not in dynes or poundals. For water the density ρ may of course be placed equal to unity.

4. The lines of equal pressure for the case of $a = b = 10$ are shown in fig. 80. Water is supplied to the upper surface B C just as fast as it will percolate into the sand, and the end surface A B is the surface that is supposed to be constructed of wire gauze or other material permitting the free flowage of the water through it. If the end A B be made impervious, the lines of equal pressure will become the horizontal lines, marked 0, 1, 2, 3, etc. In the case represented in the diagram the lines A B and B C are the lines of zero pressure, and the curves of higher pressure are represented by the hyperbola-like curves, marked "Pressure = 1," "Pressure = 2," etc.

A remarkable fact brought out by this diagram is the distinction that must be made between the level at which moving ground water stands and the actual pressure to which the ground water is subjected at a given point. It is often assumed that the level of the surface of the water in a well indicates the position of the water table and that a change in the height of water in a well indicates the same change in the level of the water table. This assumption is fallacious, unless the water exists in a purely statical condition. For example, the position of the water table in the section A B C D coincides with the surface B C, yet the pressure within the section has various values for points on the same horizontal line. The variation in pressure along H K is very slight, the pressure being zero at H and less than $1\frac{1}{2}$ at K. The pressure along M N has various values, but nowhere reaches a value so

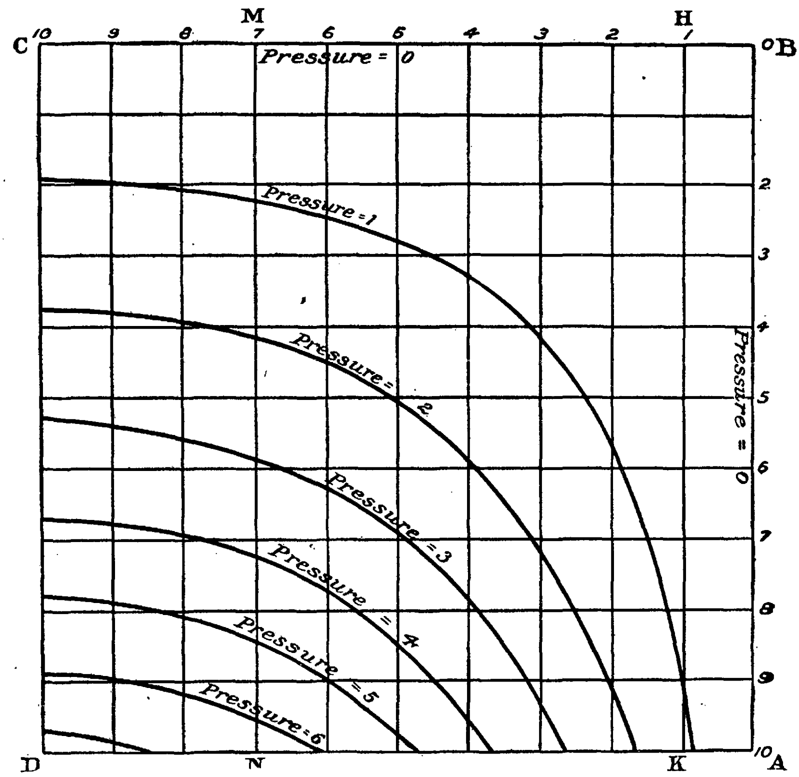


FIG. 80.—Approximate position of the lines of equal pressure for the problem in the vertical flow of ground water discussed in section 4, Chapter IV. The horizontal plane through A D and the vertical plane through C D are impervious. Water is free to escape through the vertical plane through A B, and the surface B C is kept covered with a thin layer of water.

high as 10, which is the pressure that would exist at the bottom if percolation at A B were stopped and a statical condition produced. A well sunk at M N would probably show an increasing depth of water as the well was dug deeper and deeper. A common well point driven to various depths would doubtless show a water level corresponding closely to the pressure lines in the diagram. An ordinary well, since it can receive water throughout its entire length, would probably disturb the equipressural lines in its neighborhood, and the surface of the water in the well would not be likely to correspond closely with the original pressure line at the bottom of the well.

The pressure along A D would be everywhere 10 if the surface A B were closed and a statical condition produced. As it is, the pressure varies rapidly along A D, but does not reach the value 10 at any point.

We conclude, then, that the wells in a given district might be seriously interfered with by the construction of a drainage flume near them, and yet the water table in the neighborhood of the wells might show but little change of level. Nevertheless it is sometimes maintained that a drainage flume can not be the cause of the lowering of the water in the wells of a district unless the amount of water entering the flume in a given time after it is first used is enough to lower the entire water table of the district by an amount equal to the measured fall of the wells during that time. Thus, if the wells of a district containing one square mile are found to have fallen one foot after a new drainage flume has been used for a month, and if the water-bearing soil contains 20 per cent of water, then the argument is that the drainage flume has not caused the fall of water in the wells unless the flume has actually taken off $\frac{1}{5}$ of $5{,}280^2$ cubic feet of water in the month considered. A general lowering of even a few feet in the water table of a district represents an enormous amount of water, and a flume is seldom likely to be held responsible for an interference with wells if tested by the principle just mentioned. The lowering of the wells, although a fact, would have to be explained by the hypothesis of a "dry season" or by some other convenient hypothesis. The facts as represented in fig. 80 show, however, the fallacy of the argument. The flume may not cause a lowering of the water table for any great distance from its walls, but the lowering of the pressure, as indicated by the lowered position of the water surface in the wells, may extend to great distances. This is a fact that nonmathematical reasoning shows must exist. The water supply for the flume comes from the surrounding soil; hence the water in the soil is in motion. The motion of the ground water against the resistance of the capillary spaces of the soil requires the existence of an adequate moving agent. This moving agent must be a pressure gradient extending away from the walls of the flume. This pressure gradient must come into existence as soon as the water begins to move and before there is time for an appreciable lowering of the water table to take place. The drop in the water level in the wells shows the change in pressure of the water in the surrounding soil and does not necessarily indicate a change in the position of the water table.

5. If a is indefinitely increased in length, the Fourier's series in section 2 becomes a Fourier's integral of the form

$$p=\frac{1}{\pi}\int_0^\infty\int_0^\infty \frac{\sinh \alpha(b-y)}{\alpha \cosh \alpha b}\left[\cos \alpha(\beta-x)-\cos \alpha(\beta+x)\right] g\rho d\beta d\alpha, \tag{14}$$

and, since $u=k\frac{\partial p}{\partial x}$,

$$u=\frac{k}{\pi}\int_0^\infty\int_0^\infty \frac{\sinh \alpha(b-y)}{\cosh \alpha b}\left[\sin \alpha(\beta-x)+\sin \alpha(\beta+x)\right] g\rho d\beta d\alpha. \tag{15}$$

For $x=0$, we get

$$u_0=\frac{2\,k\,g\,\rho}{\pi}\int_0^\infty\int_0^\infty \frac{\sinh \alpha(b-y)}{\cosh \alpha b}\sin \alpha\beta d\beta d\alpha, \tag{16}$$

and from D. Bierens de Haan's Nouvelles tables d'intégrales définies, table 265, formula 2, we secure the integration and obtain

$$u_0=\frac{2\,g\,\rho\,k}{b}\int_0^\infty \frac{\sinh\frac{\beta}{2}\frac{\pi}{b}\sin\frac{b-y}{b}\frac{\pi}{2}}{\cosh\frac{\beta\,\pi}{b}+\cos\frac{(b-y)\,\pi}{b}}\,d\beta. \tag{17}$$

Changing the variable to $t=\cosh\frac{\beta}{b}\frac{\pi}{2}$, we get

$$u_0=\frac{2\,g\,\rho\,k}{\pi}\sin\frac{b-y}{b}\frac{\pi}{2}\int_1^\infty\frac{dt}{t^2-a^2} \tag{18}$$

$$=-\frac{2\,g\,\rho\,k}{\pi}\log\tan\frac{y}{b}\frac{\pi}{4}. \tag{19}$$

The flux at one end is then

$$f=\int_0^b u\,dy=\int_0^{\pi/4}\frac{2\,g\,\rho\,k}{\pi}\log\tan\frac{y}{b}\frac{\pi}{4}\,dy \tag{20}$$

$$=\frac{8}{\pi^2}\,b\,g\,\rho\,k\sum\frac{(-1)^n}{(2\,n+1)^2}, \tag{21}$$

by Bierens de Haan, table 286, formula 11. We may then write

$$f=\frac{8}{\pi^2}\,b\,g\,\rho\,k\left[\left(1+\frac{1}{3^2}+\frac{1}{5^2}+\ldots\right)-2\left(\frac{1}{3^2}+\frac{1}{7^2}+\frac{1}{11^2}+\ldots\right)\right] \tag{22}$$

$$=b\,g\,\rho\,k\left(1-\frac{16}{\pi^2}\left[\frac{1}{3^2}+\frac{1}{7^2}+\ldots\right]\right) \tag{23}$$

$$=(.7420)\,b\,g\,\rho\,k. \tag{24}$$

6. The meaning of this formula is illustrated by the following problem:

A bed of sandstone 200 miles square and 100 feet thick has one side exposed so that seepage takes place freely. What annual rainfall can be disposed of by this bed of sandstone if the stone have a mean size of grain of 0.15 mm. and a porosity of 30 per cent?

The distance of 200 miles is so large in comparison with 100 feet that we may suppose a to be infinite. The constant k for stone of this kind is given in section 12 of Chapter I, but the constant there used is equivalent to $g\,k$ of the present problem (equation 24), as pressures were measured in feet of water in the formula of section 12. Taking [7.8169−10], the logarithm of the constant k, from that work, and substituting $\rho = 1$, $b = 100$ in equation (24) we obtain

$$f = [9.8169-10] \times (.7420)$$
$$= .4867 \text{ cubic foot per minute}$$

as the flux from each linear foot of the cliff. This flux requires a rainfall of 0.00864 inch per day, or 3.153 inches per year, over the area 200 miles square to furnish an adequate supply of water.

CHAPTER V.

FLOW OF ARTESIAN WELLS AND THEIR MUTUAL INTERFERENCE.

1. We shall first attempt to compute the flow into an artesian well which completely penetrates a level homogeneous water-bearing stratum,

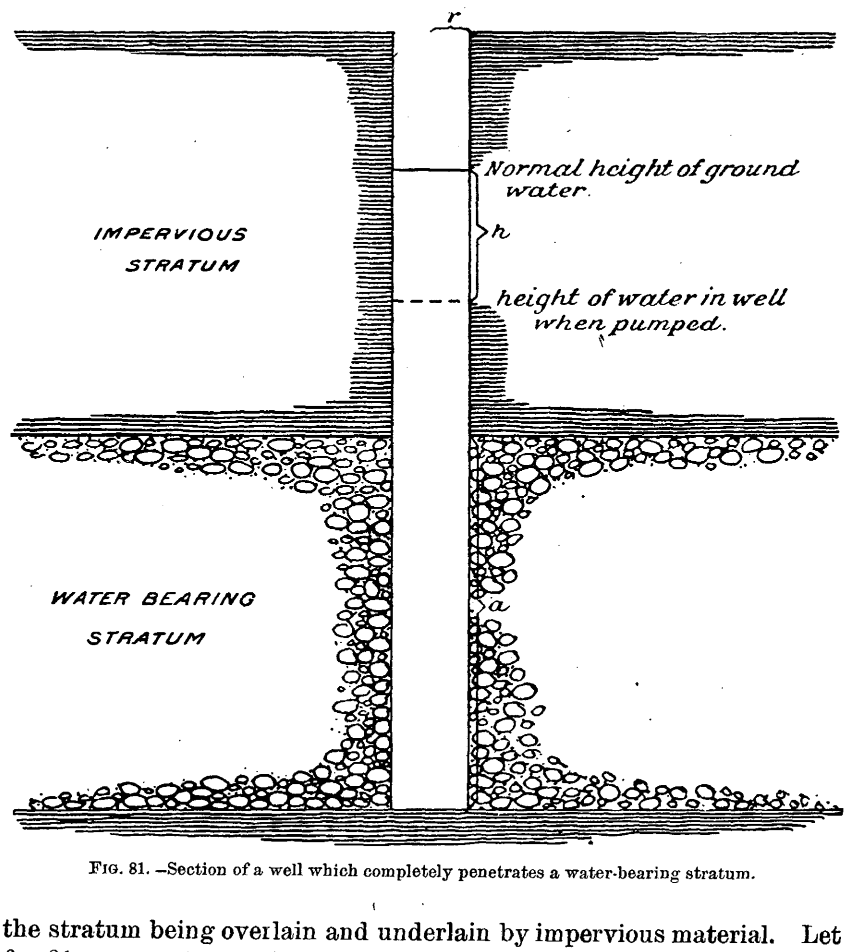


FIG. 81. –Section of a well which completely penetrates a water-bearing stratum.

the stratum being overlain and underlain by impervious material. Let fig. 81 represent a section through the well and rock, and let

r = radius of the well;
a = thickness of water-bearing rock;
h = amount of lowering of water in the well by pumping.

The amount of water flowing into the well under the constant head h can easily be deducted from the general equations of Chapter II, section 3, first transforming the equations to polar coordinates, or it may be deduced from the inverse of the problem of section 4, Chapter III, but it is quite as easy and more instructive to proceed independently of these general methods.

The velocity at a point P distant ρ from the axis of the well is given by

$$v = k\frac{dp}{d\rho}, \tag{1}$$

in which p represents the pressure at the point P and in which k represents a constant[1] determined by experiment or estimated from theoretical considerations as explained in Chapter I, equation (47). We also know that the velocity toward the well must vary inversely with the distance from the axis of the well, since the circumferences of concentric circles with their centers on the axis of the well are crossed by equal amounts of ground water in equal times. Thus we have

$$v = \frac{c}{\rho}, \tag{2}$$

in which c is a constant to be determined. From (1) and (2) we write

$$c\frac{d\rho}{\rho} = kdp, \tag{3}$$

and from this we derive

$$c \log_e \rho = kp + C, \tag{4}$$

in which $\log_e$ stands for the natural or hyperbolic logarithm. We know that $p = h$ when $\rho = r$. If we assume that R is the distance from the wall of the well at which the pressure may be assumed to be equal to its normal value (that is, $p = 0$ when $\rho = R + r$) we obtain

$$c \log_e (R + r) = C, \tag{5}$$

$$c \log_e r - kh = C. \tag{6}$$

Whence,

$$c \log_e r = kh + c \log_e (R + r).$$

Therefore,

$$c = \frac{kh}{\log_e\left(1 + \frac{R}{r}\right)} = km, \tag{7}$$

in which m is a constant.

[1] k is the quantity of water that would be transmitted in unit time through a cylinder of the stone of unit length and cross section, under unit difference in head at the ends.

Substituting the constant c in (2) we obtain

$$v = \frac{kh}{\rho \log_e \left(1 + \frac{R}{r}\right)}. \tag{8}$$

The velocity at the wall of the well is found by placing $\rho = r$; and by multiplying the velocity at the wall of the well by $2 \pi r a$, the surface of the well, we obtain an expression for the total amount flowing into the well in unit time, or

$$f = \frac{2\pi hka}{\log_e \left(1 + \frac{R}{r}\right)}$$

$$= \frac{2\pi hka}{\log_e \left(1 + \frac{600}{r}\right)} \text{ cubic feet per minute.} \tag{9}$$

The reason for taking R = 600 feet will be explained later.

By substituting the value of the constant c in equation (4) we obtain

$$p = \frac{c}{k} \log_e \frac{\rho}{R + r}, \tag{10}$$

and since $p = h$ when $\rho = r$, we obtain

$$p = h \frac{\log_e \frac{\rho}{R + r}}{\log_e \frac{r}{R + r}}, \tag{11}$$

which is the law of variation of the pressure along the radius vector ρ. p is seen to be of the form (as indeed equation (4) shows),

$$p = m \log_e \rho + C, \tag{12}$$

which agrees with equation (18), Chapter III.

By using the flux f as the constant instead of h, we may write (11) in the convenient form

$$p = -\frac{f}{2\pi ka} \log_e \frac{\rho}{R + r}. \tag{13}$$

2. To illustrate the use of these formulas it is well to apply them at once to a particular case. Suppose, for example, that we have a 6-inch well penetrating a level bed of water-bearing sandstone 100 feet thick, and that the sandstone has an effective size of grain of 0.15 mm. and a porosity of 30 per cent. What is the quantity of water furnished by the well if the water in the well be lowered by pumping 10 feet below its normal level?

Here $h=10$, $a=100$, $r=1/4$, and the value of k may be taken from equation (47), Chapter I, where we find

$$k=[1.1846]\frac{d^2}{K},$$

or, with the values of d and k substituted, as written in equation (48), Chapter I,

$$k=[7.8169-10],$$

in which the bracket incloses the logarithm of the true value of k.

The value of R, or the distance from the wall of the well to a point at which the pressure is essentially normal, is usually taken as 200 meters, or about 600 feet.[1] The natural logarithm of $(1+\frac{R}{r})$ is in this case 7.7835. From this data, equation (9) furnishes the flux of the well.

$$f=5.234 \text{ cubic feet per minute.} \qquad (14)$$

3. If we assume a larger sized soil grain and a larger porosity, say $d=.25$ mm. and porosity $=32$ per cent, the other elements of the problem remaining the same as above, we shall, of course, obtain a much larger flow. The value of k for the data just given can be found in Chapter I, equation (49). It is there found to be [8.3537 — 10], which gives a flux of

$$f=18.01 \text{ cubic feet per minute.} \qquad (15)$$

4. It is observed from formula (9) that the yield of a well is directly proportional to the amount that the surface of the water in the well is lowered by pumping. The statement for a flowing artesian well should be, of course, that the yield is proportional to the change in head from a static to a flowing condition. In the case of flowing wells, however, the yield may be largely or entirely controlled by the capacity of the tubing or well hole to transmit water. The equation (9) is obtained on the assumption that the bore of the well is large enough to carry off without appreciable resistance all of the water furnished by the percolating surface of the well. Undoubtedly, in many actual cases, where, for example, the stone is very coarse-grained and the static pressure at the well is enormous, the controlling fact is the capacity of the pipe and well-hole to carry water. In a given instance the effect of the frictional resistance of the tubing and well wall may be taken account of by means of the usual hydraulic formulæ or tables for the flow of water through pipes, as will be illustrated later.

5. If the capacity of the pipe and well is sufficient to carry off, without appreciable resistance, the water that comes to them, an increase in the size of the well will have but a slight effect on the amount of

[1] This seems to be the value used by Lueger, Frühling, and other Continental authorities.

water furnished by it. This is because that part of the expression for the flux of the well which depends upon the radius of the well, namely,

$$\log_e \left(1 + \frac{R}{r}\right), \tag{16}$$

varies but slightly for a variation in r. In fact, if we compute the flow of a 2-inch, a 4-inch, and a 12-inch well, with all other circumstances the same as in the last article, we obtain the following results:

TABLE IV.—*Capacity of wells of various sizes, extending 200 feet into sandstone of a given kind, flowing under 10-foot head.*

[No allowance is made for friction on sides of well or pipe.]

Size of well.	Capacity per minute.
Inches.	*Cubic feet.*
2	15.79
4	17.11
6	18.01
12	19.78

Of course the friction in the 2-inch well would cut the above figures down enormously, but the figures for the 6-inch and the 12-inch wells would not be modified materially for any length of suction pipe that would probably be used.

6. To illustrate the important part which pipe friction plays in the capacity of these wells, let us suppose that in case of each of the above wells the friction of well wall and suction pipe is equivalent to 200 feet of straight pipe of the same size as the well. By the use of Weston's Hydraulic Tables[1] we are able to take account of the retarding influence of friction. Turning to page 55 of Weston's table, we notice that a mean velocity of 12 feet per second (which corresponds to the computed flow of 15.79 cubic feet per minute for the 2-inch well) would require to maintain it a head of 24.62 feet per 100 feet. Inasmuch as we have assumed in the above problems that the total effective head available is only 10 feet, it is plain that a capacity of 15.79 cubic feet per minute is impossible for a 2-inch well if we count the resistance of 200 feet of pipe. On page 54 of the same table we note that a velocity of 4.08 feet per second gives a loss of head of 3.63 feet per 100 feet or of 7.3 feet per 200 feet. This would leave but 3.6 feet of the available head of 10 feet to produce a flow into the well, which, then, would give a velocity of only 36 per cent of 12 feet per second or 4.3 feet per second. This nearly agrees with the tabulated velocity

[1] Edmund B. Weston, Tables showing loss of head due to friction of water in pipes, New York, 1896.

4.08, so that the actual capacity of the 2-inch well is about 36 per cent of 15.79, or about 5.7 cubic feet per minute.

The particular entry in Weston's table that gives the desired correction can easily be found by a few trials. The correction for a 4-inch well can be found on page 97. The flow, 17.11 cubic feet per minute, found above corresponds to a mean velocity of 3.3 feet per second. A mean velocity of 2.81 feet per second gives, from page 97 of Weston's table, a loss of head of 1.83 feet per 200 feet. This is a reduction of head of 18.3 per cent of 10 feet, and a reduction of 18.3 per cent from the mean velocity of 3.3 gives a velocity of 2.7, which is fairly close to 2.81, the velocity used. A reduction of 18.3 per cent from the capacity 17.11 found above for the 4-inch well gives a corrected value of about 14 cubic feet per minute.

The correction for the friction of 200 feet of 6-inch pipe for the 6-inch well gives a reduction of about 3 per cent in the capacity of the well, or a corrected value of 17.5 for the flow in cubic feet per minute. The 12-inch well presents but an inappreciable amount of friction.

The results just found are given in the following table:

TABLE V.—*Capacity of the wells of Table IV, allowing in each case for the friction of 200 feet of pipe same size as well.*

Size of well.	Capacity per minute.
Inches.	*Cubic feet.*
2	5.7
4	14.0
6	17.5
12	19.78

The variation in pressure in the water-bearing stratum as we pass away from the well along a radius is given by equation (10) above. It is seen from this that the greatest drop in pressure is in the imme-

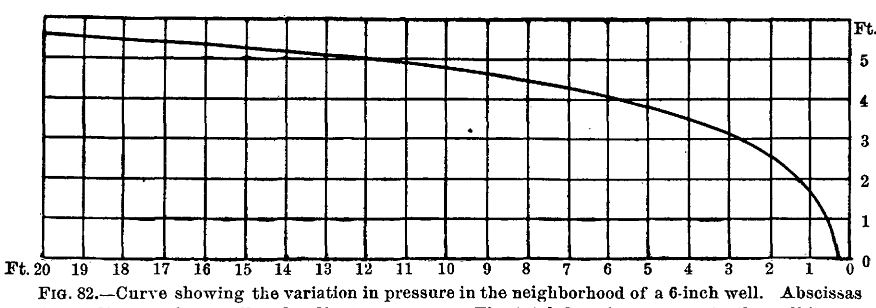


FIG. 82.—Curve showing the variation in pressure in the neighborhood of a 6-inch well. Abscissas indicate distance from well and ordinates pressure. The total drop in pressure in the well is supposed to be 10 feet.

diate neighborhood of the well, although the pressure gradient is nowhere very high. The variation in pressure for the well described in section 2 is shown graphically in fig. 82. The gradient becomes less and less as we get farther from the well, finally vanishing altogether.

TABLE VI.—*Drop in pressure at various distances from a 6-inch well which is lowered 10 feet by pumping.*

Drop in pressure.	Distance from center of well.	Drop in pressure.	Distance from center of well.
Feet.	*Feet.*	*Feet.*	*Feet.*
10	0.25	5	12.25
9	.54	4	26.67
8	1.19	3	57.52
7	2.58	2	126.50
6	5.62	1	275.50

7. If a well does not pass entirely through the water-bearing stratum, the facts controlling its flow are somewhat modified. An exact mathematical treatment of the problem is probably possible, but a simple and roughly approximate method is all that seems to be warranted at present. It is probably accurate enough for our purposes to suppose that the ground water flows into the end of the well in about the same way that it would flow into a hemispherical cavity, as shown in fig. 83. The problem consists, then, in first determining the flow of ground water into a spherical cavity within which the pressure is reduced below the normal by an amount equal to the effective head of the well.

Let r be the radius of a spherical cavity into which ground water is flowing with an effective head equal to h. If ρ is the distance of any point P from the center of the sphere, we have for the velocity at that point

$$v = k\frac{dp}{d\rho}. \tag{17}$$

The velocity along the radius vector to the point P must vary inversely as the square of its distance ρ from the center of the sphere, since equal volumes of water must pass each of the concentric spherical surfaces in equal times. That is

$$v = \frac{c}{\rho^2}, \tag{18}$$

where c is a constant to be determined. Substituting this value of v in (17) and integrating we get

$$k\,p = -\frac{c}{\rho} + C. \tag{19}$$

We know $p = h$ when $\rho = r$, so that

$$k\,(h-p) = \frac{c}{\rho} - \frac{c}{r}. \tag{20}$$

Whence

$$c = k\,(h-p)\frac{r\,\rho}{r - \rho}. \tag{21}$$

If we write v_r as the velocity at the wall of the spherical cavity, we have from (18)

$$v_r = \frac{c}{r^2}, \tag{22}$$

and substituting the value of c from (21)

$$v_r = \frac{k\,(h-p)}{r}\,\frac{\rho}{r-\rho}; \tag{23}$$

as ρ increases $\frac{\rho}{r-\rho}$ approaches -1, while p approaches 0, whence

$$v_r = \frac{kh}{r}, \tag{24}$$

wherein the negative sign has been neglected, since it merely signifies that the velocity is directed toward the center of the sphere.

Multiplying v by $4\,\pi\,r^2$, the surface of the sphere, we get the flux into the spherical cavity to be

$$q = 4\,\pi\,khr \tag{25}$$

and for a hemispherical cavity,

$$q = 2\,\pi\,khr. \tag{26}$$

8. The flow into the end of a well of radius r must present an analogy to the flux into a hemispherical cavity. To estimate the amount of this flow we may imagine that the end portion of the well of height r and diameter $2\,r$ is converted into a hemisphere of equal surface; we take the surface of the end portion of the well mentioned above as $3\,\pi\,r^2$, the radius of the equivalent hemisphere will be $\sqrt{\frac{3}{2}}\,r$ and the flow into this will be, by (26) above,

$$q = 2.5\,\pi\,khr, \tag{27}$$

in which r is the radius of the well.

The formula for the flow into a well which does not pass through the water-bearing stratum is then

$$f = \frac{2\,\pi\,h\,k\,(a-r)}{\log_e\left(1+\frac{600}{r}\right)} + 2.5\,\pi\,khr. \tag{28}$$

If the well passes through strata of various structure and various degrees of fineness, as is usually the case, then if $k_1, k_2, \ldots$ be the constants for the various strata of rock or soil, and if $a_1, a_2, \ldots$ be the thickness of the various strata, then (28) must be broken up into parts as follows:

$$f = \frac{2\,\pi\,h\,(k_1\,a_1 + k_2\,a_2 + \ldots)}{\log_e\left(1+\frac{600}{r}\right)} + 2.5\,\pi\,k_n\,hr. \tag{29}$$

9. To illustrate the application of (28), suppose that the well of the problem in section 3 extended but 50 feet into the sandstone. Then, without the end correction, the flow of the well would be 9 cubic feet per minute. Equation (27), using the value of k from section 3, gives

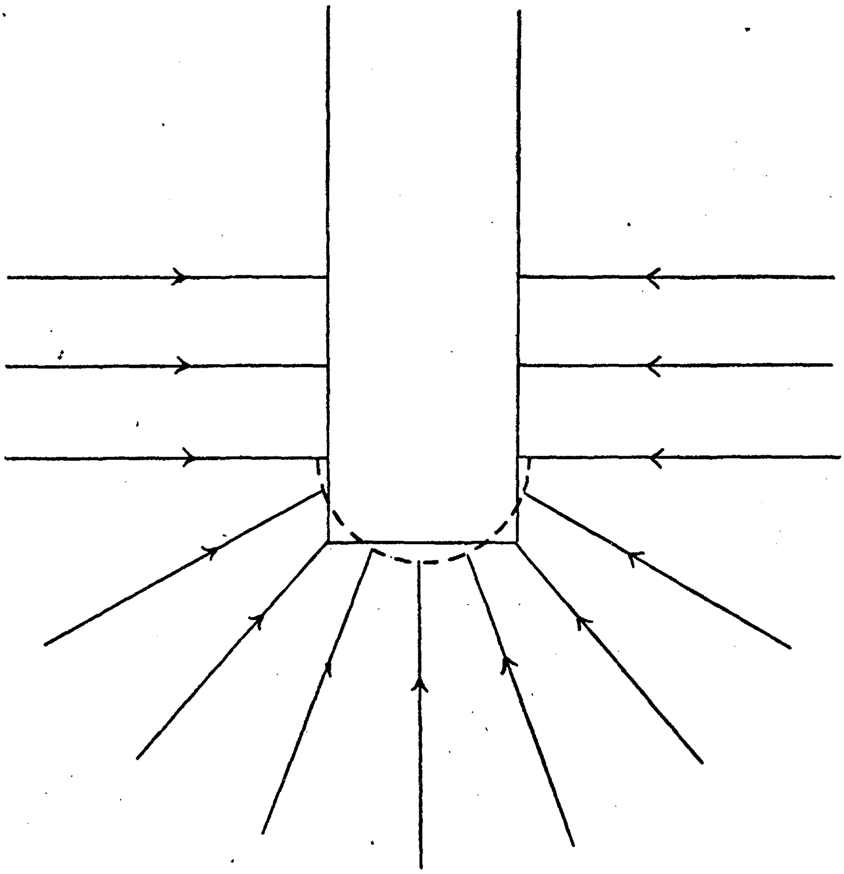


FIG. 83.—Diagram illustrating the flow into the bottom of a well.

the end flow to be 0.44 cubic foot per minute, which is 5 per cent of the total flow.

10. Suppose, however, that the well is 20 feet in diameter and has a depth of 22 feet, the soil grains and porosity remaining the same as in section 3. We desire to know the capacity of the well if the water is lowered 10 feet by pumping. We may consider the lower 10 feet of the well to constitute a case of (27) with $r = 10$, the side flow of the upper 12 feet to be determined by formula (9). For the data of this problem (27) becomes

$$q = 2.5\ \pi\ [8.3537 - 10]\ 10 \times 10 = 17.73 \text{ cubic feet per minute,}$$

and (9) becomes

$$f = \frac{2\ \pi\ [8.3537 - 10]\ 10 \times 12}{\log_e 61} = 4.14 \text{ cubic feet per minute,}$$

or a total flux of 21.87 cubic feet per minute.

11. The following table gives the theoretical flow of a 6-inch well in a bed of sandstone 100 feet thick for the effective sizes of grains given in the table and when the water is lowered the distance named by pumping. The porosity has been assumed to be 32 per cent and the temperature taken equal to 10° C. Of course many of the results tabulated for large-grained material and high pressure are entirely fictitious, for a 6-inch well can not transmit enormous amounts of water under such moderate heads. To derive true results from the tabulated figures, the depth of the well and the length of the suction pipe must be given, so that the friction may be taken account of by means of Weston's tables, as explained above.

TABLE VII.—*Capacity of 6-inch well extending 100 feet in material of various kinds, for various heads of pressure.*

[Flux in cubic feet per minute. Porosity, 32 per cent; temperature, 10° C.]

Size grain.	4-foot head.	8-foot head.	12-foot head.	16-foot head.	20-foot head.
Mm.					
0.02	0.0473	0.0946	0.1419	0.1892	0.2366
.04	.1893	.3786	.5679	.7572	.9464
.06	.5796	1.1592	1.738	2.318	2.898
.08	.757	1.514	2.271	3.028	3.785
.10	1.083	2.166	3.246	4.332	5.915
.20	4.73	9.46	14.19	18.92	23.66
.40	18.93	37.86	56.79	75.72	94.64
.60	57.96	115.92	173.8	231.8	289.8
.80	75.7	151.7	227.1	302.8	378.5
1.20	170.3	340.6	510.9	681.2	851.7
3.00	1,065	2,130	3,195	4,260	5,322

WELLS IN A REGION IN WHICH THE GROUND WATERS HAVE A CONSTANT VELOCITY IN A GENERAL DIRECTION.

12. We may suppose that the ground water in a given region has a general motion, due to the dip of strata, to a sloping water table, or to any other cause. Such general motion does, of course, take place in nearly all cases of the existence of ground water,[1] but it is only in those cases in which the motion is of appreciable magnitude that a consideration of it is of much importance.

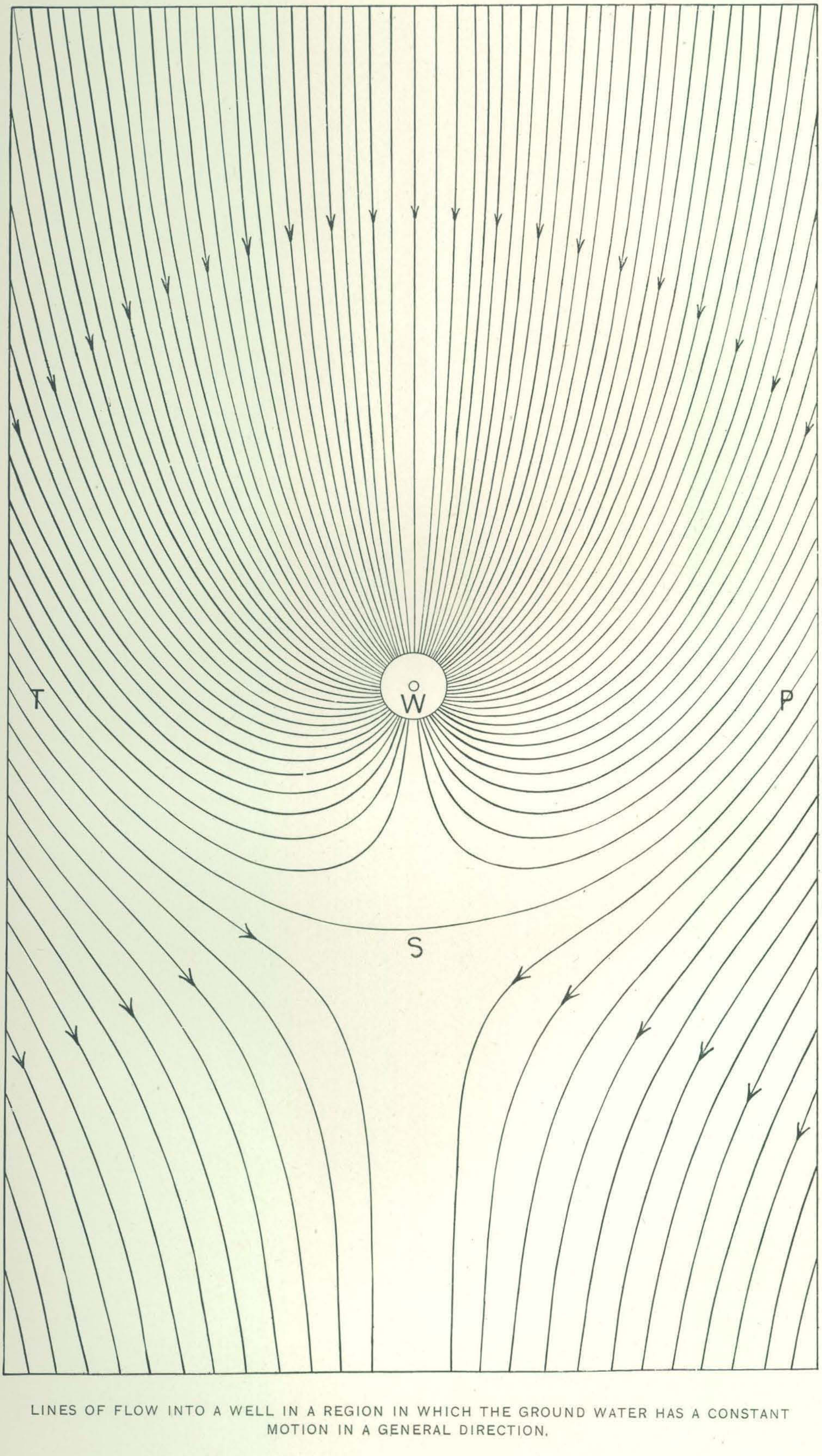
13. Assume that a water-bearing stratum has a uniform dip of m feet in 100 feet and that the ground water has a motion corresponding to the slope of the strata. We must then conclude that the lines of flow are straight lines parallel to the dip and that the lines of equal pressure are straight lines perpendicular to the dip, forming a checkerboard arrangement with the lines of flow. If a well be placed in this region, the checkerboard arrangement of lines will be disturbed and a new set of lines of flow and lines of equal pressure will be established, which will be a combination between the lines for the well and the lines for the dipping stratum.

The lines of flow and pressure can be drawn for the combination of two cases of flow, if the lines be known for the separate cases, by a very simple device. To illustrate the method let us draw the lines of flow for the case above mentioned. The lines of flow for the well are straight lines converging to a point. The lines of flow for the dipping strata are a set of equidistant parallel lines. Let both sets of lines be drawn, as in fig. 84. As a result of this construction the plane is divided up into a large number of quadrilaterals, as A C B P, etc. Indicating on each side of these quadrilaterals the direction of motion, a diagonal may be drawn possessing the elements of motion due to both systems of lines. In fig. 84 the lines are purposely drawn far apart in order to illustrate the method of drawing. If the lines of flow be taken closer together, it is easy to draw the resulting curves with great accuracy. Sixty lines of flow were used in drawing the curves of Pl. XVII.

14. Having drawn the lines of flow representing the combination of two sets of lines of flow, it is easy to combine with the resultant lines any other desired system of lines. Thus by combining the lines of flow of a second well at W_2 with the line of flow of Pl. XVII the lines of fig. 85 result. If one well is drawing more water than the other, then the number of lines of flow for the wells must be in proportion to the flow of each. Doubling the number of lines of flow corresponds to the doubling of the velocity of flow.

In fig. 85 the well W_1 draws water from the region above the curved

[1] See Indications of the movement of water in the chalk formations, by Latham: The Engineer, Vol. XLIV, p. 320.



LINES OF FLOW INTO A WELL IN A REGION IN WHICH THE GROUND WATER HAS A CONSTANT MOTION IN A GENERAL DIRECTION.

line A N B only. The well W_2 draws water from the region between the curved line A N B and a similar but flatter curve passing through

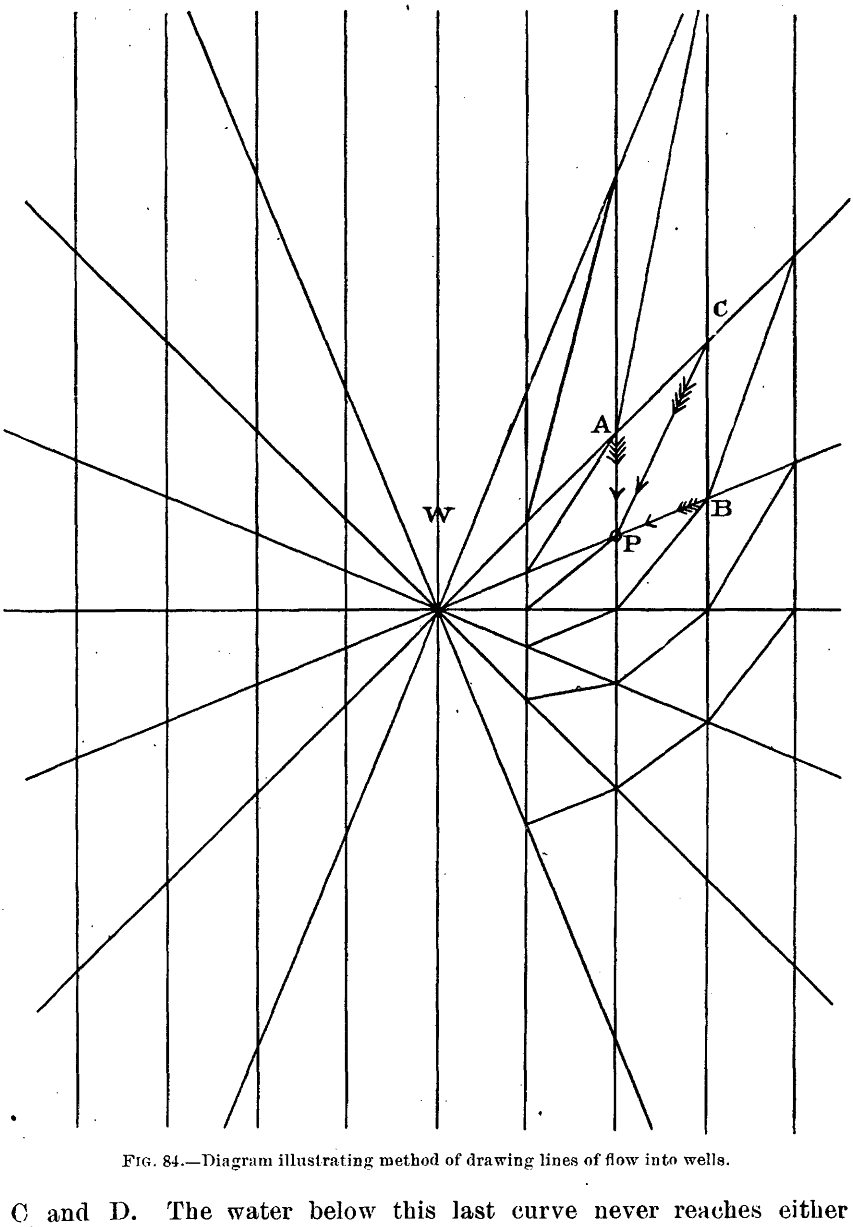


FIG. 84.—Diagram illustrating method of drawing lines of flow into wells.

C and D. The water below this last curve never reaches either well, but continually passes away in the direction indicated by the arrows.

15. The analysis of the problem of the well in a region of moving ground water is quite simple. The variation of pressure in the direc-

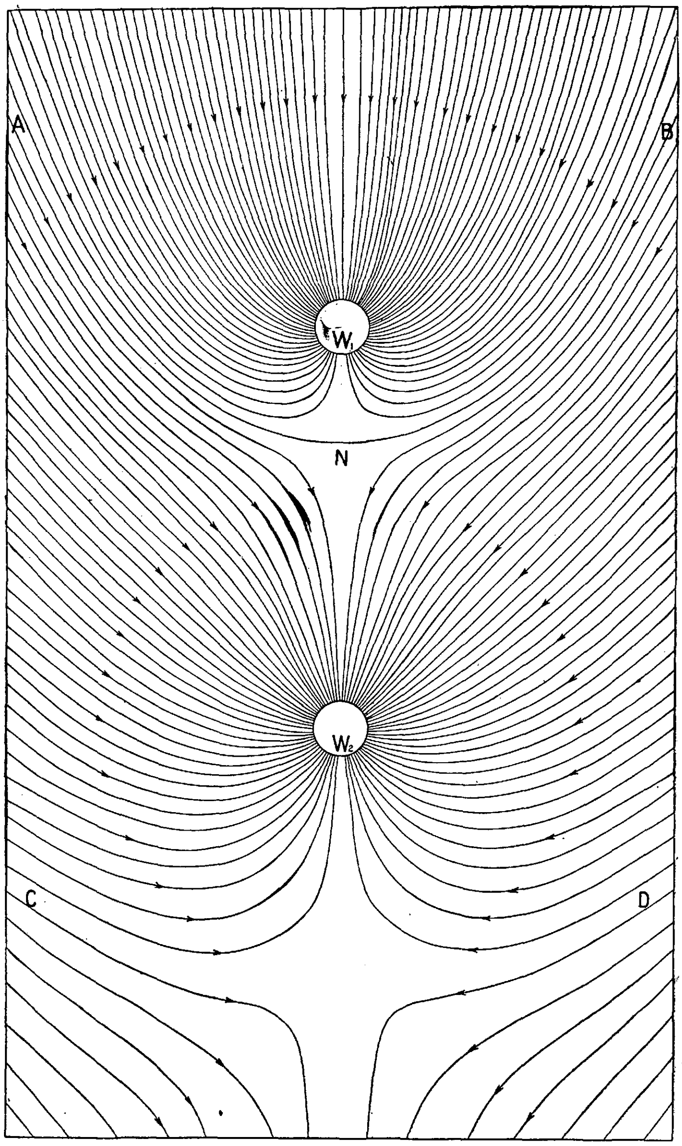


FIG. 85.—Lines of flow into two interfering wells in a region in which the ground water has a motion in a general direction. The diagram assumes that the general motion of the ground water is from north to south.

tion of flow in a uniformly dipping stratum may be written $\frac{m\,x}{100}$, if x is measured in the direction of flow and if m represents the drop in pressure per 100 feet. Combining this with equation (11) above, we may write as the law of pressure for the combined problem

$$p = h\frac{\log_e \frac{\rho}{R+r}}{\log_e \frac{r}{R+r}} + \frac{mx}{100}, \tag{30}$$

or in polar coordinates

$$p = h\frac{\log_e \frac{\rho}{R+r}}{\log_e \frac{r}{R+r}} + \frac{m\rho \cos\theta}{100}. \tag{31}$$

The flow into the well is unmodified by the general motion of the ground water, for the loss of velocity on one side of the well is just balanced by the gain of velocity on the other side.

The point S is easily determined, for it is the point at which the radial velocity toward the well is zero. That is

$$\left.\frac{dp}{d\rho}\right]_{\theta=0} = \frac{h}{\log_e \frac{r}{R+r}}\frac{1}{\rho} + \frac{m}{100}, \tag{32}$$

which is zero if

$$\rho = WS = -\frac{100}{m}\frac{h}{\log_e \frac{r}{R+r}}. \tag{33}$$

If $h = 10$ feet, $r = \frac{1}{4}$ foot, and $R = 600$ feet,

$$WS = \frac{128.48}{m}\text{ feet.} \tag{34}$$

If the slope of the ground water is 1 foot per 100 feet, $m = 1$ and

$$WS = 128.48 \text{ feet,}$$
$$WP = (1.578)\ WS = 202.7 \text{ feet.}$$

MUTUAL INTERFERENCE OF TWO WELLS.

16. Suppose that two wells penetrate the same water-bearing stratum. If the wells are not too far apart, and if one or both be pumped for a considerable time, an interference of one of the wells upon the supply of the other will soon be developed, which interference may show itself by a marked lowering of the water in one of the wells below the point at which it would stand if the other well did not exist. It is now proposed to investigate this subject mathematically. We shall suppose at first that the two wells are alike in size and in all other respects, and by the interference we shall mean the comparison of the flow of either well when both are lowered by pumping a stated amount with the flow of the same well under like circumstances, supposing the other well to be nonexistent.

17. Consider two wells of the same size, distant $2a$ feet from each other and penetrating the same bed of water-bearing strata. Let P

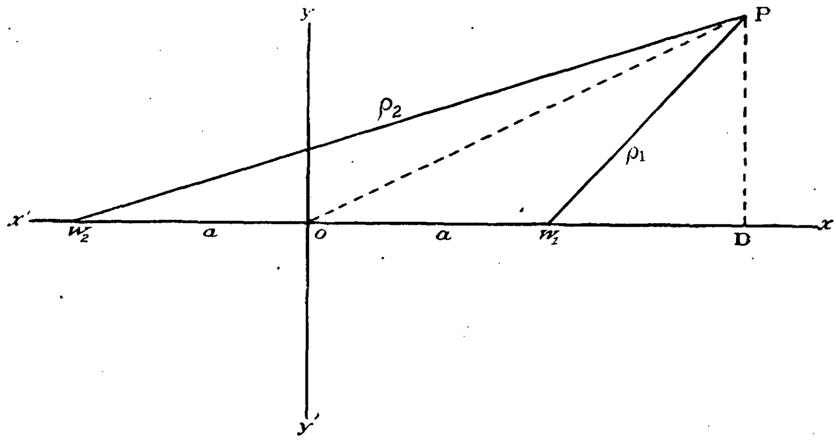


FIG. 86.—Diagram for the problem of the mutual interference of two or three wells.

(fig. 86) be any point in the stratum distant ρ_1 from the well W_1 and distant ρ_2 from the well W_2. From equation (12) above the reduction in pressure at the point P due to W_1 is

$$p' = m' \log_e \rho_1 + c', \tag{35}$$

and the reduction in pressure at the same point due to W_2

$$p'' = m'' \log_e \rho_2 + c'', \tag{36}$$

whence the reduction in pressure due to both wells is

$$p = p' + p'' = m_1 \log_e \rho_1 \rho_2 + c_1. \tag{37}$$

It is convenient to pass to rectangular coordinates by the substitutions

$$\left.\begin{array}{l} \rho_1^2 = y^2 + (x-a)^2 \\ \rho_2^2 = y^2 + (x+a)^2 \end{array}\right\}, \tag{38}$$

which gives the equation

$$p = \tfrac{1}{2} m_1 \log_e [y^2 + (x-a)^2] [y^2 + (x+a)^2] + c_1. \tag{39}$$

To determine the constants m_1 and c_1 we may write

$$y = 0, \text{ and } x = a + r;\ p = h; \tag{40}$$
$$y = 0, \text{ and } x = a + 600;\ p = 0; \tag{41}$$

the last condition meaning that the reduction of pressure is assumed to be zero at a distance of 600 feet from the well, as explained in section 2 above. From the conditions (40) and (41) we determine that

$$h = \tfrac{1}{2} m_1 \log_e (r^2)(r^2 + 4ar + 4a^2) + c_1,$$
$$0 = \tfrac{1}{2} m_1 \log_e (600^2)(600^2 + 2400a + 4a^2) + c_1,$$

and neglecting the square of r in comparison with $4a$ we may write

$$m_1 = \frac{2h}{\log_e (4ar^3 + 4a^2r^2) - \log_e 360000\,(2a + 600)^2} \tag{42}$$

and

$$c_1 = -\tfrac{1}{2} m_1 \log_e 360000\,(2a + 600)^2. \tag{43}$$

18. The flow into each well can easily be determined, for while the velocity of the ground water is very slightly greater on the right side of W_1 than on the left side, yet the average velocity is very nearly equal to the velocity normal to the line OX at the point (a, r). This velocity can be easily found, inasmuch as we have the general relation,

$$v = k \frac{\partial p}{\partial s},$$

from Chapter II, section 2. Thus we find from (39) above that

$$\frac{\partial p}{\partial y} = \frac{m_1 y}{y^2 + (x - a)^2} + \frac{m_1 y}{y^2 + (x + a)^2}, \tag{44}$$

and for $x = a$ and $y = r$ this becomes

$$\frac{\partial p}{\partial y} = m_1 \frac{2r^2 + 4a^2}{(r^2 + 4a^2)r} = \frac{m_1}{r}. \tag{45}$$

The last substitution is made on the assumption that r is much smaller than a, as is the case unless the wells are but a few feet from each other.

The average velocity at the wall of the well is then

$$v = \frac{km_1}{r}, \tag{46}$$

in which m_1 has the value given in (42) above.

19. Suppose that the wells W_1 and W_2 are 6-inch wells, and that the water is lowered 10 feet in each well by pumping, and that the wells are 200 feet apart. Then in (42) $h = 10$, $r = \frac{1}{4}$, $a = 100$, so that we find that

$$m_1 = 1.087. \tag{47}$$

The velocity at the wall of a single well is, from (2) above,

$$v = \frac{km}{r}, \tag{48}$$

in which, from (7) above,

$$m = \frac{h}{\log_e \left(1 + \frac{R}{r}\right)}. \tag{49}$$

From the data given

$$m = \frac{10}{\log_e 2401} = \frac{10}{7.8725} = 1.270. \tag{50}$$

Now, the velocity of ground water at the wall of one of the two wells is to the velocity at the wall of a single well as 1.087 is to 1.270. Thus each of the two wells under discussion will have a flow 15.35 per cent less than the flow of a single well of same size. We shall describe this fact as an "interference of 15.35 per cent."

Keeping the size of wells and the amount of lowering by pumping the same as above, but giving various values to the distances between the wells, we have computed the results given in Table VIII.

TABLE VIII.—*Mutual interference of two 6-inch wells placed various distances apart.*

Distance apart of wells.	Interference.	Distance apart of wells.	Interference.
Feet.	*Per cent.*	*Feet.*	*Per cent.*
5	38.33	200	15.35
10	34.53	400	10.51
100	20.09	1,000	6.23

20. The lines of flow into two interfering wells are shown by fig. 87. (See also fig. 73, Chapter III.) The lines of flow into two wells, one of

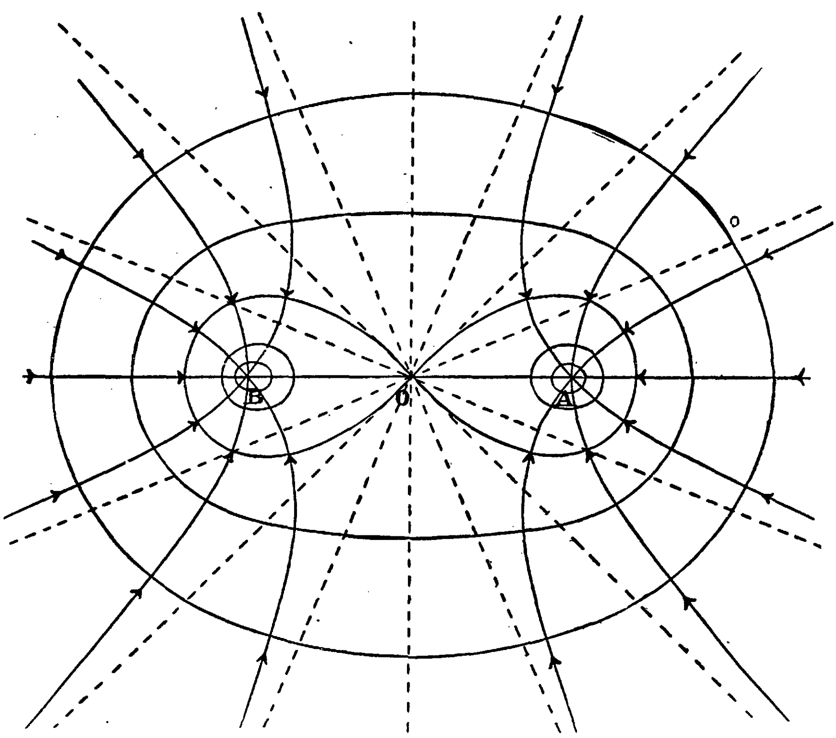


FIG. 87.—Lines of flow and lines of equal pressure for two interfering wells of equal capacity. The lines of flow are indicated by arrowheads.

which is furnishing twice as much water as the other, may be easily drawn by the method explained in section 13. The lines of flow into the well of double capacity should be represented by twice as many rays as there are used for the lines of flow of the smaller well, and

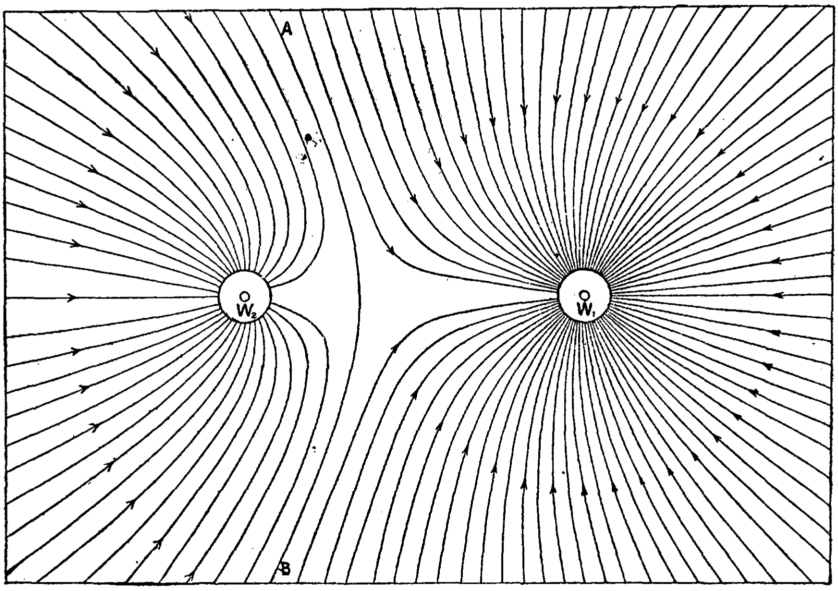


FIG. 88.—Lines of flow for two interfering wells in the case in which one well has double the capacity of the other. The well W_1 is here represented to have double the capacity of the well W_2.

similarly for any other ratio of flow. Fig. 88 was drawn in this manner, W_1 having twice the capacity of W_2.

MUTUAL INTERFERENCE OF THREE WELLS.

21. In fig. 86, let W_1, O, and W_2 represent three wells of the same size penetrating the same water-bearing stratum. We desire to determine the interference of the wells upon each other, and for that purpose we shall compare the flow of one of them with what would be its flow were the other two wells nonexistent. It is supposed that the water is lowered the same amount in each well by pumping.

The reduction in pressure at the point P is found in an entirely analogous way to that of section 17. It is easily seen to be

$$p = \tfrac{1}{2} m_2 \log_e (y^2 + [x - a]^2)(y^2 + [x + a]^2)(x^2 + y^2) + c_2. \tag{51}$$

The constants m_2 and c_2 may be determined from the data

$$y = r,\ x = a, -a, \text{ or } 0, \text{ when } p = h, \tag{52}$$

$$x = 0,\ y = 600, \text{ when } p = 0. \tag{53}$$

From these considerations we find

$$m_2 = \frac{h}{\log_e (600^2 + a^2) 600 - \log_e a^2 r}, \tag{54}$$

$$c_2 = - m_2 \log_e (600^2 + a^2)\, 600. \tag{55}$$

22. Proceeding exactly as in section 18, we find that the average velocity into the wells is proportional to

$$\frac{\partial p}{\partial y} = \frac{m_2 y}{y^2 + (x - a)^2} + \frac{m_2 y}{y^2 + (x + a)^2} + \frac{m_2 y}{x_2 + y^2}, \qquad (56)$$

for the values

$$x = 0, \quad y = r,$$
$$x = a, \quad y = r,$$
$$x = -a, \quad y = r.$$

This gives

$$\left.\frac{\partial p}{\partial y}\right]_{x=0} = \frac{2 m_2 r}{r^2 + a^2} + \frac{m_2}{r}, \qquad (57)$$

$$\left.\frac{\partial p}{\partial y}\right]_{x=\pm a} = \frac{m_2 r}{r^2 + 4 a^2} + \frac{m_2 r}{r^2 + a^2} + \frac{m_2}{r}. \qquad (58)$$

Since a is large in comparison with r, both (57) and (58) reduce to $\frac{m_2}{r}$, so that the average velocity at the walls of either of the wells is

$$v = \frac{m_2 k}{r}. \qquad (59)$$

23. Suppose that the wells are 6-inch wells and that the water surface is lowered 10 feet by pumping. We may then determine m_2 from (54) by putting $h = 10$ and $r = \frac{1}{4}$. By taking a equal to 5, 10, and 100 feet in turn, we find for the corresponding values of m_2,

$$a = 5, \quad m_2 = .576;$$
$$a = 10, \quad m_2 = .626;$$
$$a = 100, \quad m_2 = .878.$$

The value of m for a single well of same size and under same head was found (equation (50) above) to be

$$m = 1.270.$$

Therefore, since the flow into one of the three wells bears the same ratio to the flow into a single well as m_2 bears to m, the interference may be written as percentages as follows:

TABLE IX.—*Mutual interference of three 6-inch wells placed various distances apart.*

Distance between wells.	Interference.
Feet.	*Per cent.*
5	55.0
10	50.7
100	30.9

By comparison of these results with the results of section 19, some interesting conclusions are reached. Thus it follows from section 19 that two wells 10 feet apart will furnish 131 per cent of the flow of a single well. If a third well be placed half way between them, so as to make three wells 5 feet apart, we see from the table just given that the total flow from the three wells taken together would be but 135 per cent of the flow of a single well. The gain on account of the extra well is seen to be very slight—but 4 per cent. If, however, the distances apart are greater, say two wells 200 feet apart, the total flow from the two combined is about 169 per cent of the flow of a single well. If, now, a third well be placed half way between the two so as to make a row of three wells 100 feet apart, the total combined flow from the three wells is about 207 per cent of the flow of a single well.

24. With all the conditions the same as in the case of the 20-foot well of section 10, what will be the capacity of the 20-foot well, if one, two, and three 6-inch wells extend through the bottom of the 20-foot well 200 feet into the sandstone?

The capacity of the 20-foot well was found in section 10 to be 21.87 cubic feet per minute. The capacity of a single 6-inch well in the given material is given in section 3 as 18.01 cubic feet per minute for a well 100 feet deep, and is consequently 36.02 cubic feet per minute for a well 200 feet deep. This makes a total capacity of 57.89 cubic feet per minute, if we neglect the interference of the 20-foot well upon the small well. As a matter of fact, the pressure varies inversely as the square of the distance from the large well, which fact would leave about 20 feet of the upper end of the small well useless. While, of course, this part of the small well would furnish some water, it would be chiefly at the expense of the large well. Therefore, it seems more reasonable to assume that the capacity of the 6-inch well would be reduced to at least 32.6 cubic feet per minute, giving a total capacity of 54.5 cubic feet per minute for the two wells.

If two 6-inch wells are drilled through the bottom of the 20-foot well 200 feet deep into the sandstone the capacity of the combined system can be determined from Table VIII above. Taking the capacity of each well as 32.6 cubic feet per minute, then if the wells are 5 feet apart, the double of this, 65.2, must be reduced by 38.33 per cent, which gives a capacity of 40 cubic feet per minute for the two small wells, or 61.87 cubic feet per minute for the entire system. If the wells are 10 feet apart the reduction by Table VIII will be 34.5 per cent, giving a capacity of 42.6 for the two wells, or a total of 64.5 for the system.

If three 6-inch wells are drilled through the bottom of the large well for a distance of 200 feet into the sandstone the capacity of the three wells can be determined by means of Table IX. If the wells are 5 feet apart the capacity would be 55 per cent less than three times 32.6, the capacity of each, or 44 cubic feet per minute. The total flow for the system would then be 65.9 cubic feet per minute. If the three wells are 10 feet apart the interference would be 50.7 per cent and the combined capacity of the three small wells would be 49.58 cubic feet per minute, and the total capacity of the system would be 71.5 cubic feet per minute.

MUTUAL INTERFERENCE OF A LARGE NUMBER OF WELLS ARRANGED IN A ROW.

25. If there are a large number of wells arranged in a row, and penetrating the same water-bearing stratum, the mutual interference will be much greater than for the row of two or three wells considered

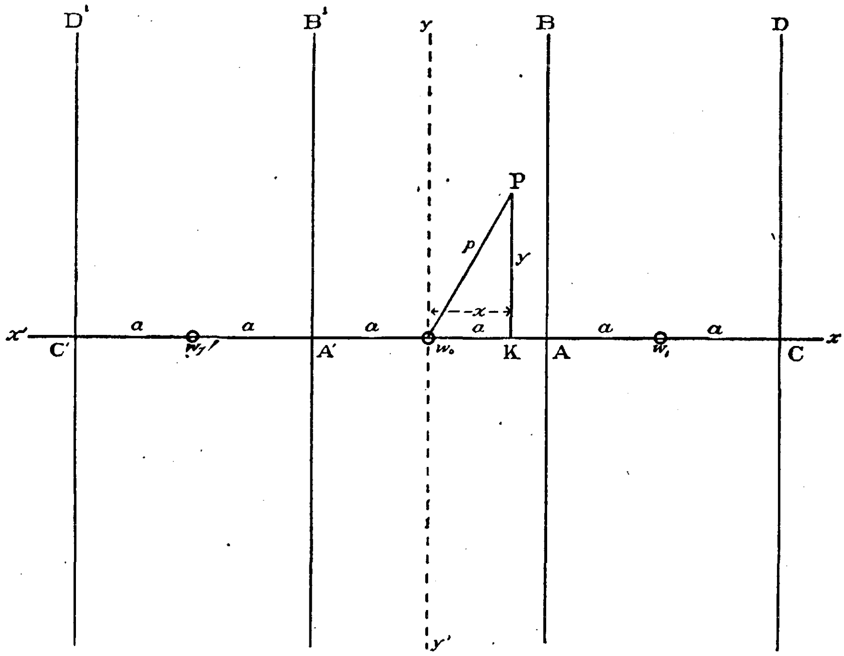


FIG. 89.—Diagram for the problem of the mutual interference of a large number of wells.

above. Let the wells be at distances of $2a$ feet from each other, as represented in fig. 89. If the number of wells is very large, no flow will take place across the planes AB, CD, A′B′, C′D′, etc., drawn half way between the wells and perpendicular to the line joining them. In fact, the lines of flow and pressural lines for the region A′B′ AB will be the same as for each similar region, as AB CD, etc. The reduction in pressure at any point P can be found by the method of images, as explained in Basset's Hydrodynamics, Vol. I, p. 59, and is expressed by the equation

$$p = \tfrac{1}{2} m_3 \log_e \left(\cosh^2 \frac{\pi y}{2a} - \cos^2 \frac{\pi x}{2a} \right) + c_3, \qquad (60)$$

in which m_3 and c_3 are constants to be determined by the conditions of the problem.

If r is the radius and h the amount of lowering of the water surface in each well by pumping, we may write

$$\begin{aligned} y=r, \quad x=0, \text{ when } p=h; \\ y=600, x=0, \text{ when } p=0; \end{aligned} \tag{61}$$

supposing that the lowering of the pressure is not important at a distance of 600 feet from a well. These conditions give

$$m_3=\frac{h}{\log_e \sinh \frac{\pi r}{2a}-\log_e \sinh\frac{600\,\pi}{2a}}, \tag{62}$$

$$c_3=-m_3 \log_e \sinh\frac{600\,\pi}{2\,a}. \tag{63}$$

The velocity at the well-wall is proportional to

$$\frac{\partial p}{\partial y}=\frac{\pi}{2a}\frac{m_3 \cosh \frac{\pi y}{2a}\sinh \frac{\pi y}{2a}}{\cosh^2 \frac{\pi y}{2a}-\cos^2\frac{\pi x}{2a}},$$

which, for $x=0$ and $y=r$, reduces to

$$\left.\frac{\partial p}{\partial y}\right]_{x=0}=\frac{\pi}{2a}\, m_3 \coth\frac{\pi r}{2a}$$

$$=\frac{\pi}{2a}m_3 \left(\frac{2a}{\pi r}+\frac{2^2}{2}\left(\frac{\pi r}{2a}\right)^2 B_1+\dots\right)$$

$$=\frac{m_3}{r}, \tag{64}$$

if r is small in comparison with a. Thus, since the velocity at the wall of a single well is proportional to $\frac{m}{r}$, where m has the meaning of section 3, the velocity at the wall of a well of the row of wells under consideration has the same ratio to the velocity at the wall of a single well as m_3 has to m.

26. If the wells are 6-inch wells and if the lowering of the water in each well by pumping is 10 feet, we have $r=\frac{1}{4}$ and $h=10$. We may then determine m_3 from (62) above for various values of a and tabulate them as below. This table may be compared with Tables VIII and IX with much interest.

TABLE X.—*Mutual interference of a row of wells whose members are various distances apart.*

Distance apart of wells.	*m.*	Interference.
Feet.		*Per cent.*
100	0.4347	65.8
200	.7007	45
400	.9755	24
600	1.1007	14
1,000	1.2002	6.4

APPENDIX.

LIST OF PAPERS ON THE MOTION OF GROUND WATERS AND RELATED TOPICS.

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GEOLOGY OF THE RICHMOND BASIN, VIRGINIA

BY

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GEOLOGY OF THE RICHMOND BASIN, VIRGINIA.

By N. S. SHALER and J. B. WOODWORTH.

INTRODUCTION.

Geographic position of the Richmond Basin.—The area described in this report lies within the region known as the Piedmont district, which forms the Atlantic face of the ancient Appalachian ranges. This bench, as is well known, begins at the eastward at a line indicated by the falls or rapids of many streams which flow into the Atlantic (see Pl. XVIII), having along this line an altitude of about 100 feet, and rises thence in a gradual manner to a height of 500 to 1,000 feet, when it meets the escarpment of the Blue Ridge. This rise is not perfectly uniform, but is divided into several indistinct steps. As will be seen by the maps, the Richmond area lies on the eastern edge of this district, on either side of the James River. The total length of the area in a nearly north and south direction is 33 miles, and its maximum width is 9.5 miles, its area being about 190 square miles.

Topography of the area.—Although geologically a very evident basin, having a maximum depth of at least 3,000 feet, the Richmond area has not a distinct topographic character, such as the geologist is accustomed to associate with mountain-built rocks. Its surface is that of a roughened plain or low table-land, which is somewhat intersected by the lesser streams and is divided by the relatively broad and deep gorge of the James River. The ancient granites and gneisses of the periphery of the area, as well as the numerous dikes within its limits, are all worn down to about the same level with the deposits of the basin itself, the materials of which are relatively more liable to decay and erosion. Only here and there is it possible for even the trained observer to trace any very distinct topographic indications of the contact between the sedimentary deposits contained in the trough and the igneous and crystalline rocks of the surrounding country. Except in certain rare localities, the surface in no wise reveals their juxtaposition.

Distribution of streams.—The relief of the Richmond area is, as before stated, low, like that of the surrounding Piedmont district. The James and the Appomattox rivers, which cross the area, have cut trenches

FALL LINE AND HEAD OF TIDE ON THE JAMES RIVER, AT RICHMOND, LOOKING WEST FROM HULL STREET BRIDGE, MANCHESTER.

from 100 to nearly 200 feet deep. The course of the former stream across the area exhibits the most marked indifference to the structure of the basin, flowing eastward across north and south belts of granite, gneiss, sandstones, and shales. The Appomattox River flows around, in a hit-or-miss way, the southern border of the area, as if it were controlled in its course by the conjunction of the sandstones and shales with the gneisses. On the other hand, the smaller stream known as Swift Creek flows southeastwardly across the middle of the area in an almost direct line. Except for the north bank of the James, which forms a bluff, here and there precipitous, the upper walls of these stream valleys have widened out—retreated—so that the descent to the streams is not steep. The rivers, where they are not artificially interfered with, are eroding their channels, as is indicated by the rapids over which they flow. This action is particularly noticeable in the Appomattox.

Between the larger streams are well-defined divides, which likewise traverse the area and the neighboring region of crystalline rocks in the form of ridges at right angles to the trend of the rocks. The ridge between the Appomattox and Swift Creek has been followed by a narrow-gauge railway from the edge of the Piedmont district to Farmville, thus avoiding the expense of building bridges. This divide separates the Clover Hill district from the Midlothian coal field. A similar ridge, having its culminating point in High Hill, in Powhatan County, is followed by the Buckingham-Midlothian turnpike. The profile of this latter divide is less even than that passing through Skinquarter, for the reason that some of the small tributaries of the James have pushed their headwaters far to the south.

The manner in which the soft shales of the lower part of the Newark section are brought to the surface on the eastern and western margins of the area in the James River section has led to tributaries of the James gnawing back from that stream along the outcrop of these rocks. Tuckahoe Creek, on the eastern margin, and Jones Creek, on the western margin, have thus been in large part determined. By reason of the development of the headwaters of Tuckahoe Creek over the Newark area north of the James River, the north bank of the last named stream has the form of a divide, sloping gently northward into the Tuckahoe drainage and steeply on the south into the James.

These divides are the healthiest portions of the area, the inhabitants enjoying a relative immunity from fevers and, owing to the porosity of the Newark rocks, an abundant supply of potable water, obtained from wells.

Economic importance of the area.—The Richmond area is important from the economic as well as from the scientific point of view. It contains the only freely-burnable coal lying immediately adjacent to tide water in the eastern portion of the United States. The quantity of this fuel, as will hereafter be shown, appears to be sufficiently large to give it a value in the industrial arts, and its quality is for many purposes satisfactory, as has been proved by nearly a century of local, yet considerable, use. The only other area containing coal on the Atlantic shore line of the United States is that of Narragansett Bay, where the extremely graphitic nature of the deposits has hitherto limited their utility. The several areas of the maritime provinces of Canada in Nova Scotia, Cape Breton, New Brunswick, and Newfoundland are remote from the ports of the United States and are in large part debarred from them by import taxes. Thus the deposits of the Richmond area, provided they can be cheaply mined, promise to afford a low-priced fuel which will be accessible to the deep water of the James River with railway transportation of from 20 to 60 miles.

Scientific problems of the area.—The purely scientific problems of this district are numerous and of much significance. They concern the accumulation of the deposits and their subsequent history; the manner in which the geologic basin in which they lie was formed; the dislocation of the beds and the relation of these movements to the forces which produced the Appalachian uplifts, and, finally, the nature of the erosion which has brought about the complete effacement of the mountainous uplifts which were evidently in existence in this field during at least a part of the Jurassic period.

It should be said that the work of N. S. Shaler, the senior contributor to this report, began in 1870, and has been continued in a number of visits to the field. On these excursions he had an opportunity to note the conditions in several mines which have since been abandoned and are no longer accessible. On the other hand, the junior contributor, Mr. J. B. Woodworth, who first visited the district in 1895, has spent in all about five months on the ground, and has personally examined nearly all of the surface exposures and such mines as were open. To his labor is due the greater part of the details contained in this report. He was assisted in the field season of 1896 by Mr. George B. Richardson.

CHAPTER I.

CONDITIONS AND HISTORY OF THE AREA.

USE OF THE TERM NEWARK.

The strata of the Richmond area, as will be seen by reference to the next division of this report, consist of a great thickness of shales and sandstones and scanty conglomerates, belonging evidently to one or more geological epochs lying above the base of the Trias. There lies above the section, which by its abundant fossils exhibits relations with the Rhetic of the Old World, a thickness of 2,000 feet or more of shales and sandstones, with traces of lignite, the geological position of which is, from the lack of well-determined fossils, somewhat uncertain. The beds contain petrified trees identical with those in the lower section of the area, and with forms found in the so-called Trias of the Rocky Mountain region. It must be admitted, however, that the higher beds may include a portion of the Jurassic. On this account the term Newark, which has come to be applied to this and similar groups of rocks lying along the Atlantic coast to the northward, will be used as a general term to designate the strata of this area. This term may seem open to criticism for the reason that it is very indefinite; it is, however, not more so than our knowledge as to the age of the strata to which it refers.

COMPARISON OF THE AREA WITH NORTHERN NEWARK AREAS.

It is noteworthy that beds which appear to be related in age, though perhaps not identical with those of the Richmond area, occur along the Atlantic coast line of this continent from the Magdalene Islands, in the Gulf of St. Lawrence, to South Carolina. They are abundantly developed in the maritime provinces, but from the shores of the Bay of Fundy to the Connecticut Valley they are not exhibited. From the valley of the last-named river southward to the Carolinas they are developed in numerous areas. As far south as central New Jersey, these deposits have a tolerably uniform character; they are in large measure made up of red sandstones and shales, with which are associated quantities of conglomerate which has a like reddish color. Now and then dark colored, more or less carbonaceous or bituminous layers are found, which in no case contain deposits of coal. They are noted, however, for their fossil fishes. The evidence goes to show that all these sections were deposited in fresh-water basins.

As we pass southward from New Jersey, the areas of the Newark deposits exhibit a distinct change in character; they become much less red, the conglomerates diminish in quantity, and in certain of the areas, notably in the Richmond basin, the lower part of the section shows, except locally, little of the red hue and contains, moreover, several beds of coal. These peculiarities make it evident either that there was a remarkable difference between the physical conditions of the southern and the northern areas, or that the beds of the Virginia district represent, in their lower parts at least, strata of an age unknown in the more northerly portion of the coastal belt.

It does not seem possible at the present time to decide which of the views suggested above is to be adopted. It may be noted, however, that like variations in the character of the deposits of the same age in northern and southern fields are found in the rocks of other ages. The Carboniferous and Cretaceous strata evidently redden as we go northward. In all these sections, as well as in that of the Newark, the red hue in the more northern regions appears to be due to the considerable amount of iron oxide which the beds contain. In the case of the Newark, at least, the presence of this iron may be due to the erosion of the beds by the agency of glacial ice, which, as in the deposits of the last glacial period, has served to bring a large amount of ferruginous matter into the gravels, sandstones, and clays that were laid down near the ice front. Under the conditions of glacial erosion and carriage, the iron from the crystalline rocks, usually in the state of magnetite, oxidizes but little before it enters the newly formed strata, wherein it undergoes slow decomposition, staining the beds in which it is contained.[1]

The above-described hypothesis[2] as to the origin of the red color of the northern rocks of the formations which have been named finds support from the fact that the beds of the last glacial period are reddening in the measure to which they are penetrated by the agents of decay, and also in the fact that the deposits in question are, as we go northward from the line of the Potomac, composed in an increasing measure of coarse pebbles, which are often formed of sound, compound crystalline rocks, particularly of the granites, materials which are rarely brought in large quanities into the pebbly or bowldery form in an undecayed condition unless by glaciation. It is therefore a reasonable tentative hypothesis that the sudden change in the general character of the deposits of the Newark formations, as we pass from the area in New Jersey to those which lie in the district south of Washington, is due to a decided difference in the conditions of preparation and transporation of the materials of the northern and southern fields.

[1] The origin of red deposits through their derivation from areas of atmospheric decay has been advocated by Russell. See Bull. U. S. Geol. Survey No. 52, 1889.

[2] On the geology of the Cambrian district of Bristol County, Massachusetts, by N. S. Shaler: Bull. Mus. Comp. Zool., Vol. XVI, 1888, p. 21.

If we assume that the northern deposits of the Newark were composed of fragmental materials derived from the bed rocks by glacial action we have a reason at hand to account for the carbonaceous deposits at the base of the section in the Richmond and Dan River areas. On the supposition that the more northern areas were formed in connection with glaciation, we should not expect to find there extensive bogs which, however, would naturally have been developed in the more southern realm, where a moist, cool climate would have existed in an ice time. Therefore we may assume that the peculiar aspect of the rocks of the Virginia basins may possibly be explained by the supposition that the exceptional features are due to the above-noted differences in the conditions under which the sediments were formed and laid down.

AGE OF THE BEDS.

As has been noted by Fontaine and others, the fossils of the lower portion of the beds in this basin are more closely related to the Rhetic deposits of Europe than to those of any other known horizon. Although the identifications are of a rather general nature and relate to a few species, they afford quite as much evidence to prove identity of age as has often served as a basis for such reference in other like instances. The reason for departing from the customary method of identification in this case may be briefly set forth, as follows:

Recent studies of faunæ and floræ, which constitute the many organic hosts of sea and land, have shown that they are in frequent migration, changing somewhat under the influence of geographic and climatal variation as they move from one region to another. From the earlier stages of Paleozoic time to the present day these hosts have been rather limited in their distribution. It is doubtful if in the past their fields have in general been more extensive than we now find them. The assumption that the Rhetic host of northern Europe was coincidently on the eastern shore of North America appears therefore to be unwarranted. It is indeed more likely that the beds on the opposite sides of the Atlantic Ocean which contain the fossils of that assemblage are of ages sufficiently far apart to have permitted the migration of the host from one region to the other. As an illustration of this principle, we may cite the case of the forests of this country as compared with those of Europe. If we would find the representatives of the existing forest trees of the Mississippi Valley in Europe, we need to look not to the living forms of that continent, but to those of the Tertiary period, which are so like the existing species of this country that they could be readily mistaken for them. Thus, if the present woods of the central portion of North America were accessible only as fossil remains, they might well lead to grave misconceptions as to the age of the beds in which the record occurred.

In the present state of our knowledge concerning the relations of the geological sections in Europe and this country, it is evidently undesirable to multiply the instances, already too numerous, in which an identity of age of beds occurring on the two continents, based on the similarity of their fossils, is asserted by a common name. On this account it has been deemed best to use the term Newark, following the plan of Russell, for the assemblage of beds in the Richmond area, which lies between the ancient foundation of the series and the overlying strata deposited after the faulting and folding occurred.

The term Newark, taken from the section of northern New Jersey, is itself open to the objection that it postulates an identity of age of deposits which have not been fairly proved to be of the same age, and which differ somewhat in fossil contents and considerably in their physical character. This objection is valid; it is of the same nature as that which leads to the adoption of the term Newark, but is much less weighty, for the reason that, while there may be some difference in the age of the two groups of strata, they both clearly lie in about the same general position in the Mesozoic section, and were formed in the same cycle of geologic events. Used, as it is in this report, to indicate a general relation in a series of strata and not as denoting an especial period in the earth's history, the term Newark leaves the question as to the correspondence in time of these beds with those of the Old World open to further inquiry. It is from this point of view a better term than Juratrias, which is so vague as to have little indicative value, or Rhetic, which assumes a definiteness of knowledge not warranted by the facts (see p. 519).

There is one consideration not noted by those who have discussed the Rhetic affinities of the Newark series, which may possibly have some value in proving the beds to be of that age. As is well known, the Rhetic of Europe generally contains one or more bone beds, composed of the remains of fishes. The condition of the occurrence of these fossils indicates that the death of the forms was sudden and widespread, such as may have been brought about by earthquake shocks, sudden changes in the temperature of the waters, or the rapid diffusion of some disease. Bone beds of this nature are rarely found; none of them, so far as is known to the senior writer, occur between the summit of the Carboniferous and that of the Triassic series. In the Richmond area, as is noted elsewhere in this report, there are layers of remains which indicate an apparently sudden destruction of a very great number of fishes. The coincidence, though interesting, may be merely accidental.

CONDITIONS OF THE AREA AT THE TIME OF THE DEPOSITION OF THE NEWARK BEDS.

The facts set forth later in this report show that the deposition of the Newark beds in the Richmond area began upon a surface composed of igneous and crystalline rocks from which any unmetamorphosed strata formed at an earlier date had been swept away. This series of beds, as is shown in Pl. XXII, begins, at points where the basement is seen, with a bowlder bed, which lies immediately on the contorted igneous and crystalline rocks. So far as this incomplete evidence goes it is reconcilable with the existence of strong transportative agents, competent to bring into the area very coarse débris at the time when the formation of these strata was begun. But it may be explained by the supposition that the fragments were formed by antecedent decay of rock in place, followed by a slight rearrangement of the materials by water action, the bowlders being the hard remnants of blocks formed by decay proceeding along joint planes.

It is a matter of importance to determine the shape of the surface at the time when deposition began. The opinion which may be formed on this point affects not only the scientific aspects of the problem; it is also, as will shortly be seen, related in an immediate way to the question as to the continuity of the coals in the basin and their probable extension in other basins of the same age, which occur in Virginia and the Carolinas. It is evidently possible that either of two conditions existed at the time when the beds of the Newark of this district were formed. They may have been laid down on the seaboard face of the continent or Appalachian land in the manner in which the beds of the Carboniferous of fresh-water origin were deposited along the western face of the Blue Ridge, or they may have been accumulated in a valley lying between the site of that ridge and an elevated district on the eastward. If the first supposition is accepted, it then follows that the several basins of the Newark of this district are to be regarded as the remnants of an originally continuous sheet of strata, which owe their preservation in their basin-like form to their downfaulting into troughs, due to mountain-building action. In this case the beds of coal contained in the Richmond area should have had an original extension quite independent of the present limits of that trough. They are likely to have extended far and wide over the field in which the present detached fragments of the Newark beds occur. If the second supposition be correct, it is clear that each of these basins may have had its independent history, and that the deposits of any one of them do not afford a criterion for determining the character of those contained in the areas which lie near by.

It has elsewhere[1] been urged by the senior contributor to this report that along the Atlantic coast of North America, and presumably along all continental shores which have been subjected to great and repeated changes of level, it not infrequently occurs that deep and broad valleys, excavated in crystalline rocks by river action, are partly depressed beneath the sea or, as the modern geographers term the action, *drowned*, thereby becoming the seats of rapid sedimentation. If after these troughs are filled or during the process of filling they are subject to

[1] Geology of the Narragansett Basin, Part I, by N. S. Shaler: Mon. U. S. Geol. Survey, Vol. XXXIII. (In press.)

the action of mountain-building forces, they may be much compressed, the more so as the rocks which they contain are likely to offer relatively weak resistance to the pressure which is applied to them. They will therefore give way and be sharply folded and otherwise distorted, while the surrounding crystalline beds may show no such evidence of dislocation. It is, in a word, evident that while on a gently and uniform sloping shore line, such as now exists on the coast of the Atlantic south of New York, strata will be deposited in broad continuous sheets to be afterwards folded into mountains, which will have their shapes determined by relatively simple conditions, it is quite otherwise with strata that are laid down in submerged valleys in the manner in which it is possible that the beds of the Richmond area were deposited. Beds thus formed will be exceptionally conditioned as regards their accumulation and the effect of subsequent accidents, such as are brought about by compressive strains. Their foldings will differ in character from those which are produced in normal mountains. In place of the symmetrical ridges, which are characteristic of the typical elevations of the Alleghanies, we may expect to have the strata cast into more irregular folds and faults, which will be steepest on the margins of the old valleys and nearly flat in the central portions of the field, where the region is removed from the thrust of the rigid unyielding masses of the old crystalline rocks, which, having no distinct bedding, move with little freedom when impelled by mountain-building forces. Moreover, in such filled valleys we should expect to find the deposits consisting of masses of detritus brought in by a number of streams from the various sides of the bay, or lake, or river, each mass having the general character of an alluvial fan or delta, the several contributions of sediment overlapping one another in an irregular way, giving to the deposit a measure of local variation such as does not exist in an area found in the bed of the open sea or in some parts of the Carboniferous rocks formed on the surface of a widespread swampy lowland.

A study of the Atlantic coast deposits from the beginning of the Carboniferous to and through the Newark makes it seem probable that in the region north of the Carolinas a large part of the strata of the periods of most considerable accumulation have been formed in preexisting valleys, and have been mountain built under conditions determined by these peculiar lodgments. As has been noted in the memoir on the Geology of the Narragansett Basin,[1] this appears to be the condition of the Carboniferous rocks in that area, it being held that they occupy the valley of an ancient river system which now in part lies in the bay of the name. The Carboniferous deposits of Nova Scotia and New Brunswick were most likely formed within similar antecedent valleys, the beds having afterwards been more or less dislocated by

[1] Mon. U. S. Geol. Survey, Vol. XXXIII.

orogenic forces. An excellent instance of this relation of previously existing depressions to the deposition of the Newark strata is afforded by the narrow valleys radiating from the principal troughs, which now appear as filled with deposits of somewhat doubtful but possibly Newark age. Thus at Gays River, Halifax County, Nova Scotia, the valley in crystalline rocks and ancient auriferous shales and schists which leads down to the Bay of Fundy is in large part filled with a conglomerate made up of débris from the neighboring fields. This valley has a width of not more than a mile; the conglomerate which occupies it has been proved to exist to a depth of 138 feet and has probably more than twice that thickness. The beds have been somewhat affected by mountain-building stresses. This is not shown by dislocations of the ordinary kind, the deposits being, it would seem, too massive for such movements, but by the compression of the pebbles, which indent one another in a manner common to massive conglomerates where they have been subjected to pressure. A lesser instance of the same nature is to be seen in the town of Dartmouth, Nova Scotia, where, a little west of the railway station, a cutting reveals a small river gorge filled with material of the same nature as that at Gays River. This channel is not over 60 feet in width, the upper part having been evidently eroded away, the material in which it is excavated being the auriferous slate of the region, which yielded readily to the glacial wearing. Since the formation of the deposit the movements of the slate walls have apparently caused them to crowd over the conglomerate; it is impossible, however, that this overhang may have been an original feature in the river gorge.

Turning now to the more southern areas of the Newark, we find that of the Connecticut Valley, where the beds were pretty certainly formed in an antecedent valley which was walled on either side by the ancient crystalline rocks of the Berkshire Hills and the Worcester plexus of ridges. The pebbles and other detritus have evidently been derived from one or another shore of the ancient bay in which they were deposited. The deformation of the area is considerable and peculiar. It evidently departs far from that which gives us the typical folded mountains of the Allegheny type.

So much of the Lower Hudson River Valley as is occupied by remnants of the Newark affords conditions in large part the same as those of the Connecticut field. The beds must have been laid down in a relatively narrow valley, and their deposition has been effected under the peculiar limiting conditions which such a field affords. In New Jersey there is no sufficient evidence that the deposits of Newark age were laid down in lakes or other distinctly and narrowly bounded areas. This, indeed, seems to be the one portion of the Newark deposits which may have been formed as a broad sheet. Yet here, as elsewhere in the deposits of this age along the Atlantic coast, we note that the fossil contents, as well as the general character of the beds, are alike evidence that the materials were gathered not in the sea, but in shallow lakes or in estuaries to which the ocean water had but scant access, if, indeed, it penetrated to them at all.

The same fresh-water character of the organic and inorganic sediments of our coast line which has just been noted in the case of the Nova Scotia deposits, is also to be found in other northern beds of Carboniferous age. The evidence alike makes for the conclusion that they were laid down in submerged valleys. This conclusion is forced when we note that both these formations contain thick deposits of conglomerate, the fragments of which are often more than a foot in diameter and show marks of wear, such as could not well have been effected except by the action of mountain torrents operating on glacial pebbles. In lake basins we could not look for the production of such bowlders. The action of waves on their beaches is not sufficiently energetic for the work, and there are no currents competent to impel the fragments to considerable distances from the shores. The only conditions in which they could well be formed are those afforded by torrents building their cones and deltas from the shore line outward in the manner so commonly found in lakes or river valleys which have high borders.

Where, as in the case of the Carboniferous strata west of the Blue Ridge, we find deposits of detritus accumulated to a great thickness and extended for a great distance outward from the old shore line they are characterized by certain very marked features. The sheets of the strata are tolerably uniform and continuous. The pebbles, where such are present, are of small size and of the most enduring materials. Generally they are of quartz or quartzite, rarely of compound rocks, and the fragments are commonly less than an inch in diameter. Such are the conditions of the millstone grit, the most characteristic monument of the outward washing of the débris into an extensive basin. It is only in the northeastern areas of the Carboniferous in the district where we have tolerably good reason to suspect that the beds were laid down in submerged valleys that we find coarse conglomerates and an irregular bedding, such as raise the presumption that they were formed in restricted areas which were invaded by torrent deposits.

In the case of the Richmond and the other like areas of the Piedmont district, the evidence as to the original condition of the surface on which the deposition of the Newark was made can not be regarded as complete. In favor of the supposition that the beds were laid down as a broad sheet of sediments which connected the many detached areas of the formation that occur between the Potomac River and South Carolina the following may be said: In the first place, the presumption is that the processes of construction which went on in this region were those that have usually occurred where beds once united have been faulted by orogenic action and the uplifted masses have been destroyed by erosion, leaving the depressed portions in the form of detached basins as the remnants of the deposits. Moreover, the several troughs in which the strata lie have their axes approximately parallel to the present coast line and to the Blue Ridge, a position which is quite in accord with the view that they are due to normal folding, but is not accordant with the supposition that they are the seats of ancient deep erosion valleys. If such valleys had existed we should expect to find them developed transversely to the shore, as in the Connecticut and Narragansett areas, rather than parallel to it, as is the case here. Furthermore, in none of these basins do we find any evidence of the original drainage outlet of the trough. In that of Richmond, the depression now has a depth of not less than 3,000 feet—it is likely that in places it exceeds that measure. If any considerable portion of this depth were due to an initial depression effected by erosion, we should expect that a wide valley connected it with the sea; of such a valley in the case of this or the several other basins of the district no trace has been found.

Against this array of considerations others of nearly equal strength which make for the other view are to be set; these are as follows: The Richmond area, at the few places on the western side where the contact with the subjacent rocks can be traced, shows, at the bottom of the Newark series, a coarse conglomerate, the materials of which might well have been brought into place by torrent action. Above this the beds are accumulated in a manner which indicates a very rapid aggradation; there is apparently little continuity of strata except in the shale deposits. The order, or rather the lack of it, is such as would be brought about by the interlocking of detrital fans or deltas and not by the growth of great sheets of strata accumulated as were those of the Millstone grit. The beds of coal vary greatly in their position and their relations to one another. In one instance, at least, and probably in several, the beds divide, the partition increasing laterally in thickness until the separation is wide. Accidents of this nature are easily to be explained on the supposition that the infilling of the area was brought about by the extension of deltas which progressed until the basin was in some measure filled up. On the eastern margin arkose deposits, evidently derived from neighboring high ground, have been abundantly accumulated.

The character of the sediments in the basin, except the shales, is such as we would expect it to be in case the sources of supply had always been near the seat of deposition. As compared with our standard example of distant offshore carriage, the Millstone grit, the difference is striking. The Newark deposits of this district are, as regards certain of the beds, imperfectly assorted, or, where well distributed, coarse and fine beds rapidly alternate.

A theory, or rather a combination of working hypotheses, which seems to explain the conditions of deposition of the beds in the Richmond area may be set forth as follows:

Before Newark time the rocks of the Piedmont district from the Connecticut area southward were, probably since the Silurian period, above the level of the sea. This is shown by the absence of any beds of the later Paleozoic series in the field. We may fairly presume that the region was the seat of more or less considerable river valleys, and that these depressions were broad, and also that the margin of the land was much farther east than it is at present.

The geographic change which attended the beginning of the Newark deposits did not admit the sea to this area, but led to the development of sedimentation in the river valleys, which were possibly locally or temporarily converted into lakes, the materials being brought in about the low grounds by torrents from the highlands. At first these valleys were probably shallow, but as the deposits accumulated their weight would tend to bear their foundations down until the section of strata they contained became much thicker than the original depth of the valleys would have permitted them to be. In this deposition and consequent subsidence the main channels of the streams—those which led to the sea—probably received relatively little sediment, and, therefore, if they were filled at all, were not occupied by any considerable thickness of strata and, therefore, did not subside; so that in the subsequently occurring erosion of the area about to be noted these exit river channels might well have disappeared.

So far as can be determined by the sediments of the Richmond area, the erosion which supplied them was not effected by glaciers. The detritus appears to have passed through torrents of moderate steepness, the coarser débris, except that locally accumulated at the base, apparently indicating a fall of the streams of 50 to 100 feet to the mile. This determination is based on a study of the carrying force of the streams in the Appalachians and the Cordilleras.

After the strata now remaining in the Richmond area had been laid down, it is possible, indeed probable, that a continuation of the series may have been formed which extended far beyond the limits of the present border of the Newark rocks. It is possible that the extension was sufficiently great to have covered this portion of the Piedmont district connecting the several areas of these strata in one field. There is, however, no clear evidence that such was the case. The probability of it rests upon the fact that much erosion has occurred in the long interval during the Jurassic period, in which time this district was apparently above the level of the sea. This view also receives support from the similarity of the succession of deposits exhibited in some of the southern areas.

When the epoch of deposition was over, there was a reelevation of the land, coming rather early in the Jurassic period. It was most likely at this time that the main stressing of the deposits took place, though some as yet unassignable portion of it may have occurred during the period of deposition. The result of this principal development of mountain-building work was, so far as we may judge from that which is known concerning the structure of the area, to break the beds into many fault blocks and dependent folds, and probably at the same time there was an extensive penetration of trappean masses.

The faulting and folding, as well as the intrusions of the trappean rocks in this basin, differ widely from that which is found in the normal west Appalachian Mountains—the anticlines and synclines of the Alleghanies. In those mountains, especially in the synclines, faults are relatively rare; the synclines are indeed very uniformly boat-shaped in their structure. They lack the numerous small folds of the strata, the heavy faults, and the numerous dikes which are so characteristic of the Richmond area.

So far as can be determined from the evidence at hand, the dikes which intersect the Richmond Basin series were formed at a much greater depth in the earth than they now occupy. Some of these intrusions show a tendency to depart from a vertical path and to extend as sills parallel to the bedding, even where the planes of the layers are at relatively low inclinations. This is shown in the case of the coal beds which have been changed to coke by contact with the traps. The only known sills are near the base of the section, in the coal measures.

As yet there is no evidence that the igneous action which occurred in this region was of a true volcanic sort. No ash beds have been discerned, nor is there reason to believe, from the beds that remain, that any contemporaneous flows of trap exist. There is but one possible case of stock or volcanic pipe; the walls of the dikes are not much metamorphosed, as they would have been if they had been the path of a long-continued upward flow of lava.

It is a noteworthy fact that in the case of all the areas of Newark rocks on the Atlantic seaboard which are of a nature to lead to the supposition that they were accumulated in preexisting valleys, we find evidence of much diking and occasionally of true volcanic action. This geographic association is suggestive. Thus in the Connecticut Valley there are many dikes and flows of lava within the basin, while a few miles beyond its border, beyond the region which the Newark may have occupied, there is reason to believe that such lavas broke through the basement rocks in much less proportion. It seems, indeed, possible that the great local thickness of the accumulations which were formed in these periods may have in time served to bring up the isogeothermal planes so that the melting zone of the rocks was near to the base of the stratified section. Thus when the mountain-building stresses were brought to bear on the mass, the movements of the crust below it may well have been sufficient to afford exits to the molten matter.

It is easily seen that the conditions of folding when the pressure acted on a broad area of slowly built strata, such as that of which the Alleghany Mountains were formed, may have been very different from those which existed in thick localized accumulations laid down on floors of preexisting gradually down-sinking valleys. In the former case the influences tending to bring about the upward movement of the igneous rocks might be much less considerable than in the latter.

In summing up the evidence concerning the question as to the deposition of these Newark beds in a preexisting valley, it may be said that it is more reconcilable with the supposition that the beds were laid down in troughs of lakes or rivers than that they were formed as a broad, tolerably uniform sheet. That they were not laid down in the sea is clearly indicated by the absence of marine organic remains and by the abundance of land and fresh-water plants, as well as the remains of fishes of groups which may fairly be deemed of fluviatile or lacustrine habits. Therefore, the choice in conclusions is between a large valley—one of sufficient area to have included all the neighboring areas of these formations—or a number of lesser basins, each of so limited an area that it would have been filled with coarse sediments derived from the highlands about the depression; or, thirdly, a widely extended sheet formed on a seaward sloping plain, such as that of northern Siberia of to-day. Taken in connection with what is known of the history of the Atlantic coast in the Paleozoic and Mesozoic ages, the facts gathered in the Richmond district lead us to believe that the area was high land during the greater part of the time from the Silurian to the close of the Paleozoic, and that at the beginning of the Newark time the surface abounded in broad valleys which became filled with lake or river deposits. It is evident that the climate was humid and equable, so that it for a time permitted the development of peat deposits, which have since been converted into coal.

TOPOGRAPHY OF THE PRE-NEWARK TERRANE.

In the repeated changes of land form on the Atlantic coast since Triassic time no vestiges of the surface of that period can have escaped destruction except where it was covered by deposits and further protected from denudation by burial beneath the ultimate base-level of erosion of subsequent geologic periods. The floors of the several Newark areas, from Nova Scotia to South Carolina, thus afford, since they have been locally preserved in the manner described, the sole clue to the geography of that time other than such inferences concerning the land as may be derived from a study of the Newark sediments and organic life. The exposures of the Newark land surface are extremely limited. In most of the Newark areas the visible evidence is found along the line of boundary on the basal edge of the tilted beds. Locally similar observations may be made on the opposite border, where similar conditions occur. In the case of the Richmond area the eastern border presents by far the most continuous exhibit of facts concerning the Triassic land surface. From point to point on the western margin evidence of the contact of the Newark beds upon the ancient gneisses may also be had.

The information obtained from the study of these fragmentary portions of the old land floor points to a few conclusions which are presumably true for this immediate region. First, it is evident that the area had been one of long and deep erosion, since both coarse granites and gneiss were exposed at the surface, both of these rocks indicating by their structures an original thick cover of rock. Secondly, the denudation of these rocks appears to have gone so far as to have reduced them to something like an even surface. So much disturbance of the rocks has since taken place that it will be necessary to explain the apparent objections to this latter statement.

The eastern boundary of the Richmond basin has a general direction east of north. Viewed in its several parts, it consists of more or less straight segments, which are determined by one or the other of two conditions of the Newark strata in relation to the basement rocks. The longer of these segments appear on examination to be formed by the intersection of the present Piedmont plain with the ancient tilted land surface on which the Newark strata repose. Although the actual contact of the Newark strata with the granites and gneisses is seldom seen, the essential straightness of the line of contact, as shown by the strike of the coal measures of the basin and the distribution of granite and gneiss exposures for long distances, leaves no room for those irregularities in the line which must have resulted had the Newark beds been laid down on the rugged surface supposed by some to have existed here in Triassic times. The localities which exhibit these relations will be described in detail in the account of the boundary.

The shorter of the segments, which are those parts of the boundary line departing most widely from the general direction, afford evidence of faults. When due allowance is made for these disturbances of the eastern border, the ancient surface of the granite and gneiss appears to have been without much relief. This apparent evenness of the land is the more remarkable when it is considered that the central part of this floor of the basin, on the eastern margin, is composed of granitic rock. The topographic relief, in other words, was nearly as weak as that of the present surface of the Piedmont district. Such glimpses as may be obtained of the east and west extension of this ancient land surface bear out the explanation of the irregularities traced along the eastern border. In following down the floor of the basin in mines the irregularities in the slope are found to be due to disturbances in the granitic basement taking place after the deposition of the coal measures. The evidence from the western border is in general harmony with that already stated.

The argument thus derived from an examination of the ancient land surface is supported by the sedimentary character of the basin. The basal beds especially are rich in the disintegrated minerals of the granites. In a region of steep slopes and abundant waterfall mechanical abrasion keeps pace with or proceeds faster than the formation of loose material by decomposition and disintegration. On gently inclined plain-like surfaces the products of disintegration linger about their sources until a change of geographic or climatic conditions gives to streams or waves the power to transport and assort the waste. The basal sediments of the Newark group in this field point to the latter geographic conditions rather than to those first stated, although the real state may have lain between the extremes thus implied.

Such is the evidence for the belief that the floor of this area of deposition, or at least so much of it as is now revealed, was essentially without strong relief. That the lands of the Newark area were not in this featureless condition throughout the period of deposition of the strata is demonstrated by evidence which is of a more general nature. However low may have been the relief of the land at the beginning of Triassic deposition, the thick beds of sandstone and shale in this basin alone demand an adjacent area of erosion whose constructional height above base level must be measured in terms of the detritus derived from it. It is not necessary to suppose, however, that high mountains at any one time, and particularly at the beginning of deposition, existed in this area of erosion. Concomitant depression in the area of deposition, with elevation in the area of erosion, maintaining a moderate or only slightly elevated relief would have given the same quantitative results in the deposits of the neighboring depression as an initial mountainous relief. Whatever relief may have existed in this field as the result of the Appalachian diastrophe had largely vanished by the opening of Newark sedimentation.

CONDITIONS OF FAULTING AND FOLDING.

It is evident that the orogenic disturbances of this Newark field are due to actions which affected the ancient crystalline rocks that underlie it. The disturbances have been propagated to the sandstones, shales, and coal beds of the basin, which have adjusted themselves to the dislocated foundation. On the supposition that the basin existed before the orogenic movements began, it is difficult to determine how much deformation was due to these movements. The extensive faulting of the ancient base appears to have been produced subsequent to the deposition of the lower 1,000 feet or so of the Newark section; it most probably occurred after the whole of that section was laid down; but it is possible that some disturbance took place before the upper parts of the section were deposited.

It will be observed that the facts noted in this report lead to the conclusion that many of the faults pass in their vertical extension into flexures or into sections of the beds where the material of the layers is shoved about in the state of finely divided bits, which indicate the movement to which they have been subjected by the slickensided character of their faces. This evidence of comminution and shoving is so general that it may well be regarded as a characteristic feature of the rocks in this basin. It appears to be due not only to the somewhat local disturbance directly induced by the faulting but also to general stresses affecting the whole mass of the rocks, such as would be produced by lateral compression.

It appears impossible to account for the disturbances of the strata in this basin on the assumption that the only movement has been that of downsinking of its floor attendant on the abundant block-faulting, the result being the formation of a trough of the "graben" type. It is necessary to suppose a lateral compression of considerable though indeterminable amount in order to explain the evident packing of the strata, such as is shown in the several cross sections of this report.

It is evident that the seat of the stresses which have affected the rocks of this district other than those due to the weight of the Newark beds lies in the hypogene section. Concerning the origin and adjustment of these stresses little of value can be said, except to direct attention to certain possibilities as to the source and nature of the movements.

It appears unreasonable to suppose that the whole of the disturbance of these rocks was due to the yielding of the basement on which they lie, brought about by the weight of the sediments. The block-faulting, with the upthrust of large masses, evidently indicates a stress other than a simple gravitative downbearing. While the weight of the Newark section and whatever else may have rested upon it doubtless entered into the equation of forces which determined the faulting and folding of this basin, it has to be supposed that the principal factors in the equation were deep-seated. So far as we can perceive, the only action competent to produce the results is the contraction of the deeper parts of the earth mass, resulting in a compression of the superficial portion, the work done being locally affected by the accumulations of sediments which took place on this area.

Although under certain little-known conditions it is evident that massive rocks, such as granites, may be flexed, it is well ascertained that they are most likely to yield to the strains involved in mountain-building forces by faulting, the included blocks slipping past one another as they have evidently done in this basin. The hypothesis of direct downfaulting, unassociated with horizontally acting compressive stress, such as is assumed by some writers in accounting for graben valleys, does not seem to be applicable in this area. The order of the disturbances, so far as observed, is most reconcilable with the supposition that they were produced by a thrusting movement acting from the eastward, which was competent to urge the basal rocks landward against the resisting mass of the Blue Ridge. The strong downfaulting on the western margin, combined with the remnants of sharp flexures much broken by faults, appears to indicate that the resistance to the thrust was great, while the relatively gentle declivity of the trough on the eastern border may be taken as showing a less restrained movement.

There appear to be reasons for supposing that there is a tendency of the rocks beneath the sea to thrust against the land. All along the Atlantic coast of the United States, from Boston Harbor to Cape Hatteras, there are marks of disturbances of the strata next the shore by processes which, beginning in the Tertiary, have continued down nearly to the present day, if they are not still in action. The extensive dislocations of the deposits on Gay Head and Cape Cod are evidences of such action. Like conditions are shown to exist along some of the shores of the Old World. It seems not improbable that the source of these movements may be found in the expansion in the rocks beneath the sea floor, which would be brought about by the rise of the isogeothermal planes due to the blanketing effect of the strata which are accumulating there, where the increase in the depth of the sediments serves to elevate the planes of equal internal heat more rapidly than the secular refrigeration of the planet operates to lower them, a condition which we may deem practically active whenever sedimentation has long been going on. The effect is necessarily to bring about a tendency to expand in the section thus heated.

It is evident from the movements of strata involved in mountain-building actions that, whatever be the nature of the conditions beneath the superficial portion of the earth's crust, they permit its ready movement under the stresses to which they are subjected; we may, therefore, suppose that the result of the expansion from the increase of temperature may well be a thrusting action against the coast line of the areas of sedimentation. Beneath lands which have long been the seats of erosion the isogeothermal planes are presumably lowered toward the center of the earth in such conditions of cooling. These sections would probably not have the softened base which permits the ready movement observed in places where great sedimentation takes place. It will be observed that this hypothesis is little more than conjecture, but in this difficult field of inquiry it appears to be worth while to suggest it.

EFFECT OF IGNEOUS INJECTIONS ON CARBONACEOUS STRATA.

At no other place in this country are the effects of the intrusion of lavas in carbonaceous rocks so well exhibited as in the Richmond basin. At many points numerous dikes cut the coal beds and bituminous shales, and in several instances they have moved parallel to these deposits in the manner of sills. As yet the relatively slight workings of the coal deposits have revealed what is certainly but a small proportion of these interesting contacts, yet in half a dozen of the old mines the explorations disclose them.

The most evident effect of the contact or even the propinquity of the trap injections is the expulsion of the more volatile portion of the coal and the rearrangement of the remainder in the form of what is well termed "natural coke." This change has, in cases, occurred at the distance of 20 feet or more from the nearest side of the injected matter, the alteration being very even in its character so far as it is effected, but ceasing along a fairly well-marked line, showing that there was a critical point in the scale of temperature, beyond which the heat was not sufficient to bring about a change.

It is interesting to note that the heat which was sufficient to coke the coal at a considerable distance from the source of the temperature in the trap dikes has not distinctly affected the conditions of the other rocks at like distances from the originally molten mass. These rocks are slightly indurated, but not often sufficiently so to make them resist weathering more effectively than those remote from the paths of the dikes.

It is a noteworthy fact that the distillates arising from the coking of the Richmond coal in the presence of the trap have left no traces in the rocks about the changed beds. These beds of natural coke are not infrequently thick. At places they have been found 10 feet or more in depth. The amount of the volatilized material may be estimated at about one-third of the compact coke which remains, yet there is no trace of oil, beyond a slight odor of that substance, or of coal tar in the neighboring strata, though these are quite open enough to afford a place for them. These heavier products of the coking process having disappeared, it is not to be expected that the more volatile gases would have remained. It may be noted, however, that no traces of them have been found.

It seems unlikely that the materials which were expelled from the coke at the time when it underwent its change from coal could have found their way to the surface without leaving any traces on their path of escape. It is a natural suggestion that they might have entered into various combinations, as with the iron oxide, but nothing has been observed that warrants this conjecture. The interpretation of the facts must await further study.

It has been suggested that the formation of diamonds is brought about where beds of carbonaceous materials are penetrated by dikes. This hypothesis is evidently warranted, for the reason that this crystal has been, in its smaller and least perfect forms, produced by subjecting carbon to a high temperature. There seemed one bit of evidence, slight but possibly instructive, which served to make it not improbable that these gems had been formed in the natural laboratory of the dikes of the Richmond basin. According to a well supported tradition, a diamond of some size was found many years ago in the terrace deposits in the western part of the town of Manchester, some 10 miles down the James from the eastern margin of the coal field, in a position where it might reasonably be supposed that it came from the rocks of that area. It is, indeed, by no means unlikely that the Newark beds originally extended to the eastward as far as the place where the crystal was discovered.

Acting on the clew above noted, a considerable amount of the gravelly material from the small streams which drain the region about Midlothian, where the traps cut the beds of the basin, was subjected to a careful study. This study, which was performed by Dr. Palache, showed no trace of crystalized carbon.

It should not be understood that the test above indicated has more than a slight negative value. It is, perhaps, overweighed by the fact that one diamond has been found in the area. It seems desirable that some one who has had experience in searching for these crystals, and whose eye is accustomed to their aspect in the rough state, should make a careful study of the country. Such an inquiry should be directed to the region about the eastern margin of the field, for there the coal beds which have been affected by the heat of the trap have been subject to disintegration.

If a study of the rock in the mines with reference to the occurrence of diamonds is undertaken, as seems desirable, the effort should be to select the deepest points at which the dike stones can be found cutting the carbonaceous layers. It is evident from the effect the injections had upon the coal that the lava parted rapidly with its heat in the higher portions of the dikes. Its temperature when it entered the stratified deposits may have been much higher than in the places remoter from the sources of supply.

In this connection it may be noted that the injection of the dikes appears to have taken place with less than the usual violence. No brecciation has been observed, nor any inclusions of the country rock in the igneous masses. The sheets are uniformly rather thin; their walls show little of the effect of chilling. These facts point to the conclusion that the injections occurred at a considerable depth, and probably in a slow manner.

FORMER EXTENT OF RICHMOND NEWARK AREA.

It is evident that the field now occupied by the Newark beds of the Richmond basin was at one time much more extensive than it is at present. Its extreme limits can not well be determined. As is well known, the eastern margin of the field is bordered by several small detached areas, in which are preserved the lower coal-bearing strata. In the opinion of the miners of the district, other undeveloped basins lie yet further to the eastward. Occasional patches of sands having the hue common to the decomposed beds of the Newark are exhibited in shallow road cuts and gullied fields for some miles east of the recognized outcrops of the rocks. It is not improbable that small basins similar to the Black Heath lie beneath the common mantle of residual deposits as far to the east as the meridian of Richmond, or, say, 12 miles from the ascertained exposures of the Newark series. It should be noted that the considerable area of Newark rocks at Taylorsville is well toward the edge of the Piedmont district. No effort has been made to seek for these smaller outliers; their discovery will depend on chance cuttings or on searching for water, or on a systematic exploration by borings, a work which, though of importance from a scientific standpoint, can not at present be commended to those in search of coal.

On the western margin the same conditions of detached small basins may exist, as is indicated in the field to the eastward; but the higher elevation of the country and the deeper incisions of the streams make it less probable that such areas have been overlooked in that part of the field. One such, however, exhibiting the basal conglomerate, is noted on page 490 of this report.

On the northeastern margin of the Richmond basin there are two small subsidiary basins, those of Deep Run and Taylorsville, which are much further separated from the main area than those lying in the eastern and western margins; they are also much longer than the other outliers.

The general arrangement of the several Newark areas in Virginia exhibits a rude en échelon order, such as is usually found in the position of mountainous folds. About the greater basins lie those of smaller size, which are similarly distributed. The grouping is in general consistent with the supposition that these troughs are due to mountain-building action, in which the faulting of the basement of pre-Newark rocks has had more influence on the attitude of the stratified beds than is evident in the structures of the Alleghanies. This feature is perhaps more apparent than real, for the reason that the foundations of the folds in the western field of disturbances is not revealed to us. The distribution of the remaining portions of the Newark beds in Virginia is consistent with the hypothesis that the deposits once mantled that field over, the several areas still existing owing their preservation to their inclusion in the troughs arising from the dislocation of the basement. It is also reconcilable with the supposition that the beds were laid down in preexisting valleys, the lesser basins grouped about the greater being peripheral remnants of the once more extended areas.

The fact that the coal-bearing beds of the Newark group fail to appear in several of the basins of the Virginia district is presumptive evidence that the conditions of the areas differed as regards the development of swamps. From what is known of these basins the coal beds, with the exception of those of the small area north of the James River, seem to be limited to the field south of that stream.

EXTREME EROSION OF THE EASTERN APPALACHIANS.

It is evident that the disturbances which have affected the district east of the Blue Ridge must have produced a mountainous topography, which has been lost by the processes of denudation that have brought the region to its present level, while mountains formed on the western side of the Blue Ridge at probably an earlier period exhibit a strong topographic relief. This feature of an excessive amount of effacement of mountain-built structures in the region next the coast as compared with that of regions farther inland is distinctly to be observed from Georgia to the Potomac and less evidently thence to the Bay of Fundy.

There are two obvious ways in which this difference in the condition of the inland and coastal reliefs may be accounted for. It may, on the one hand, be explained by the supposition that the form of the Piedmont area is due to the action of the sea, mainly by its waves, which, with the incessant changes of level, have acted in a zone extending from below the present coast line to the height of some hundred feet above that plane. On the other hand, it may be accounted for by the hypothesis that the western region has been uplifted at one or more periods, so that its relief has been worked out by streams since a time when it had the level character of the Piedmont area on its eastern side. As the evidence from the Richmond Basin is but a small part of that which has to be considered in the discussion of this question, the matter will be passed by with the suggestion that a close study of a section from the eastern border of the Piedmont district across the Blue Ridge to the western portion of the Alleghanies is likely to afford valuable data for the inquiry.[1]

RECENT CHANGES OF LEVEL.

The rapid fall of all the rivers of the Atlantic coast is evidence that this shore land has been subjected to a slight uplifting movement in relatively modern times, so recent, indeed, that the rivers have not been able to cut down their beds to the normal depth. Thus the James River has evidently done but little work since it was revived by the last elevation of the district in which it lies.

The amount of the last downsinking of this district can not be accurately determined. As noted in a report on the Dismal Swamp area,[2] many of the flooded valleys have deeper water some distance from the coast line on the great bays, such as Pamlico Sound, than exists in them nearer the sea. In some cases this inward deepening amounts to 40 feet or more. Allowing the least possible amount for sedimentation in these still, deep channels, it appears likely that the last incursion of the sea carried it to a level between 50 and 100 feet higher than it was when the river valleys took their present form.

It is possible that some of the obscure terrace-like structures along the James River to the seaward of the Newark Basin may represent the work of the sea rather than that of the river. So, too, the curious, small shelf morasses of the county of Hanover, north of the James

[1] See Hayes and Campbell on the Geomorphology of the Southern Appalachians (Nat. Geog. Mag., Vol. VI, 1894, pp. 63-126), wherein the ground is taken that the Piedmont district and the Appalachians were base-leveled by subaerial agencies, and that the Appalachians have been subsequently uplifted, allowing the streams to carve out valleys in that part of the continent.

[2] See Tenth Ann. Rept. U. S. Geol. Survey, Part I, 1890, pp. 313 et seq.

River, may owe their origin to deposits of marine sands formed during some one of the recent subsidences of this region. What is known of this section of the country makes it admissible to suppose frequent advances of the sea to the lower part of the Piedmont slope.

At first sight it might be supposed that this section of the country had been much more subjected to marine invasions than the other parts of the eastern United States, but a comparison of the evidence of such action with that which may be obtained in New England or in the more northerly parts of the continent shows that the Virginia district is in this regard in no way exceptional. In the report on the geology of Mount Desert[1] the existence of more than half a dozen elevated shore lines is noted. In the Cape Cod district of Massachusetts there is evidence of at least four advances and recessions of the ocean waters since the beginning of the Pleistocene epoch. The number is probably much greater than is noted.[2] In fact the more the shore-land district of this country is studied the more it becomes evident that the relations in height of the land to the sea have been subjected to continuous and swiftly repeated changes.

As before remarked, the advance or recession of the sea on the face of land may be due either to the rise or fall of the sea level or to a positive movement of elevation or subsidence of the land itself. In most cases, as both sea and land are undergoing independent movements, the position of the shore at any one time is likely to be determined by an equation between these two independent swayings. It is, of course, quite impossible, in most cases, to say to which of these groups of causes a particular change of level is to be attributed; but in the case of the last great movement of the sea, that which has recently drowned the lower part of the river valleys of this region, it may reasonably be assumed that the action was due to a positive uprising of the ocean. This is indicated by the fact that, throughout the world, all shores, with rare exceptions, exhibit the same drowned valleys which are so conspicuous a feature on the Virginia coast. That they are rather more evident on this shore than elsewhere is due to the fact that here the streams are small, and owing to the generally decayed and open nature of the subjacent rocks, they carry little sediment wherewith to form delta deposits, which, as in the case of the Mississippi River, has so often served to obliterate the original incursion of the sea.

CLIMATAL CONDITIONS OF NEWARK TIME.

The evidence as to the climatal conditions of the time during which these beds were laid down, though not great in amount, is interesting enough to warrant some discussion of the matter. As regards the temperature of the district, the beds lying at the base of the section

[1] See Eighth Ann. Rept. U. S. Geol. Survey, Part II, 1889, pp. 987 et seq.
[2] See Eighteenth Ann. Rept. U. S. Geol. Survey, Part II, 1898, pp. 497 et seq.

contain numerous plants which must have had permanently living foliage, and which thereby indicate a substantial immunity from frost. The part of the section containing the distinct coal beds has a thickness not yet accurately known, but which probably does not exceed 100 feet.

During the time when the coal beds were being deposited the climate was presumably humid, for it permitted the accumulation of thick beds of peat, which in general character must have been not unlike those formed during the Carboniferous era. As such masses of peat rarely, if ever, are found in tropical conditions, it may be presumed that the mean temperature was not much above what it now is in this field. As the production of thick morass deposits does not go on in regions which have regular and long dry seasons, we may conclude that the climate was one of tolerably constant humidity. These conditions would hardly be satisfied by the present climate of the area, but they would be met were the extremes of winter cold and summer drought excluded.

After the deposition of the lower coal-bearing section there came a distinct alteration in the conditions of this area, which may have been due to a change of climate, but is explicable on the supposition that it was caused by topographic alterations. The beds no longer contain evidences of ancient swamps. They show the existence of conditions such as may be found in the low lands of rather arid fields. The like may be found in the valleys of the Cordilleras, where the rainfall is less than 20 inches per annum. On the other hand, the thick beds of detrital materials show that at certain times of the year, at least, the rainfall was considerable.

Although no trace has been found of salt deposits in this field, the assemblage of facts leads one to suppose that the upper part of the section, which amounts to 2,000 feet or more in thickness, was accumulated in arid rather than in humid conditions of climate. The beds were probably laid down in a fresh-water lake or in a broad river valley. It is evident that vegetation frequently developed upon the shores. That it attained no great depth can best be explained by the supposition that the climate was not such as to favor the growth of peat deposits. These conditions would be met by the assumption that while there was rainfall sufficient to produce strong erosion, a dry season inhibited the development of thick peaty deposits.

EVIDENCE FROM THE CONGLOMERATES AS TO PERIODS OF METAMORPHISM.

Conglomerates such as those of the Newark have a peculiar but much neglected value in that they afford what may be termed a census or test of the conditions of the rocks whence the fragments were derived at the time when the pebbles were formed. Such information, when once approved, enables the geologist to fix the period when the chemical and physical changes of the rocks of a country were effected. By safe methods of inference the evidence may lead to conclusions as to the ancient deep burial of rocks which are now exposed at the surface, and as to the former extension of deposits which are now limited in their area, or which have quite disappeared by erosion, or which have been changed in their mineralogical character. In a word, a true conglomerate is likely to be a collection of the rocks of the country in which it lies, one made at the time when the strata were formed.

As the pebbly deposits of the Richmond Basin have escaped other changes than those of the slighter sort, such as arise from compression and a trifling amount of iron deposition, we are from their contents enabled to make the affirmations stated below. The first of these is that the foundation rocks of the James River district had in Newark time the character we now find impressed upon them. They were crystallized, sheared, and hardened as they are at the present day. The only difference between their present and their ancient aspect consists in the fact that the dike stones are new. This is indicated by the absence of pebbles of distinctly igneous rock, such as would have been derived from the dikes which cut the sedimentary deposits. The second affirmation is that the only sedimentary deposits abundant at the time when the pebble beds were formed, but now rare, were certain quartzites which form a large share of the fragments that make up the pebbly beds of the more superficial deposits which overlie the Newark. These quartzites have been pretty generally cleared away from the James River Valley, except in and near the Blue Ridge.

AGE OF THE UNDERLYING ROCKS.

As to the age of the fundamental plexus in this region there is no evidence of value. The deposits, however, probably date to Laurentian or Huronian time. So far as it goes, the evidence as above noted indicates that in Newark time there were no beds accessible to the streams which drained into this basin of newer age than Cambrian or pre-Cambrian. In other words, the upper Paleozoic section was wanting in this field.

It is to be noted that the James River now cuts a great variety of Paleozoic beds, and that its current conveys waste from all the important members of that section, from the Cambrian to the Carboniferous, inclusive. It therefore seems probable that this river, or a stream draining through the Blue Ridge, did not exist at the time when the deposits of the Richmond Basin were accumulated. This view is consistent with the hypothesis that these strata were deposited in an antecedent basin which was part of a system of drainage different from that which now exists in this field. The map of the basin shows that there is no trace of a prolongation of the beds in the axis of the existing valley. The margins cut directly across that trough, as they would not be likely to do if the basin had existed at the time when they were formed.

The most reasonable supposition concerning the derivation of the pebbly beds of the Newark is that they came through purely local streams, and that the James River drainage had not worked through the Blue Ridge, but, so far as its upper waters are concerned, forced a way parallel to that barrier to some other point of discharge into the sea. The narrow, canyon-like character of the water gap in that great ridge indicates that the streams which more or less completely traverse it have cut their passage in relatively modern times. The upper James River may have been a part of the Shenandoah drainage, or perhaps of the Roanoke system, which was here diverted or robbed by the cutting back of a torrent that at one time headed near Lynchburg.

CHAPTER II.

THE ROCKS OF THE AREA.

ROCKS BORDERING AND UNDERLYING THE BASIN.

The term geologic basin implies a mass of strata surrounded on the present surface and underlain by rocks of more ancient date, presenting frequently a marked difference of attitude and invariably of structure; at least such is the conception gained if we examine the areas to which the name basin has been, in the common use of geologists, applied. Of the distribution of the rocks of this earlier group beneath the Richmond Basin we have as yet no knowledge other than those apparently valid suppositions which may be based upon a fair interpretation of the dominant structure of the rocks about its margin.

The porphyritic granitite.—The bordering rock on the eastern side of the area is a coarse porphyritic granitite, well developed in the vicinity of Midlothian, and extending with variations of texture as far north as Gayton and as far south as Winterpock. Its large porphyritic crystals, often in the form of Carlsbad twins, are arranged in a general north-and-south direction, due to the flow of the once fluid rock (see Pl. XIX). The disintegration of these feldspars has played an important part in the development of the Newark sediments.

This granitite shows, at least in the middle of the area in which it is exposed, no signs of dynamic metamorphism. It is cut by a few small aplite dikes in the vicinity of Midlothian, but its relations to the neighboring pre-Newark rocks have not as yet been investigated. From the general distribution of the mass, it is evident that it underlies the eartern part of the Richmond Basin, but its extent toward the west and the position of the line of contact between it and the gneiss of the western border are not definitely known.

The gneisses.—The extreme northern and southern ends of the Richmond basin are bordered by gneissic rocks, which are continuous along the western margin except for occasional dikes of granite interpolated in them. The gneiss appears to be largely igneous rock also, but in an altered condition from the effects of pressure and shearing. The most common type resembles quartz-porphyry, which has been extensively sheared, faulted, and jointed. Some of its secondary structures are shown in the accompanying reproduction of a photograph taken along the western border where streams have removed the weathered subsoil (see Pl. XX).

PORPHYRITIC GRANITE FROM BOTTOM OF ETNA SHAFT, MIDLOTHIAN.

Gneiss is exposed in the southern end of Cornwallis Hill, near Manakin, where quarries have been opened for "road ballast." The intrusion of granitic sills gives the rock a banded structure, the dip of which is low. Minute cavities in these rocks sometimes contain freely terminated black quartz crystals, and are said to yield a few drops of "coal oil." The overlying carbonaceous shales have probably furnished this material. This quarry also exhibits two faults, the bearing of which on the structure of the basin is described on page 464.

These rocks are everywhere, except in stream beds and artificial openings, deeply decayed (see Pl. XXI), and their detailed investigation has been postponed until the mapping of the area surrounding the Richmond basin is undertaken. It is sufficient to state here that granites and gneisses were exposed at the surface in this part of the continent at the time deposition began in the Richmond basin. The age of these rocks is not locally determinable.

CHAPTER III.

STRATIGRAPHY OF THE RICHMOND AREA.

The grouping of the strata in this area and their representation on maps has never before been attempted. The nearest approaches to a classification of the strata made by those actually acquainted with the field are the tables given by Sir Charles Lyell and Oscar Heinrich. The former geologist recognized a lower coal-bearing zone and an upper series of sandstones. To these obvious subdivisions of the strata in the Richmond area this distinguished geologist gave no distinctive names beyond the reference to a European horizon with which he considered the coal measures contemporaneous. Heinrich's grouping of the strata is based on local observations in the shafts and mines about Midlothian. Other schemes of grouping have been proposed, but in no case has the attempt been made to apply these standards to regions outside of the section whereon the subdivisions were based.

A casual observer, traversing the Richmond area on any one of the section lines described in this report, can not but note that there are several leading lithological features displayed in bands by which the strata may be roughly grouped. When one seeks to trace out these bands along the strike of the strata the futility of the task is at once apparent. It is only on the broadest possible lines and probably with a considerable error in the placing of boundaries between distinguishable groups of strata that a mapping of the basin can at present be carried out.

GNEISS OF WESTERN BORDER, SHOWING JOINTS AND THRUST PLANE, THREE CHOP ROAD LOOKING NORTH.

TABLE OF FORMATIONS.

The accompanying table of divisions is an expression of the present knowledge concerning the lithological and biologic characters of the area.

Table of formations in the Richmond area.

Lithologic.		Biologic divisions.	General characters.
Divisions.	Subdivisions.		
Chesterfield group.	Otterdale sandstones.	Araucarioxylon beds.	Coarse sandstones, often feldspathic, with silicified trunks of Araucarioxylon; well developed north, south, and west of Otterdale. Thickness, 500+ feet.
	Vinita beds	Estheria beds .	Black fissile shales, carrying *Estheria ovata*, passing upward and intercalated with gray sandstones; in James River bluff, west of Vinita station, on Tomahawk Creek. Thickness, 2,000 feet.
Tuckahoe group.	Productive coal measures.	Macrotæniopteris beds.	Interstratified beds of bituminous coal (usually 3 seams), coke, black shales (*a*, fish bearing; *b*, estheria shales; *c*, vegetal shales), sandstones (feldspathic and micaceous), fossil plants; teeth, bones, and tracks of reptiles. Thickness, 500 (?) feet.
	Lower barren beds.	....	Sandstones and shales under coal beds, often with arkose. Thickness variable, from 0 to 300 feet.
	Boscabel bowlder beds.	....	Local deposits; bowlders of gneiss and granite. Thickness variable, 0 to 50 feet.

The divisions of the strata thus recognized will now be described more in detail.

THE TUCKAHOE GROUP.

The Tuckahoe group includes the lower coal-bearing beds of the Newark system in the Richmond Basin.

The beds are well exposed in the shafts and mines bordering Tuckahoe Creek, in Goochland County, in the vicinity of Gayton. At various points in the area the facts go to show the existence of a series of beds of variable thickness below the coal-bearing strata; and, throughout the group, although shales predominate, feldspathic sandstones and arkose beds occur. The Tuckahoe group, as a whole, may be treated under the head of (1) the Boscabel bowlder beds, (2) the lower barren measures, (3) the productive coal measures. The thickness of these strata amounts, in certain sections, to as much as 500 feet; in some localities the formation containing coal appears, from trustworthy information, to measure not more than one-tenth of this estimate.

THE BOSCABEL BEDS.

Bowlder deposits, believed to be associated with the Newark rocks, are found at two points on the western margin, north of the James River. Heinrich[1] reports their existence at the base of the formation, at Midlothian, on the eastern margin; but such deposits have not been discriminated at the surface in that district. It may be that the large granitic blocks left upon the granitic area at the border line by atmospheric decay form a part of this layer, but there is no proof to that effect.

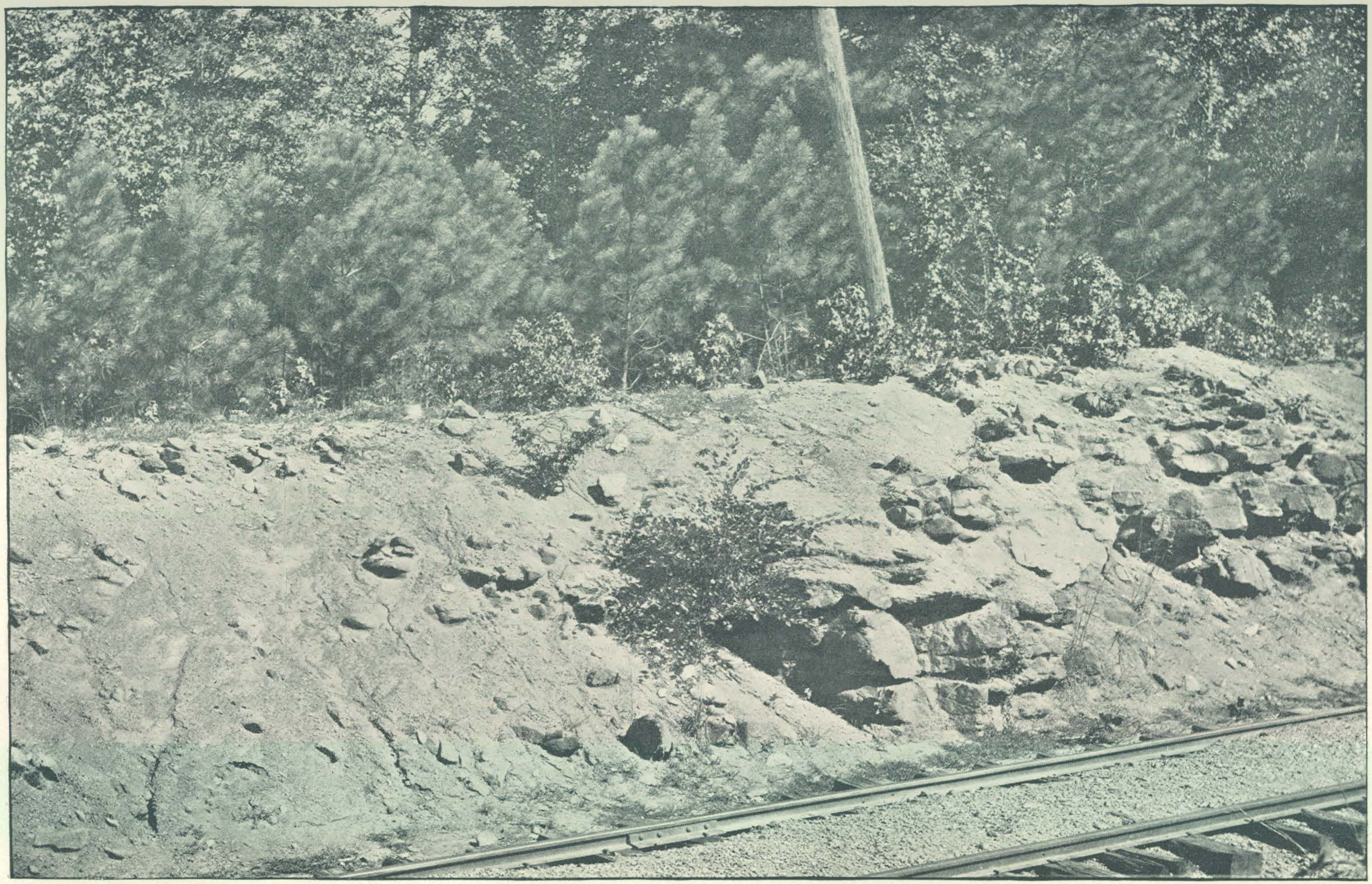
The bowlder deposits along the western margin are best exposed at Boscabel Ferry, in a small area separated from the main basin at Manakin by the gneissic ridge of Cornwallis Hill. The deposit consists of subangular fragments of gneiss of various origins. While a few of the fragments are rounded, others show almost unabraded joint faces. Flat blocks 3 feet long and 2 feet wide, and even 4 feet long, occur in pell-mell disorder, with a partial bedding of reddish gritty sandstone.

This conglomerate, so far as can be determined from the intercalated sand bands above-mentioned, dips westward, as do the shales on the south side of the James River, in the same wedge of strata. The beds sink southward, and, although their thickness is not exactly ascertainable, it is at least 50 feet at the western base of Cornwallis Hill.

A second and more extensive exposure of a conglomerate of the type above noted is met with on the Manakintown road just north of its junction with the Three Chop road. This deposit is exposed only in the road cutting. The locality is three-fourths of a mile west of the boundary of the Richmond area, with an intervening strip of the pre-Newark gneisses. The stratigraphic relations of the bowlder deposit to the Newark section are therefore undeterminable by direct evidence. Analogy with the area to the south and with similar outlying patches of sediments suggests its correlation with the base of the strata in the Richmond area.

The bowlders of gneiss and pegmatitic granite here assume large dimensions. One rounded block of gneiss is upwards of 6 feet long, 4 feet wide, and as much as 2 feet thick. The accompanying photograph

[1] Trans. Am. Inst. Min. Eng., Vol. VI, 1879, p. 227.



DISINTEGRATION OF GRANITITE ON EASTERN BORDER, IN SOUTHERN RAILWAY CUT, NEAR MIDLOTHIAN.

A similar condition of the rock preceded deposition in Newark time.

(Pl. XXII) exhibits this bowlder and the adjacent smaller fragments, together with the characteristic pell-mell structure which results from some of the fragments lying on their sides and some on their ends. The bowlders exhibit none of the decomposition and disintegration previous to their deposition which must be supposed to have taken place in the case of the granitites of the eastern margin of the Richmond area. As will be shown in this report, deposition in this area began with land to the eastward strewn with the products of the weathering of granites. The difference in aspect between these bowlder deposits of the western margin and the basal arkose beds of the eastern margin is in part accounted for by the presence of metamorphosed quartz-porphyries in the gneiss of the former district. It is a noticeable fact in the rocks of the Atlantic slope that the ancient surface or volcanic equivalents of granite, viz, quartz-porphyry and felsite, weather much more slowly than rocks of the granitic family under the same conditions of exposure to the atmosphere. This difference in the nature of the rocks of the eastern and western margins of the Richmond area, coupled with the probable action of water in removing the finer products of disintegration from bowldery accumulations, makes it possible to regard the Boscabel beds as local phases of the area of deposition.

In the two small tracts in which these bowlder beds have been studied, the materials present a strong local character, neither their lithological peculiarities nor their form calling for distant transportation. A search for striated surfaces failed to bring to light evidence of the glacial abrasion or transportation of the bowlders. On the contrary, when we consider these deposits in connection with other sediments at the base of the section in the Richmond basin, it is probable that weathering, aided by the work of running water or possibly by waves, affords a satisfactory explanation of these basal accumulations.

THE LOWER BARREN MEASURES.

It was the opinion of Prof. W. B. Rogers that the coals of the Richmond basin rested immediately upon the granitic terrane of the eastern margin. While this view appears to be true of some of the sections in the old mines, investigations made subsequent to his studies have shown that there is frequently a considerable thickness of strata interposed between the actual base of the Newark group and the lowest coal bed. In some of the instances in which the coal has been seen resting on the granitic basement it is known that the relation has been brought about by faulting. In other cases the occurrence of barren beds at the base of the section is to be explained by the local failure of coal-making conditions rather than by the supposition that the beds in question were laid down before the lowest coal bed elsewhere deposited in the area. In many cases in this basin, where barren strata occur beneath a coal bed, it is impracticable to determine whether these beds are older than the coal measures proper. The fact, however, that a considerable thickness of sandstones and shales has been encountered below the coal beds where these are fully developed seems to indicate that mere variation in the thickness of the coal beds is not a sufficient explanation of the facts.

Arkose beds.—In the areas which have produced coal these lower barren measures consist of beds of arkose often resting on the granitite of the region. This arkose is often so little changed in appearance from the less porphyritic varieties of the granitic rock as to be indistinguishable to the inexpert eye. Indeed, it is probable that in some sections the ancient disintegrated granitite grades upward by constantly increasing rearrangement and wear of its constituent feldspar and quartz grains into the recognizable arkose beds. The occasional occurrence of a waterworn pebble of vein quartz or cleavage fragment of the large porphyritic feldspar, where the attrition and rounding of the smaller grains or granitic quartz and feldspar is not apparent, will suffice to determine the passage of the granitic rock into arkose.

While the arkose is the basal member on the eastern margin, there is no horizon to which it may be said to be limited. Beds of arkose reappear from horizon to horizon with increasing marks of water wear throughout the section in the Richmond Basin. The beds of it are, however, best developed about the granitic masses of the eastern margin. From their stratigraphic position, it is probable that the basal beds of arkose are the approximate equivalents in time of the bowlder beds of the western margin. The arkose beds thus become of importance in determining the general conditions under which deposition elsewhere in the area began.

It is well known that when a member of the petrographic group of granites disintegrates under exposure to the atmosphere, grains of quartz and feldspar are set free in a condition to be transported by wind and water. The nearly equal weight and hardness of these common rock-making minerals and the approximate identity of size of thousands of the particles thus formed make it possible for the agents of transportation to remove them indiscriminately to nearly equal distances. The result is the formation of a new clastic rock having the dominant minerals of the granite family.

The iron-bearing silicates of the granitites decompose more readily than the feldspars with which they are associated, and may thus break up into new compounds before transportation of the loosened bed rock sets in. Even when these iron-bearing silicates are micaceous, or become so through alteration, their lightness and their softness lead quickly to their separation from the heavier grains which make the arkose beds.

If the weathering of the land surface goes so far that the feldspathic rocks are kaolinized, the resulting products of erosion and transportation will be beds of quartz sand and of clay rather than arkose. Such is the condition of preparation of the granitic rocks at the present sur-

COARSE CONGLOMERATE, WESTERN BORDER, NEAR THREE CHOP ROAD.

The gneiss bowlder in the foreground is 6 feet long.

face in the area about the Richmond Basin, at least in the superficial portion of the decayed zone. The arkose beds at the base of the Newark section therefore indicate a condition of the ancient granites in which disintegration rather than decomposition of the feldspars had been attained.

The arkoses of the Richmond Basin in the higher beds, as well as near the base, except for recent discoloration by iron oxides, are prevailingly white or gray. These whitish arkoses are noticeably free from the micaceous element of the original granitite. On the contrary, in some of the fine-grained arkose beds of the central and higher portions of the basin reddish colors appear in association with bleached micas, probably the biotite of the original granitite, the iron from which mineral has oxidized after transportation and deposition, and so has discolored the surrounding rock. Had the biotite of the parent rock decomposed or lost its iron before erosion set in the contiguous feldspars would have received the coloring matter in their cleavage planes, so that red arkoses like those of the Connecticut area would have been widespread in this field.

Russell[1] has shown that red sandstones are in certain cases the result of slow disintegration of the bed rock previous to the transportation of the material. The bleaching and whitening of sediments is a correlated process, also dependent on the conditions affecting the detritus in situ. With the slow bleaching of the beds near the surface in the zone of the subsoil the iron-bearing solutions work downward, giving red iron-stained sedimentary grains out of which to recompose red sandstones, leaving above whitened materials for the making of white clays and light-colored sands. The manner in which these zones of color are massed and the mode in which they are eroded will necessarily vary and may result in the formation of white sandstones and red sandstones or alternations of these rocks.

A peculiar variety of feldspathic rocks found on the eastern margin of the basin consists of a matrix of carbonaceous compact clay interspersed with quadrangular cleavage pieces of the large porphyritic feldspars of the granitite (see Pl. XXIII). The means by which these feldspar fragments were dispersed in the clays without accompanying grains of quartz and the more minute feldspar fragments is not in accordance with the ordinary work of running water. Wind or floating ice is apparently demanded for the transportation of the feldspar grains, since currents of water strong enough to bring the large feldspar pieces to the area of deposition would have swept away the mud; moreover, such currents would have assorted and stratified the materials.

Climate as indicated by arkose.—Dr. Geo. P. Merrill[2] has shown that the disintegration of feldspar may proceed to the point of furnishing particles for transportation without perceptible decomposition of these

[1]Subaerial decay of rocks and the origin of the red color of certain formations: Bull. U S. Geol. Survey No. 52.

[2]Rocks, Rock-Weathering, and Soils, 1897, pp. 241-242.

complex silicates. Fragments of this character may thus form in arid or cold climates, where the chemical and mechanical work of running water is at a minimum. The geologists of India[3] have argued from the abundance of detrital feldspar in certain formations of that region that these deposits mark periods of cold, when disintegration was in excess of decomposition. Applying the inference from the occurrence of feldspar detritus just stated to the Richmond Basin, we should suppose that the Newark time opened with a cool climate; but this supposition does not exclude the idea of aridity as well. Since it is not proved that the pre-Newark land surface was in this district at sea level, it may be that a low-mean annual temperature was the effect of high elevation rather than that there was a lower temperature in that latitude than now prevails there. It should be noted also that the argument for cool climate, based on the occurrence of feldspar, relates to the time of disintegration of the arkose rather than to the time of its transportation and deposition. That a marked climatic change was possible between the time of preparation of the material and its deposition is manifest from the very considerable geographic change which brought a part of the pre-Newark land surface to the condition of an area of deposition.

Barren shales.—On the western margin of the area a series of shales is exposed on the west bank of Jones Creek, near the James River. From their position, with reference to the bowlder beds and the Cornwallis Hill fault block, it is inferred that these shales underlie the coals which outcrop on the east of that disturbed section. The strata measured in the road are as follows:

Section near Boscabel Ferry, on Jones Creek.

Strata.	Thickness.	
	Ft.	*In.*
Clay, brownish and whitish	70	0
Shale, carbonaceous	2	0
Clay, gray, decomposed shale	35	0
Sandstone, brown	1	0
Shale, slate-colored	2	0
Shale, brown and gray, laminated	14	0
Shale, brown	8	0
Sandstone	0	6
Shale, brown	10	0
Sandstone, red	6	0
Shale, brown	16	0
Sandstone, red	6	0
Shale, brown	36	0
Sandstone	9	0
Total	215	6

[3] R. D. Oldham, A Manual of the Geology of India, 2d ed., Calcutta, 1893, p. 201. Also Green, Quart. Jour. Geol. Soc., Vol. XLIV, 1888, p. 244.

ARGILLACEOUS ARKOSE CONTAINING FRAGMENTS OF PORPHYRITIC FELDSPAR IN BASAL BEDS, ETNA SHAFT, MIDLOTHIAN.

This section dips 20° W. The base is not seen, but the upper tilted surface of the Cornwallis Hill fault block rises up out of the creek on the east side of the stream, so that this section is near the local base of the Newark.

Southward, in the Turkey Branch section, where the coal measures appear to fail or to be represented only by red and green shales, the lower beds of the Newark are decidedly of a local character, showing in a marked way their derivation from the neighboring gneisses. White clays and thin layers composed of angular fragments of gneiss occur. Still farther south, in the sections exposed on the approaches to the Goode and Bevil road bridges, on the Appomattox, the basal beds of the Newark are clays and sands—decomposed rocks—without trace of carbonaceous material. In these localities the lower barren beds, which rest directly on the gneiss, exceed 50 feet in thickness.

THE COAL MEASURES.

The term coal measures, as applied to the Richmond basin, is used in the sense of a group of coal-bearing strata of variable thickness lying at or near the base of the Newark section, but being usually separated from that base by the stratified rocks already described. The areas in which these coal beds may be seen are restricted to the margins of the area or to the detached tracts which occur on the east of it.

THE OLD WORKINGS.

The coal measures are best known from the old workings on the eastern margin. From the published accounts of the sections exposed in these mines, it is clear that usually three and sometimes five beds of coal are met with, separated by beds of sandstone and shale. The upper of these seams has usually been found to be the thickest, the estimates varying from 30 and 40 feet in the old workings about Midlothian down to 5 and 8 feet at other points. From the vicinity of Midlothian northward to Gayton (Edge Hill or Carbon Hill of the old reports) this uppermost bed is wholly or partly converted into coke from the proximity of igneous rock. At Dover, on the western margin, Lyell states there was an upper bed of coal 16 feet thick, with two thick beds below.

The Raccoon shaft.—The accompanying plate, reproduced from a paper by Mr. Clifford, sets forth all the known information concerning the abandoned Raccoon shaft, on the eastern margin, near the Appomattox River (see Pl. XXIV). The middle seam in this section is the thickest, the coal-bearing beds being comprised within 100 feet of strata. The pinches or rolls where the basement rock takes the place of the coal beds is well shown in the section. A similar disturbance of the section was observable in a slope driven through the old workings of the Cox shaft at Winterpock in 1896.

Jewett's coke shaft.—The section at Jewett's coke shaft, near Midlothian, not now accessible, was studied by Clifford, who gave the section represented in Pl. XXV, reproduced from his paper. He also gave a plan showing the relations of the Blackheath field to the main basin (Pl. XXV) and a section of the Blackheath district. Explorations made during the progress of the present survey showed that the thick coal seam of this tract is brought against the granite on the north end by a fault, and that there is a thin seam of coal below the main bed, separated from it by a few feet of shale, which rock again intervenes between this coal bed and the granite.

The Sallé and Burfoot tracts.—Three beds were encountered in the Sallé and Burfoot tracts, the uppermost being converted into coke. According to Lyell, this tract afforded a seam of coal 30 feet thick at its outcrop. Between the coal and the granite were 200 feet of strata containing two beds of coal, the upper 3 and the lower about 1 foot thick.

Special map of the Midlothian district.—The accompanying map of the Midlothian district (Pl. XXVI) was prepared to show the position of the outlying basins of that part of the area and to exhibit the position of the coal beds. In part the tracing of the outcrop of the coal is based upon old surveys. The extension of the main seam of coal from the region bordering the James River into the region of Falling Creek has not been demonstrated. It is possible that the failure to reach coal in that part of the field is due to a coating of post-Newark deposits which cap the ridge dividing the waters of Falling Creek from the James River. None but shallow pits have been sunk in this part of the field. Properly directed boring at points a few hundred yards west of the bank marking the supposed outcrop of the coal-bearing horizon would explore a portion of the old marginal coal field as yet untouched.

The Manakin mines.[1]—At Manakin, on the western margin north of the James River, very extensive operations were carried on after the civil war, and shafts were sunk to depths of 300, 400, and even 900 feet. Three seams were found, the first 6 to 8 feet, the second 12 feet, and the third 3 to 4 feet thick, and of good quality. The dips varied from 25° to 90°, being steeper than on the east side and frequently complicated by faults. The 900-foot shaft failed to strike the coal and the company abandoned work.

Scott, Norwood, and Old Dominion pits.—South of the James, on the western border, three seams of coal have been recognized, coal having been taken out from the Scott pits,[2] the Norwood pits, and the Old Dominion pits.

FOSSILS OF THE COAL MEASURES.

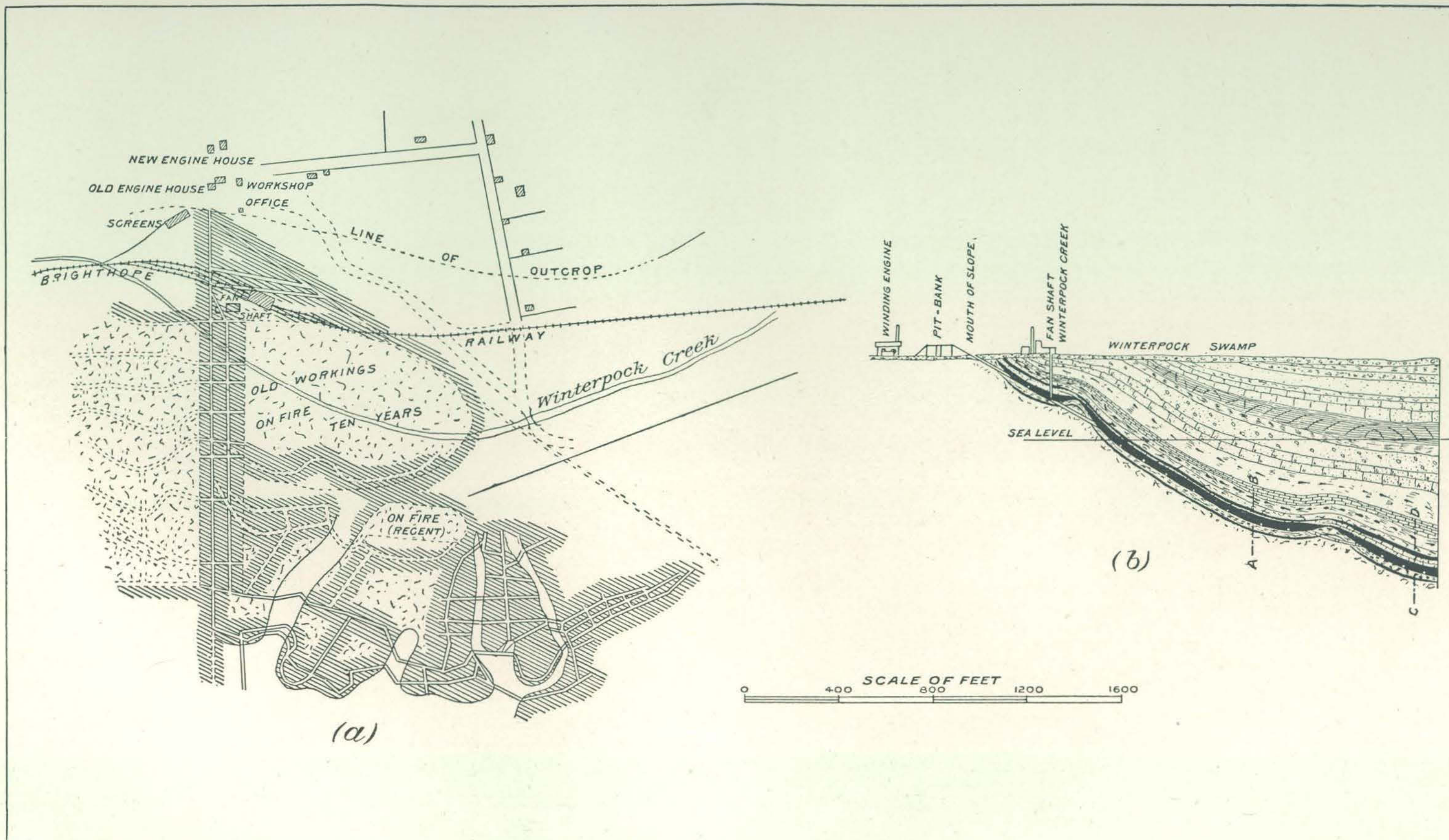
The fossil plants of the Richmond area have been thoroughly studied and illustrated by Professor Fontaine,[3] and for information concerning them the reader is referred to his monograph and the later writings of Professor Russell.[4]

[1] From notes furnished by Dr. J. E. Wolff.

[2] John Bladen: [Report of the] Powhatan Coal Company (1885), p. 8. This report gives a section of the strata encountered.

[3] Mon. U. S. Geol. Survey, Vol. VI, 1883.

[4] Bull. U. S. Geol. Survey No. 85, Washington, 1892.



PLAN AND SECTION OF RACCOON COAL MINE, NEAR WINTERPOCK.

(After Clifford.)

The following notes set forth the observations made during the present survey upon the occurrence of fossils, heretofore undescribed, in the coal measures of the area. Other memoranda will be found under the head of the group of rocks with which the fossils are associated.

PLANTS.

The following fragments of plants were collected by J. B. Woodworth about the old workings in Midlothian: Impressions of the stems of cycadean plants similar to forms described by Emmons from North Carolina; the fruit of a cycad, Zamiastrobus, similar to that figured by Ebenezer Emmons from North Carolina; a bivalvular seed vessel, about the size of a cherry stone, stated by Knowlton to be a Cardiocarpon.

Coal-making vegetation.—No recent microscopic study has been made with a view to determine the nature of the plants from which the coal beds of the Newark were formed. The species fossilized in the shales above these deposits do not afford trustworthy evidence as to those which formed the peat. Lyell[1] states, on the authority of Hooker, who examined specimens from mines no longer open, that vegetable structure was discernible. This statement may be accepted as well founded. The generally close resemblance of these coals in chemical composition to those of the Carboniferous period suggests that the plants from which they were formed may well have been those of the same groups mostly related to the mosses and ferns.

The prevailing small amount of ash in the Richmond Basin coals is evidence that the ancient swamps were so conditioned that they were exempt from the influences of river overflows, for such incursions of muddy waters would greatly change their character. It affords a fair presumption that these marshes were of large area.

ANIMALS.

The fish beds.—The remains of fishes were early reported from the mines for coal on the eastern margin of the Richmond area. Sir Charles Lyell[2] collected these fossils at Midlothian on his visit of 1841 and subsequently described *Dictyopyge macrura* and a species which he referred to *Tetragonolepis*. Of the correctness of this latter determination, Newberry[3] has since expressed some doubt.

Fish beds were met with a few years ago in sinking the new shaft near the Etna mine, just north of the Richmond and Danville Railroad at Midlothian. In 1896 work upon this shaft had ceased and there was no means of determining the stratigraphic relations of the fish-bearing layers to the Newark section.

The fish beds at Midlothian, as exhibited on the Etna shaft dump, are hard, even, and thinly laminated pelites or shales of black color

[1] Quart. Jour. Geol. Soc. London, Vol. III, 1847, p. 268.

[2] Ibid., pp. 276, 277.

[3] Mon. U. S. Geol. Survey, Vol. XIV, 1888, p. 20. In this volume, entitled Fossil Fishes and Fossil Plants of the Triassic Rocks of New Jersey and the Connecticut Valley, Prof. Newberry figured a *Dictyopyge macrura* from Clover Hill, Virginia, on Pl. XVIII, figs. 1 and 2.

and highly bituminous. The remains of ganoid fishes are abundantly scattered through the layers, and where the entire fishes do not occur their scales are sometimes so numerous on the parting planes as to give the rock the appearance of a dark micaceous schist. Small fish bones are also commonly found with these scattered scales.

Small blocks of strata at this locality showed fragments of a layer about 4 inches thick entirely made up of these ganoid fish scales and bones. The following analysis of the material was made in the laboratory of the Survey.

Analysis of fish-scale bed at Midlothian, Virginia.

[By Geo. Steiger.]

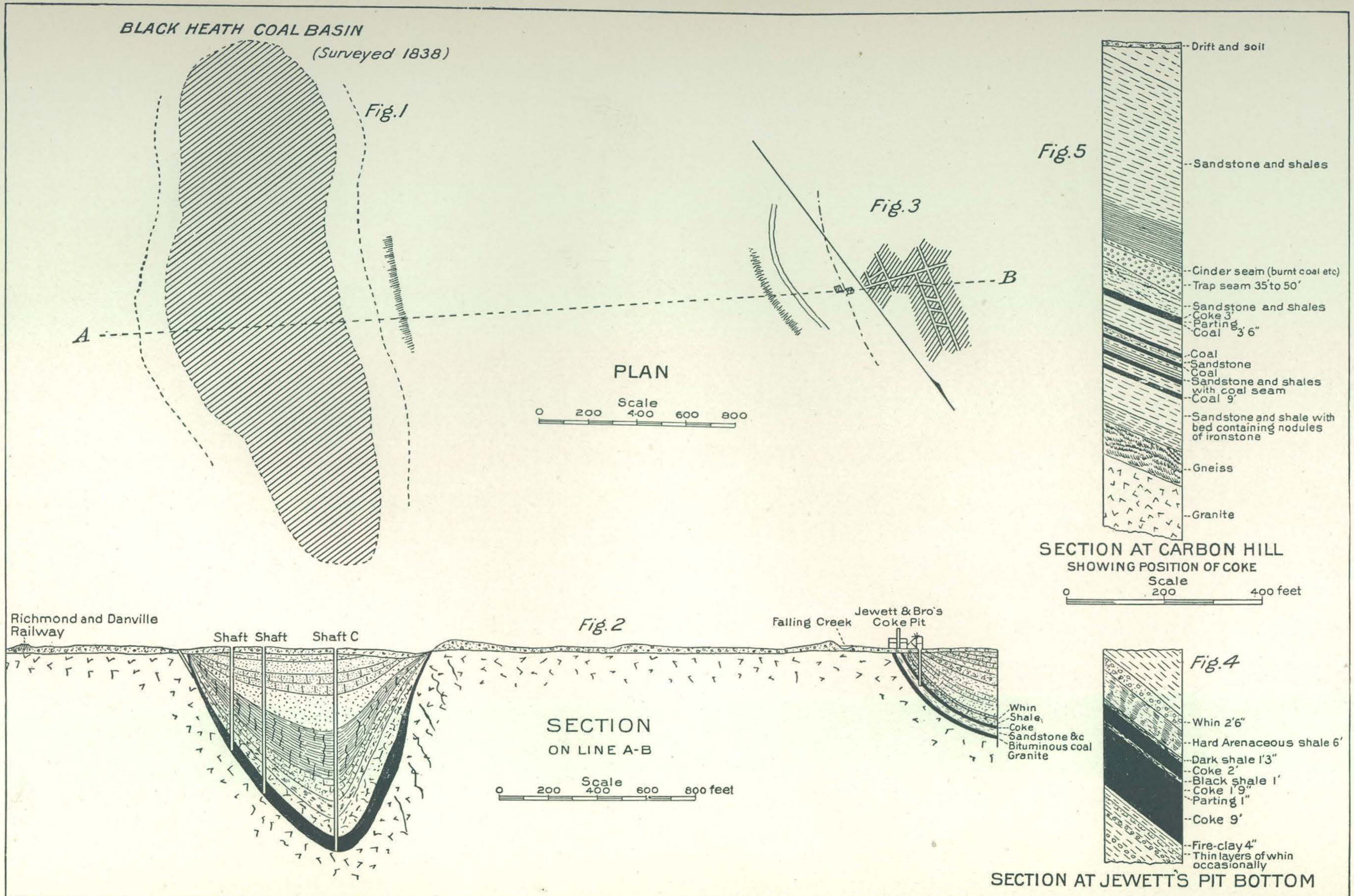
Constituent.	Per cent.
Insoluble in dilute HCl and HNO_3	10.69
Al_2O_3	4.73
Fe_2O_3	8.84
CaO	29.30
P_2O_5	22.02
CO_2	1.44
S. as sulphides	6.68
If S be all combined with the Fe, it equals FeS_2.	14.32

This bed therefore contains about 50 per cent of phosphate of lime, but on account of other ingredients is of doubtful value as a fertilizer. The content of sulphur probably combined in the form of sulphide of iron is so high as to diminish the value of the lime phosphate. At Midlothian the pyritiferous shales are said to "burn up" the vegetation. It may be noted in this connection, as having a bearing on the caustic properties of the soils in the belt under discussion, that in the case of a box of specimens shipped from this region in June, 1896, the materials were, when opened in September, unidentifiable for the reason that the labels and paper wrapping had been destroyed by the chemical action of the soil water coming from the rocks and clays.

Scattered in the layers with the distinct fishes are rounded or ovoid masses composed of aggregates of ganoid scales and having a diameter of from 1 to 4 inches. Similar masses of fish scales have been reported by C. T. Jackson[1] from the Carboniferous beds of Hillsboro, New Brunswick. He suggested that these masses were accumulated by the action of eddies and whirls. Dr. Gould thought they were the contents of the stomachs of fishes.

The occurrence of these balls in the even lamination of clays suggests that they were not formed by current action, else the bedding of the clays would also exhibit signs of the currents. The scales frequently exhibit a concentric arrangement, and cases have been observed where

[1] Proc. Boston Soc. Nat. Hist., Vol. IV 1854, p. 66.



PLAN AND SECTIONS OF OLD WORKINGS ON EASTERN BORDER, RICHMOND BASIN.

(After Clifford.)

a group of scales retain the order of growth as if held together at the time of burial by integumentary shreds.

The fish-scale layer before described appears to be but a more complete collection of these particles than that in the isolated balls. While these rounded masses suggest a coprolitic origin alone, there is little in the widespread distribution of the material in the sheet form by which to discriminate between the accumulations of current sweepings and the bottom débris of the feeding grounds of predaceous fishes or reptiles. It remains to note that the occurrence of fish beds has been taken as evidence of the withdrawal of water from a restricted basin occupied by the fish, of the occurrence of an earthquake shock, or of the poisoning of the fish by the emanation of deleterious substances, as in volcanic eruptions. While these causes may explain the death of fish in large numbers, it is not usually possible to find the evidence which supports the conclusion that any particular one of these agencies operated in a given instance. Considering the hardness and durability of ganoid scales, it is not improbable that these gatherings represent the death and dissolution of the bodies of these fishes throughout a considerable lapse of time. Thus what at first sight appears to demand a catastrophic interference in the aquatic life of the Richmond basin may really be but one of the effects of its normal development. There may well be noted here the "bone-bed" in Europe at the top of the Trias in black shales of Rhetic age.[1]

Associated with the globular masses of fish-scales are flattened patches of a black bituminous substance, with a subconchoidal fracture. A black substance named "molluskite" was described by G. A. Mantell[2] as occurring with the phosphatic nodules of the Upper Greensand of England.

The English substance is believed to be phosphatized animal matter. The discussion concerning its origin is referred to by Penrose.[3] The material from Midlothian decrepitates before the Bunsen burner, and burns with difficulty.

The horizon of the fish-bearing bed was not ascertainable at the time of our visit. Fish-bearing shales are found in all the workings on the eastern border, and the waste about the old mines in the western part of the field exhibits scales apparently of the same ganoids. The scales are generally black, shining flakes, though rarely of a light-bluish color.

Mr. Oscar Heinrich, who gave an account of the sinking of a deep shaft at Midlothian, reported evidences of these fishes at several horizons. Sir Charles Lyell, who visited the eastern border when the mines were more accessible than now, placed the fossil fish horizon in the upper part of the lower Newark in a set of beds from 400 to 500 feet

[1] A. Geikie, Text-book of Geology, third ed., 1893, pp. 866-867.
[2] Medals of Creation, Vol.I, London, first ed., 1844, p. 432.
[3] Nature and origin of deposits of phosphate of lime: Bull U. S. Geol. Survey No. 46, 1888, pp. 87-89.

thick, having the coal beds at their base. At present there is not enough known concerning their distribution to warrant the use of these vertebrates in identifying or distinguishing local deposits in this small area. In a well at Hallsboro, Mr. H. G. Myers found greenish-gray shales carrying Tetragonolepis (?). These beds are probably beneath the horizon of the Otterdale sandstones; further than this it is impossible to make a definite statement in regard to their stratigraphic position.

The thin lamination of the fish-bearing shales in the lower part of the Newark section in this area suggests lacustrine conditions during their deposition. But even if the layers were deposited at the bottom of standing water, their occurrence, where they bear the footprints of small batrachians or reptiles, shows that the depth of water was so slight at times as to permit the baring of the bottom to the tread of wandering quadrupeds.

Footprints of batrachians.—As above noted, tracks of batrachians, or possibly in some cases of reptiles, occur on the surfaces of certain layers of the thin laminated shales in which the ganoids are found at Midlothian. Some of these tracks are represented in the annexed figures. The footprints are crowded together in great numbers, and exhibit two dominant types, one resembling Cheirotherium, but much smaller than the forms commonly figured from the European Trias, the other lizard-like in the flexible digits and the joints (see fig. 90). All of the tracks, where well shown, exhibit more than three digits.

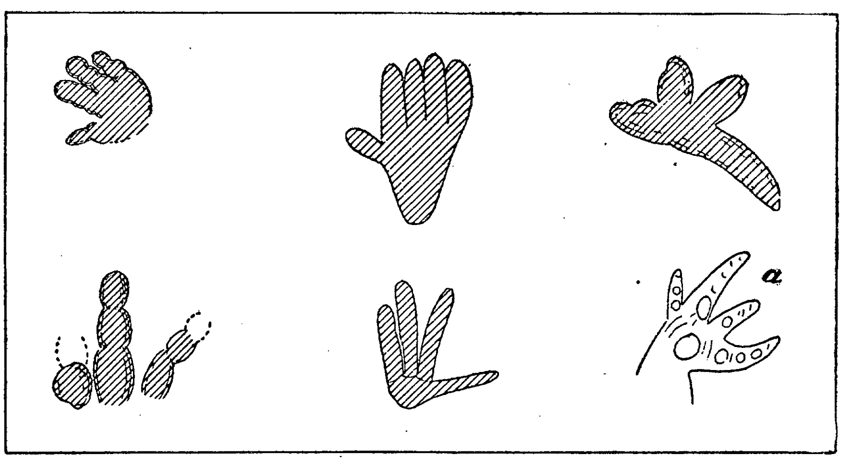
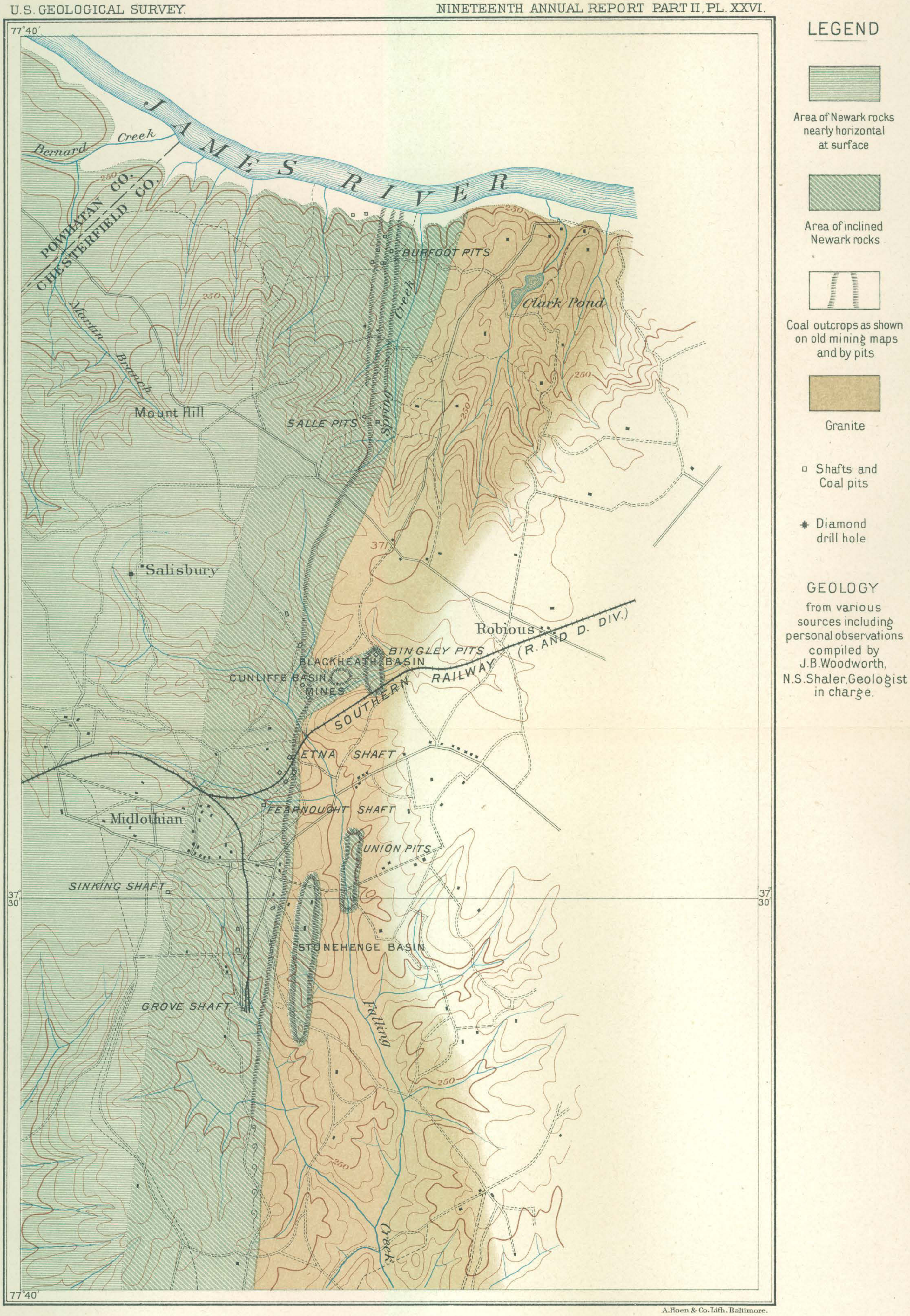


FIG. 90.—Batrachian footprints from the laminated shales of the Etna shaft at Midlothian, Virginia; natural size. Two of the upper figures show forms allied to Cheirotherium; below are irregular and probably partial impressions of the feet of unknown generic affinities; *a*, fore foot of a living toad.

The bearing of these track-covered layers on the depth of water in which the laminated shales were laid down has already been noted. The absence of larger forms may probably be ascribed to the occurrence of widespread and deep mud banks on which the larger forms of quadruped life could not tread without risk of becoming mired. An apparent



MAP OF A PORTION OF

THE MIDLOTHIAN DISTRICT

RICHMOND COAL FIELD

SURVEYED BY U.S. GEOLOGICAL SURVEY

Contour Interval 25 feet

exception to this condition is found in the case of a single slab found on the dump of the Jewett coke shaft at Midlothian, which exhibits the rude impression of a somewhat short three-toed foot, with strong nail marks. Here, as in the case of the small tracks found on the dump of the Etna shaft, the precise position of the track layers with reference to the coal is not known, though the testimony of old observers in these mines would indicate that the track layers occur above the coal seams.

Annelid burrows.—Annelid burrows of cylindrical form occur in a light greenish-gray shale at Midlothian in the refuse from an old mine. The casts are about 5 mm. in diameter. Their surface is marked by roughly longitudinal but occasionally decussating raised lines, giving the cast the appearance of cord of coarsely woven strands. These little ridges are about 3 mm. in length. They are probably the impressions of appendages. The casts lie mainly in the bedding, but a burrow will suddenly pass upward or downward across the laminæ or become sharply recurved on itself in a vertical plane. The filling is not distinguishable from the matrix of the burrows.

THE CHESTERFIELD GROUP.

THE VINITA BEDS (ESTHERIA BEDS).

Lying above the sections encountered in the old workings on the eastern margin of the Richmond area is a group of arkose beds with black shales, the latter containing great numbers of the flattened shells or impressions of Estheria. Although these fossils are perhaps not more abundant in this group of rocks than in particular zones in the underlying coal measures, they are, so far as the scanty exposures show, the principal organic feature of a thick section of strata overlying the coal beds. These beds occur in the bluffs on both sides of the James River. The Estheria-bearing shales may be seen cropping out in numerous alternations with sandy layers on the eastern slope of Goat Hill, near Vinita, between that part of the bluff on the James River and Manikin, where the underlying coal measures come to the surface. The Newark strata, in the area north of the James and lying above the coal measures, appear to be restricted to this group of rocks. The shales may be seen again south of the James, on Little Tomahawk Creek, and in outcrops south of this stream, at distances of from 1½ to 2 miles from the eastern border.

The sandstones of this group are often heavy bedded. They are white where not colored by iron oxides due to recent surface changes. The thickness of the formation is not accurately determinable, but may be provisionally stated as 2,000 feet.

OTTERDALE SANDSTONES (ARAUCARIOXYLON BEDS).

Petrified wood.—In the vicinity of Otterdale, in a broad, shallow trough in the central part of the basin south of the James River, and consequently near the summit of the section which still remains in the

Richmond area, is a thick series of sandstones, usually of coarse texture, in which prostrate trunks and fragments of petrified trees are abundant. These trees have been referred by Prof. F. H. Knowlton to the genus Araucarioxylon. In this series of beds, but apparently higher up, are traces of lignites in clays. The thickness of the group may be estimated as 500 feet.

The occurrence of petrified wood in the Richmond Basin is a well-known phenomenon to the inhabitants, fragments of the material being generally called "fossil hickory," on account of a supposed resemblance of the silicified structure to the wood of that tree. Professor Fontaine[1] mentions the occurrence of this petrified wood, and it was noticed earlier by Nuttall. Nuttall[2] reported finding a piece of petrified wood east of Midlothian in the region of granites.

Broken pieces of fossil wood are found in the sandstone beds on the eastern and western margins of the Richmond area in a stratigraphic position clearly lower than that of the beds here termed Otterdale sandstones, thus indicating a considerable vertical range of the silicified material. How much above the present surface some of the specimens may have been originally embedded is not certain in the case of the loose material. Angular fragments of the silicified wood are occasionally found in the feldspathic sandstones along the western border. These pieces were probably transported as lignite, and have been since silicified. Instances occur where the silicification of lignite has not been complete.[3]

In the region about Otterdale, on either side of Swift Creek, prostrate trunks, from 15 to 25 feet or more in length, having a diameter of from 2 to 4 feet, may be seen. One of the longest of these trees lies across the public road about 1 mile southwest of Otterdale. A view of this fossil log, as partially exhumed in 1897, is shown in the accompanying illustration (Pl. XXVII).

Professor Knowlton's report on these trees and on the lignites, next to be described, will be found in an appendix to this paper.

Lignite (jet) beds.—A few years ago a prospect hole sunk on the northeast side of Nysons Branch, in the central part of the basin, along one of the small tributaries of that stream, near its junction with Swift Creek, encountered a bed of light-colored clay containing scattered fragments of a jet-like lignite. This material occurs in pieces of various sizes, mostly small chips, but often as large as a man's hand. It is jet black, breaks with a clean, smooth, mirror-like cross fracture, and flies off in small bits when cut with a sharp knife, leaving minute surfaces of conchoidal fracture. In the opinion of an expert in the employ of a well-known jewelry firm in Boston, this material is a jet of fair quality.

[1] Mon. U. S. Geol. Survey, Vol. VI, 1883, p. 6.

[2] Observations on the geological structure of the valley of the Mississippi: Jour. Phila. Acad. Nat. Sci., Vol. II, Part I, 1821, pp. 14-52.

[3] On the silicification of wood and lignite, see T. Sterry Hunt: Smithsonian Report for 1882, Washington, 1884, pp. 344-345.

A PETRIFIED TREE (ARAUCARIOXYLON SP.) ON PUBLIC ROAD SOUTH OF OTTERDALE.

The fragments of jet are compressed limbs or branches and parts of the trunks of trees. According to the determination of Professor Knowlton, who examined sample specimens, this jet is a coniferous wood of the genus Araucarioxylon.[1]

The occurrence of lignite in the upper strata of the Richmond Basin is briefly noted by Professor Fontaine; but as yet practically nothing is known of its distribution beyond the locality here described.

UPPERMOST BEDS IN THE RICHMOND AREA.

The question of the highest strata in the section of the Richmond Basin is involved in theoretical considerations which depend upon the possible occurrence of faults. In the southwestern part of the area, where westerly dips prevail quite up to the western border, it is not impossible that beds exist lying stratigraphically higher than those included in this paper under the head of the Otterdale sandstones. The reddish color of certain beds in this part of the area and slight differences which serve to indicate a different grouping of strata are suggestive of a later horizon. The faulted structure of this part of the basin, however, coupled with the insufficient exposures of a wooded district, make a definite statement with regard to a higher group of beds in the present state of our knowledge impossible. It is evident that a great thickness of strata has been carried away from this Newark area, and we are prepared to find that patches of sand and shales, covering the Otterdale sandstones, occur in downfaulted portions of the area south of the James River.

THE SEDIMENTARY SUCCESSION IN THE RICHMOND BASIN.

There are three orders of gradation in the vertical arrangement of sediments: (1) from coarse sediments at base to fine at top, (2) from fine sediments at base to coarse at top, (3) mixed conditions, in which the order is reversed after a partial arrangement of the sediment in accordance with one of them, or in which the repetition of an order is discernible.

The first of these cycles of sedimentary arrangement is characteristic of great marine formations, or of areas of deposition with sinking shore line and overlap. Not only the sedimentary succession but the organic contents of the Richmond Basin show that this area has not passed through this history.

The second of these cycles is characteristic of fluviatile and lacustrine areas. The great bodies of shale in the Richmond Basin are near the base; the bulk of the sandstones and coarse members occur high up in the section. The general change in the sediments is from fine below to coarse above.

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[1] See report accompanying this paper, p. 516.

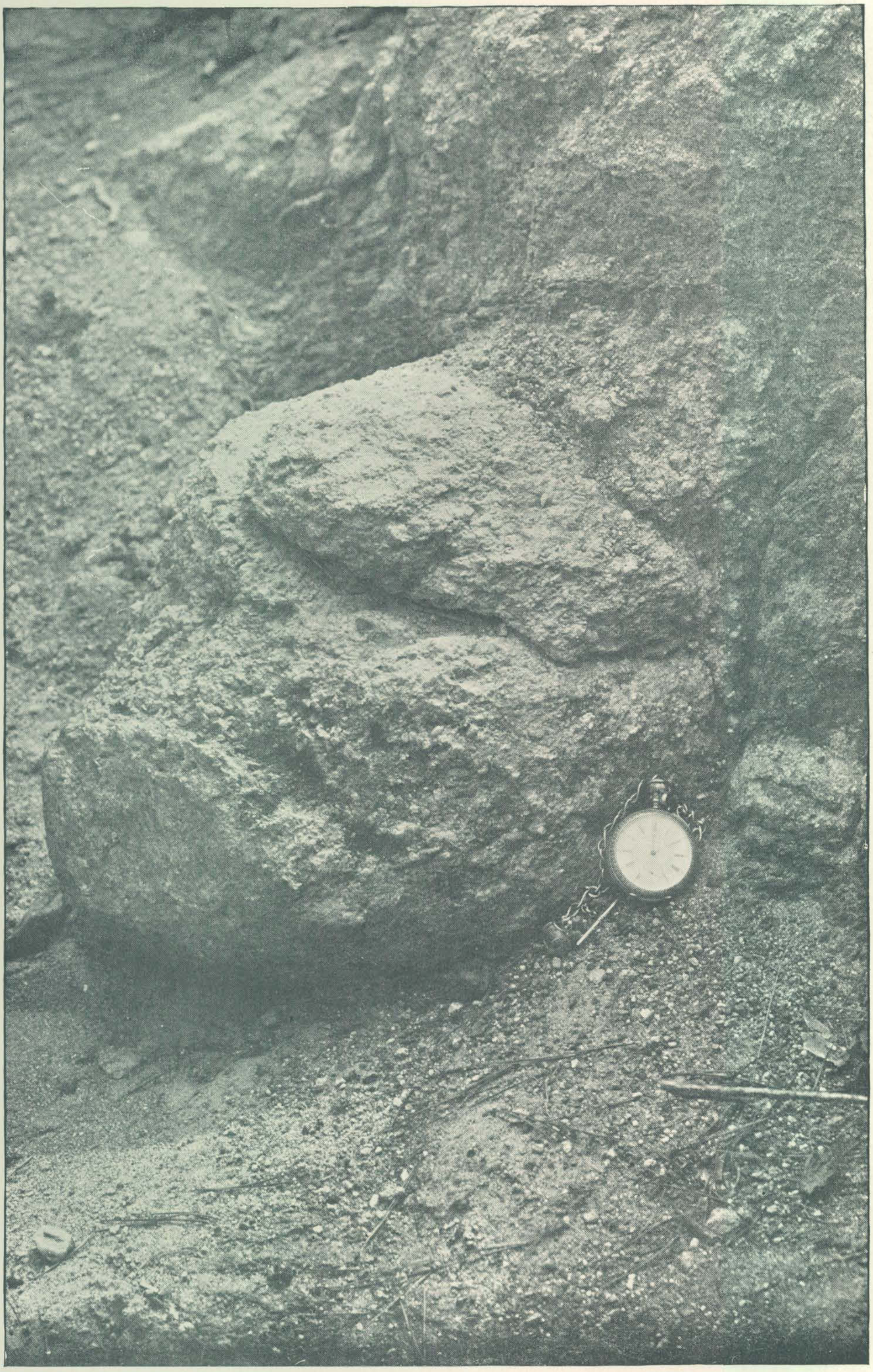
SOURCE OF THE SEDIMENTS.

There are several groups of deposits in the Richmond Basin whose component particles have a bearing on the source of the detritus. The first of these deposits in the order of occurrence is that of the basal bowlder bed before described as existing in patches along the western border of the area. A second class of sediments, by bulk of more importance than the first named, is found in the arkose or "granitic sandstone" which forms so large a part of the section. A third line of evidence exists in the feebly developed conglomerate beds which occur here and there at horizons far above the base of the section.

In discussing the origin of these sediments it should be borne in mind that the geography of that time has been so far changed that it is as yet a matter of doubt whether this area was connected with other Newark areas or not. On the supposition that Newark strata covered all or even a large part of the area within the limits of which the present patches lie, it would follow that the sediments in the original Newark area above the lower or first-formed strata must have been imported from outside of the tract thus covered. To suppose the derivation of any given kind of fragmentary material, therefore, from those outcrops of the rock which are nearest at the present day is an assumption in making which it is necessary to concede that the rocks exposed at the present land surface may have failed to appear at the original Newark surface. This is a limitation applicable to the more remote of the granitic masses on the eastern margin of the Richmond area as it exists to-day. In referring fragmental materials to adjacent terranes, it is obvious that those particles which are in or near the base of the Richmond Basin are more likely to have been derived from a source near where they lie than those which occur higher up in the same geologic section. As sedimentation in the area advanced, its margins would have extended by overlap upon the area of erosion, shutting off sources of sediments before available. With these considerations in mind we may now turn to the available evidence for a determination of the source of detritus in the Richmond area.

The bowlder deposits of both the western and the eastern margins evidently came from near-by sources. This is particularly true on the western side of the area. Here bowlders of gneiss predominate and they rest upon a gneissic terrane. On the east granitic bowlders and pebbles have been observed, and the basement terrane of the Newark is largely granitic.

The general absence of gneissic bowlders along the eastern margin, as in the vicinity of Midlothian, where granitic waste enters into the basal beds, while negative in its evidence, since the granite probably extends to the west as well as to the east of the point where the deposits have been studied, assumes some significance when the presence of occasional granitic fragments on the western border is taken



BOWLDER OF FINE CONGLOMERATE IN BASAL NEWARK BEDS, WESTERN BORDER, SOUTH OF MOSLEY JUNCTION.

into account. Here, however, it is necessary to remark that the possibility of derivation of these granitic bowlders from areas of granite on the western side of the present Richmond area can not be denied. So far as the evidence goes, it seems likely that the drift of the coarse materials at the base of the formation may have been from the east toward more westerly sites. This supposition concerns the movement of the gneiss blocks on the western side as well as the granitic bowlders. The line of contact of the granites on the east with the gneisses on the west is somewhere beneath the middle of the basin, perhaps to the east of the center. It is permissible to suppose, therefore, that the gneissic bowlders on the western margin may have come from points east of their present position.

The meridional component in the movement of the detritus at the base of the Newark section is, as the following explanation is intended to show, readily ascertainable. The granitic mass which is about central at Midlothian is replaced by gneisses toward the northern and southern ends of the basin. In the northern part of the basin, at Coal Hill, where the coal measures repose on the gneisses, the Newark beds are conglomeratic, with rolled cobbles of granite. Assuming that these pebbles came from the granitic batholite on the east of the Richmond area, there is indicated a northward movement of the detritus, however far it may have traveled to the west. There are at present no facts known from the southern part of the eastern border bearing on the question of the movement of detritus.

The second group of phenomena bearing on the source of the detritus—that found in the beds of arkose—is decidedly in favor of the derivation of these deposits from the granitic terrane on the east. Arkose and sandstones composed of more or less waterworn grains of feldspar and quartz occur throughout those portions of the Newark strata which now remain in this area. Toward the base of the formation the derivation of the feldspar from the coarsely porphyritic granitites which occur in the vicinity of Midlothian is made certain by the fragments of these minerals which abound in the fine-grained sediments. These arkose rocks are thicker and more abundant on the eastern than on the western side of the area as it now exists.

It is to be noted, however, that the westward movement of detritus on the eastern margin of the basin does not preclude the easterly set of detritus on the western confines of the area of sedimentation, involving a convergence of detritus such as would take place in a river valley. The white clays with interpolated layers of white quartz pebbles—themselves the remanié of quartz veins in the gneisses, which abound along the western margin from the vicinity of Mosley Junction to the sections on the Appomattox River—point clearly to the derivation of some of the basal sediments from the gneissic terrane. In view of these facts it can not be assumed that the movement of the sediments was uniformly in one direction unless it may have been from the southeast. The occurrence of the gneisses south and southeast of the points named, along the western border of the present basin, makes it possible for the material to have moved from that direction toward the north and northwest.

It is a noticeable fact that surface exposures in the southern part of the basin, where it is inclosed by these gneisses, exhibit less of the arkose than the middle and northern sections. In other words, the arkose from the granitic terranes on the east of the present area seems not to have been borne southward into the area of deposition.

The westward movement of detritus during the deposition of some of the upper sandstones is further illustrated, as is noted on page 441, by the cross-bedding structure, the fore-set beds of which indicate an advance to the westward (see Pl. XXIX).

LOCAL UNCONFORMITIES.

The assemblage of fossil plants and the general character of the sediments long ago established rather firmly in the minds of geologists the fresh-water origin of the deposits in this area. A point remaining in doubt is as to the nature of the fresh-water action—whether it was fluviatile or lacustrine, or alternately one and then the other. A great river valley, such as that of the Ganges, or a coastal plain with parallel rivers, like that of Siberia, may become the seat of thick deposits of alternating silts, sands, and pebble beds with vegetable deposits. By the shifting of streams deposits before laid down may be eroded, and tracts thus denuded may be suffused again with detritus. In such an area of alluviation local unconformities would be more apt to occur than in lakes. Lakes exhibit these structural features only when deposition from rivers has filled up the lake basin, and the area passes into the condition of a river basin.

The occurrence of local unconformities in the Richmond Basin is a well-marked feature at several localities and on horizons separated by many feet of strata. It is proper here to mention a few instances which have been observed.

On the northwestern part of the Salisbury track, near Midlothian, in a stream bed at a place called Big Rock, sandstone is seen overlying the truncated edge of a bed of black Estheria shales.

Near the base of the Newark, at the western margin, south of Mosley Junction, where the beds turn westward on the Irwin Bass place, there is a small pothole or channel eroded in the red shales and filled with gray sands marking an unconformity. In a succeeding layer of the red shale is a 15-inch bowlder of the coarse sandstone derived from the erosion of the pebble beds already laid down in the basin (see Pl. XXVIII).

In the bed of West Sappony Creek, about 1½ miles south of Skinquarter Station, there is a marked instance of local unconformity, where a brown sandstone bed lies upon red shales. The red shale, with its lamination preserved, stands up in the sandstone in the form of eroded and

CROSS BEDDING IN HORIZONTAL NEWARK SANDSTONES, NORTH BANK OF JAMES RIVER, NEAR TUCKAHOE. LOOKING NORTH.

undercut knobs, one of which is 3 feet high, indicating the minimum erosion of the shale stratum (see fig. 91). The section is north and

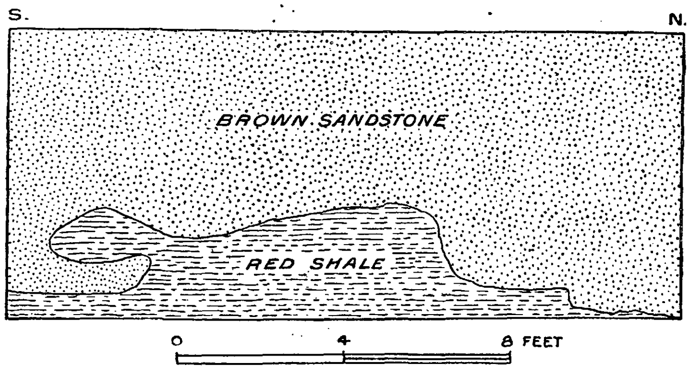


FIG. 91.—Partial section of unconformity in West Sappony Creek, looking west.

south, the eroded ridge of shale having an east and west direction, an observation consistent with the theory of the westward drainage of the area in Triassic times.

CROSS BEDDING.

The coarse granitic sandstones in the central portion of the basin near the top of the Newark section and, as well, those lower down in the Turkey Branch section, described on page 479, exhibit marked cross bedding.

In a small branch of Bakers Creek, on Mr. J. H. Bailey's plantation, cross-bedded sandstones occur. The strata here dip very gently westward. The cross bedding seen on the west bank of the creek shows a lower set of cross beds apparently dipping south, and an upper set truncating the first and apparently dipping north. These dips are recorded as *apparent*, for the reason that the exposed section may not be at right angles to the true dip of these small fore-set beds. This inclination may well be somewhat divergent from a north and south line.

Again, in this section of nearly horizontal rocks on the north side of the James River, coarse cross-bedding structure occurs. The layers dip and thin out to parallelism with the underlying beds to the westward, indicating a current and stream setting in that direction (see Pl. XXIX).

CONTINUITY OF STRATA.

The thickening and thinning of strata in this area have been discussed by Newell and Clifford,[1] the former concluding from his studies of the bedding in the mines on the north side of the river that the strata do not thin toward their present outcrop, the latter holding that in the Midlothian district such thinning is exhibited.

[1]Richmond coal field, Virginia, by F. H. Newell: Geol. Mag., Decade 3, Vol. VI, 1889, pp. 138-140. William Clifford: Trans. Manchester Geol. Soc. [England], Vol. XIX, 1888, p. 333.

The data for a trustworthy decision upon this question for all parts of the area are not yet at hand. Thickening and thinning of particular beds in the mines on the eastern margin is locally exhibited, but in most instances can be associated with movements of the strata. The results of these movements are most pronounced in the coal beds themselves, where the coal pinches out over uplifted areas and is greatly thickened in depressed places. In the Scott pits, in Powhatan County, the coal bed thickened from about 2 feet near the surface to 10 or 12 feet at the bottom of the incline.[1] The irregularities in the mines at Clover Hill (Winterpock) appear to be due entirely to secondary changes, and this is in general true of the mines at Gayton, on the north side of the river. In all these comparisons reference is had to the change of bedding along east and west lines parallel to the dip.

That the strata of the basin vary in thickness from point to point along the strike is indicated by the thinning of the coal beds and by their occasional confluence in this direction. The beds of sandstone and shales outside of the coal-bearing zone have not been, and can not be, traced with that accuracy which would permit a definite statement as to their uniformity and extent. The local unconformities which have been observed in the upper parts of the section (see p. 440), notably in the central part of the basin, show that the shales have been partly denuded before the deposition of the overlying sands and grits. Where this process of local erosion has occurred in this basin, the bedding is discontinuous and lenticular, as we might expect. The small lenses of grit in the shales and sands of the western margin point to the same conclusion (see Pl. XXX). In fact, a comparison of the Turkey Branch section, giving a nearly complete exhibit of the strata near the base on the western margin, with the familiar strata of the same place in the section on the eastern margin, shows that there is a marked change in the lithologic and structural characters between the two points. Similar evidence is derived from the distribution of the coal beds. While their failure to appear at certain points on the upturned margin may be plausibly explained as due to downfaulting of the beds in these places, there are other sections in which their absence is real and is due to a failure to be formed in those places or to their erosion as the prelude to the incursion of coarse sediments. From these considerations we are led to conclude that the strata in the basin are not persistently continuous.

The most pronounced discontinuity of strata is the case above referred to—on the Irwin Bass place, along the western margin. In the case of the thinned shales in the coal measures, as seen in mines, it is to be noted that these shales are frequently beset with slickensides, due to "creep," in these cases associated with the orogenic movements which mark the basin as a whole. By reason of these movements the shales

[1] John Bladen, Powhatan Coal Company, p. 4.

GRIT LENSES AND BLEACHED JOINTS IN BASAL NEWARK SHALES, WESTERN BORDER, SOUTH OF MOSLEY JUNCTION. LOOKING SOUTH.

have been thinned over the edges of fault-blocks and in the compressed parts of flexures. The evidence derived from a shale bed is consequently not decisive on the question of marginal thinning, unless it is shown that crushing has not taken place.

THICKNESS OF THE NEWARK STRATA.

Various estimates of the thickness of the strata in this area have been made. In most, if not all, of these estimates the authors have properly recognized the untrustworthiness of their data, due to the occurrence of faults either observed or inferred.

The most direct measurement of the thickness of strata is that afforded by the breadth of upturned beds on the margin of the nearly flat strata of the interior. The occurrence of faults in this belt of the area probably makes the estimate too low. The throw of these faults is not constantly in one direction. Some of them are downthrown on the west. Lyell states that in sinking a shaft west of the Midlothian mine the coal was found 300 feet above the expected level.

Prof. W. B. Rogers,[1] in 1842, gave the thickness of the explored beds on the eastern margin as 800 feet, and indicated a probably greater depth for the center of the basin. He thought a shaft 1,000 feet deep would reach the coal at several places in the middle of the basin.

The breadth of outcrop on the eastern margin would of itself indicate, at the distance of a mile from the border, a probable depth of 1,500 feet. Explorations by shafting and the diamond drill, subsequent to Rogers's estimate, have shown that the basin is deeper than 1,000 feet at less than a mile from the eastern margin and more than double that depth at a distance of a mile and a half.

Sir Charles Lyell[2] described the fossiliferous strata, including the coal beds, as probably never exceeding 400 or 500 feet in thickness. Above this group he recognized a thick series of grits, sandstones, and shales of unknown depth. Although the thickness of these beds was unascertained, he expressed the opinion that in the central parts of the basin the coal measures might lie under a cover of from 2,000 to 3,000 feet of these barren measures.

Our observations show that the greatest thickness of the strata is toward the western margin of the area. The greatest depth will probably be found in the central part, near the western margin, in the region occupied by the Otterdale sandstones. At least 3,000 feet of strata may be expected there. Precise measurements are rendered impossible by the occurrence of faults and by flexures where faults have not been detected. A boring near Midlothian, at a distance of 1½ miles from the eastern margin, attained a depth of nearly 2,500 feet without reaching the bottom of the Newark group.

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[1] Geology of the Virginias, 1884, p. 69 (reprint).

[2] Quart. Jour. Geol. Soc. London, Vol. III, 1847, p. 263.

RESTORATION OF THE SEDIMENTARY MASS IN THE RICHMOND BASIN.

If the broken and downthrown strata now in the Richmond Basin, together with the basement of older rocks on which these beds rest, could be restored to their attitude before deformation, there would evidently stand above the present surface a mountainous mass, the relief of which would be equal to the depth of the existing basin below that surface. Accepting the view that the strata are essentially uniform in thickness from section to section, the strata which lie nearly horizontal in the central part of the basin would form the surface of a tableland rising about 3,000 feet above the granitic base. The edges of the tilted beds of the margins, whose average dip is now 25° inward toward the axis of the trough, would, if replaced in the horizontal attitude, produce slopes of about 25° outward from the mass. The detached basins on the east would form small outliers separated from the main body of the strata by bare strips of the granitic basement. The general appearance of these masses may be represented as in fig. 92.

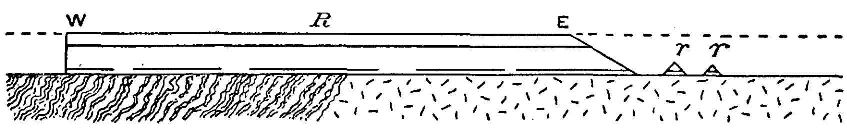
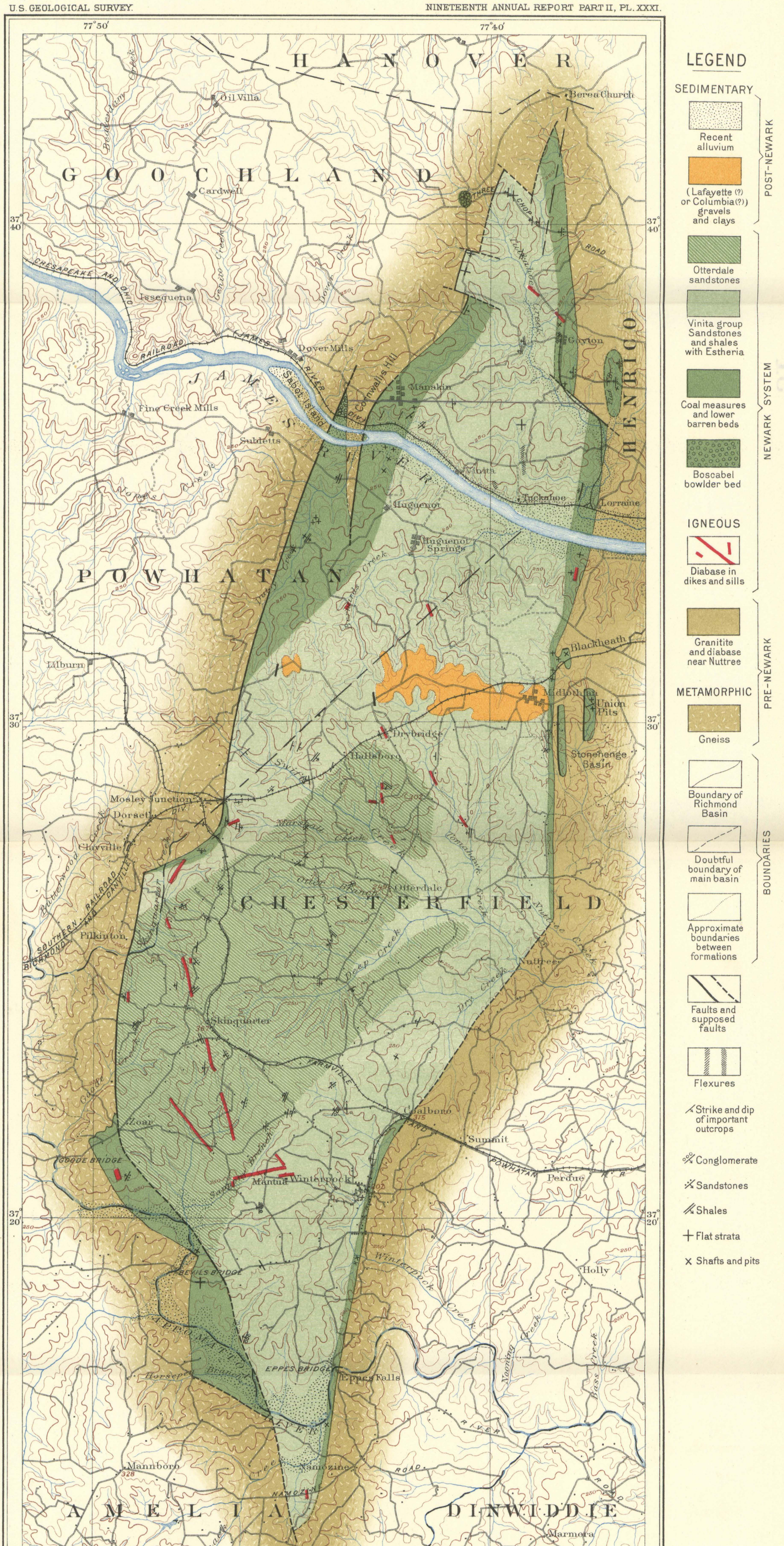


FIG. 92.—Theoretical restoration of the mass of strata now in the Richmond Basin. Horizontal and vertical scale the same. *R*, Richmond Basin strata; *r r*, outlying basins. The dotted line represents the supposed extension of the formation before deformation and erosion of the area.[1]

The truncated edges of the sections as thus replaced demand of the imagination an indefinite extension of the beds in an east-west direction. A similar section drawn from north to south would elicit the same suggestion. We are thus brought to face the question remaining to be solved for the several Newark areas in Virginia, whether they were originally continuous or not. While the basal portion of the Richmond section may have been separated from other remaining areas of Newark rocks by divides of land, it is quite possible that the upper section may have been united across Powhatan and Cumberland counties with the Farmville area, in accordance with the stratigraphic likeness between the two basins, to which Russell has called attention.

[1] A similar section has been drawn by Prof. W. M. Davis for the western margin of the Connecticut Triassic area. See Eighteenth Annual Report U. S. Geol. Survey, Part II, 1898, p. 21, fig. 3.



PRELIMINARY GEOLOGIC MAP OF THE RICHMOND AREA, VIRGINIA

BY J. B. WOODWORTH, ASSISTANT GEOLOGIST

N. S. SHALER, GEOLOGIST IN CHARGE

Scale
0 1 2 3 4 5 Miles

Contour interval 50 feet

1898.

CHAPTER IV.

STRUCTURE OF THE RICHMOND BASIN.

HISTORY OF THEORY OF STRUCTURE.

Closely associated with the scientific problems of this field is the economic question of the occurrence of coal beneath the central parts of the area. The depth at which this coal may be expected to occur depends upon the solution of the difficult problem of the structure of the basin. That this question has not been satisfactorily solved is because of the insufficiency of the evidence obtainable at the surface or in mines and borings. The history of opinion regarding the structure of the basin is a suitable introduction to the data and conclusions which are presented in this report.

The Volney view (*1803*).—Perhaps the earliest hypothesis to account for the coal deposits of this field is that advanced by the traveler and geologist, C. F. Volney, and published in Paris in 1803, of which the following is a summarized translation. He notes that the bed of the James River 10 miles above the rapids at Richmond lies upon a very considerable deposit of coal. At two or three points where search had been made upon the left bank there had been found, under about 120 English feet of red shale, a bed of coal nearly 24 feet thick resting upon an inclined bank of granite. It is evident, he states, that the rapids lower down, which still are an obstacle in the river, had formerly completely dammed it; then there was stagnant water in this place and very probably a lake. He says: "The reader will observe that wherever there is a rapid there is stagnation in the sheet of water which precedes it, as when it comes to the water gates of a mill. The trees continue to accumulate in this place. When the river has cut out a breach and lowered its level, the high-water floods of each year come then to deposit the red clay that one finds there, and this clay affords the evidence of a strange origin, in that this quality of earth belongs to the upper current of the river, and especially to the plain known as the southwest."[1]

The W. B. Rogers view (*1836*).—The idea of the structure of the Richmond Basin entertained by Prof. W. B. Rogers involved the supposition that the inclined strata were largely deposited in this attitude, a hypothesis applied by H. D. Rogers to most of the Newark areas. W. B. Rogers clearly recognized the apparent synclinal structure of

[1] Tableau du Sol, etc., Paris, 1803, pp. 104–105; English translation, London, 1804.

the Richmond area. A simple synclinal structure is delineated for the north bank of the James River in a minute section, published as section 86, on Pl. No. VII of the Reprint of the Geology of the Virginias. In a "profile to accompany the Geological Reconnoissance of the State of Virginia," dated 1836, and published as Pl. No. I of the Reprint, the structure of the Richmond Basin is represented as due to a succession of downthrown fault blocks, producing a graben structure (see fig. 93).

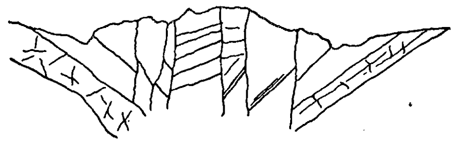


FIG. 93.—Structure of the Richmond Basin, according to W. B. Rogers.

The Lyell view (*1847*).[1]—Sir Charles Lyell examined the Richmond Basin in 1841, and accepted the Mesozoic age of the beds; doubting only whether they should be referred to the Trias or the Oolite (Jura) horizon of Europe. The coal-field is described as occurring in a depression in the granitic and other hypogene rocks. The beds lie in this trough, usually highly inclined along the sides where the lowest of them are seen, while the higher and uppermost beds appear nearly horizontal in the middle of the basin.

Lyell gives the accompanying cross-section showing the manner in which he supposed the strata to rest. The whole country has been planed off almost horizontally. This section has been repeated in several editions of Lyell's Manual of Geology.

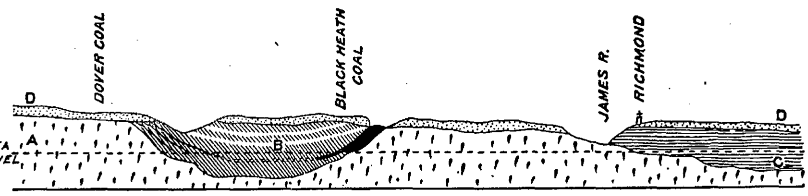
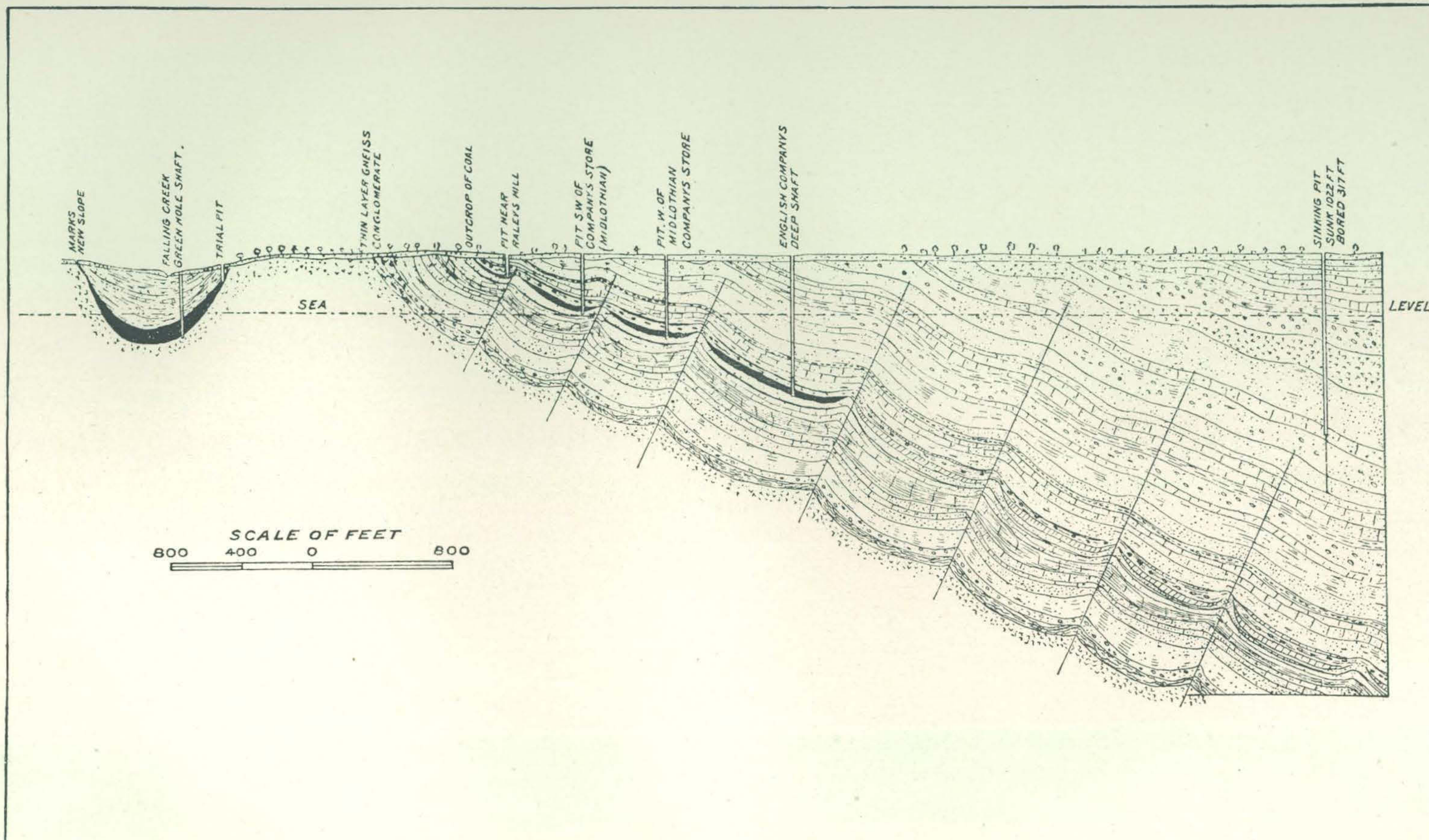


FIG. 94.—Geologic cross section of the Richmond Basin, according to Sir Charles Lyell. A, granite and gneiss; B, coal measures; C, newer Mesozoic strata; D, drift.

The granitic floor is described as very uneven, causing the coal to be squeezed out at one point and made to swell up at another. These changes in thickness are attributed to the movements of the rocks, and "the forcing of the granite against the coal, the distinct layers of which are often cut off abruptly one after the other by the granite in contact."

The trough-like form of the basin is described as exhibiting many deviations, such as the strata dipping toward the granitic margin or being nearly horizontal at that contact, a relation which implies faulting, although the author does not thus explicitly state this conclusion.

[1] On the structure and probable age of the coal-field of the James River, near Richmond, Va.: Quart. Jour. Geol. Soc., Vol. III, 1847, pp. 261-280.



STRUCTURE OF MIDLOTHIAN DISTRICT.

(According to Clifford.)

The Taylor view (*1855*).[1]—Mr. R. C. Taylor reviewed the literature of the Richmond Basin and presented a cross section of the coal-field, which diagram is reproduced in the annexed figure.

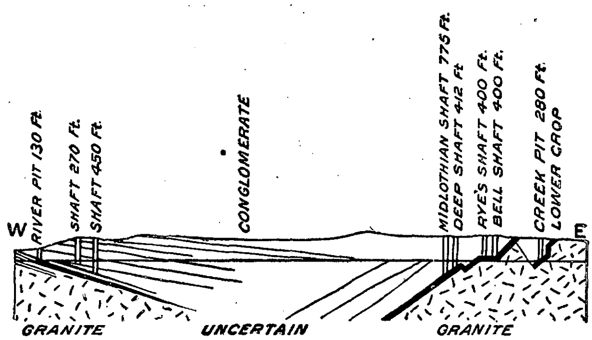


FIG. 95.—The Taylor section of the bituminous coal-field near Richmond, Va.

The structure thus represented is not described further than in the notes appended to the diagram, in which the arrangement of the beds and the depth of the coal-field in its central parts are marked as uncertain. The representation of the occurrence of faults on the eastern margin in the detached area may possibly be intended by certain lines introduced in the section.

The Daddow and Bannan view (*1866*).[2]—This view appears to be the result of an examination of the area by S. Harries Daddow. He thought the granite floor exhibited undulations, rising to the surface as so many sharp and abrupt peaks. He regarded these original irregularities of the basin as having been partly smoothed over by the deposition of strata before the accumulation of coal. In his view, the coal here and there rests upon these granite peaks where they had not yet been buried. No subsequent movements of the crust, in this or the other eastern basins, is supposed to have taken place. The deposits are said to be thickest in the deeper basins or synclines, limited on the inclining sides, and very thin on the anticlines or ridges, proving, as this author thought, that the basins existed much in their present condition when these deposits took place.

Daddow denied that there are "slips" or "heaves," described by Taylor. All the irregularities, with one or two exceptions, are egarded as due to original irregularities in the floor. The view is illustrated by two sections.

In Daddow's view, the basin was an original crater-like depression in the earth's surface, broken by numerous granitic ridges and peaks into

[1]Statistics of coal, 2d ed., Philadelphia, 1855, pp. 287-297. See also Richmond Coal Basin and its coal trade: Pennsylvania State Jour., Vol. II, 1833-34, p. 567. Memoir of a section passing through the bituminous coal field near Richmond in Virginia: Trans. Geol. Soc. Pennsylvania, Vol. I, 1835, pp. 275-294, Pls. XVI and XVII.

[2]Samuel Harries Daddow and Benjamin Bannan: Coal, Iron, and Oil; or, the Practical American Miner. Pottsville, Pa., 1866, p. 786. Richmond Basin, pp. 292-293, 395-402.

separate basins. By sedimentation these irregularities were gradually buried, the strata conforming more or less to the shape of the bottom and the inclination of the sides. This view totally neglects the visible faults and plain indications of disturbance in the basin, and affords no clew to the structure of the area.

The Lesley view[1] (1873 ?).—The following extracts from a paper credited to Prof. J. P. Lesley give the original-valley hypothesis in its most comprehensive form.

The geological history of the Richmond coal field is easily understood. There was once a time when a mountain range of granitoid rocks rose high above the sea level, where Richmond and Petersburg now stand, and stretched away northward through Virginia, Maryland, and southeastern Pennsylvania, as far as Trenton, on the Delaware River. Toward the south it ranged past Raleigh and Fayetteville to the Dahlonega country of Georgia. A few miles farther west another and lower mountain range ran parallel to the first, but united with it before reaching the Potomac River. The valley between these two ranges of mountains was everywhere at least 1,000 feet deep, and may have been thrice that depth. Its length was at least 300 miles, and may have been 400.

At the same time that middle New Jersey, eastern Pennsylvania, and the Piedmont country of Virginia and North Carolina were receiving their New Red deposits on a long wide estuary or arm of the sea, having its capes at Trenton and Manhattan Island, the valley described at the beginning of this sketch as lying between two ranges of mountains which stood where Richmond and Raleigh now are got also filled up with over a thousand and perhaps with several thousand feet of sand and mud. These are the Richmond coal measures.

The valley had, of course, irregular, bossy sides, like all valleys between granite mountains. On its two slopes and in its bed grew one of the rankest vegetations ever seen, a vegetation chiefly of moss, on and through which grew many species of ferns and shrubs long since extinct, and also an irregular forest of trees of species also extinct.

In short, it was supposed by this author that the coal accumulated almost immediately after this valley was excavated, having grown on the sides of the valley as well as filling up depressions. After the period of coal making the continent is supposed to have been depressed beneath the sea level, so as to turn this valley into a lake or arm of the sea.

The Fontaine view (1879–1883).—Prof. W. M. Fontaine, in his work on the Older Mesozoic Flora of Virginia,[2] reaffirms the synclinal structure of the Richmond basin. He believes that "it did not possess this structure in its early history in such a marked manner as now. It, like the other areas, was a progressively subsiding region, probably, during most of the era of deposition."

Still earlier the same author presented his explanation of the Newark areas, including the Richmond Basin:

The strata were laid down in depressions, which, originally shallow, were subsequently deepened by a more or less rapid subsidence. The subsidence was due, as

[1] Cited in McFarlane's Coal Regions of America, 1873, pp. 510–514, from Lesley's United States Railroad and Mining Register (date unknown). Also cited by Clifford, Trans. Manchester Geol. Soc., Vol. XIX, 1886–1888, pp. 355–358. Lesley gives a section of the Richmond Basin in his Manual of Coal and its Topography, 1859, p. 46, fig. 7.

[2] Mon. U. S. Geol. Survey, Vol. VI, 1883, p. 7.

previously stated, to the operation of a lateral thrust. It continued until faults and overturned anticlinals were produced. In the interior belts (the New York, Virginia, Barboursville, Scottsville, Danville, and Dan River areas) these operated to produce a constant northwest dip. This resulted from the fact that the western sides of the severed earth prisms dropped, producing sometimes by a roll of the prisms an upthrow of the eastern side. This appears to occur in some of the faults of the Richmond coal field also. When the strain did not result in producing rupture and faulting it caused the development of an anticlinal, affecting but a narrow belt, which was overturned to the eastward, thus producing also a continuous northwest dip. Where the strata have suffered enormously from erosion, and where almost precisely similar beds are formed by the similar conditions of deposition found repeated at different horizons, as is often the case in the interior belts, it is almost impossible to detect reduplications by faulting and folding. When the period of faulting was reached eruptions of trap took place. It will thus be seen that the continuous dips would by no means give a true indication of the thickness of the series.

In the Richmond coal field the faults and narrow overturned folds are not of sufficient magnitude to produce, as in the interior belts, continuous dips, but suffice only to render very variable and uncertain the dip and position of the strata toward the center of the field. The general result seems to have been to flatten the dip here and to steepen it on the western side. Some of the twists in the strata produced by the overturned anticlinals are of extremely limited extent. I have seen them only a few feet wide.

The direction in which the lateral thrust operated in this field was from east to west, and it seems not yet to be exhausted, for this region is often affected by minor earthquakes, and at intervals of ten or fifteen years by very powerful ones, the last occurring a few years ago. The shocks pass from east to west. It is probable that the gradual depression of the coast is connected with this westward thrust.[1]

The Clifford view (1888).[2]—Mr. William Clifford, M. E., published an account of his observations upon the geology and methods of mining in the Richmond and Deep Run areas. He describes the coal measures as deposited in a huge hollow, probably 3,000 feet deep, having a length of 30 miles and a width of from 4 to 10 miles. The detached areas on each flank he speaks of as occupying hollows scooped out of the granitic rock, or as formed by the junction of ridges whose summits have been eroded, or by the local subsidence of the underlying granite. The author favors the hypothesis of original depressions, for he infers that the strata thin toward the sides of the basin as though the deposits had slidden down slopes on which they accumulated. Thickening toward the middle of the basin is held as the cause of flat strata in that part of the field.

The disturbances of the bed are described as waving longitudinal "ledges" separating the basin into more or less regular zones. These are traceable on the floor and roof alike of the coal measures.

He concludes that there is no evidence to show the nonoccurrence of the coal beneath the middle of the basin. The failure to find workable beds of coal in the "Sinking shaft" at Midlothian, described by Heinrich, he attributes to the bore hole not reaching the depth at which the

[1] Notes on the Mesozoic of Virginia: Am. Jour. Sci., 3d series, Vol. XVII, 1879, pp. 36-37.

[2] Richmond coal-field, Virginia: Trans. Manchester Geol. Soc. [England], Vol. XIX 1888, pp. 326-354, pls. 1-5.

coals should appear. He supposed that the strata at Midlothian continued to dip westward at about 25° at least to the vicinity of the "Sinking shaft." (See map, Pl. XXVI, and section, Pl. XXXII.) His theoretical section is based upon this conception of the structure, with marginal thinning.

The Newell view (1889).—Mr. F. H. Newell[1] criticised Clifford's conclusion to the effect that the strata in the Richmond Basin thinned toward the edges of the present area and that the plants from which the coal is derived grew on inclined surfaces. Newell states that one of the principal coal beds, dipping at an angle of about 30°, was worked along the strike for about a mile and was explored down the dip for 1,500 feet, and that throughout the area thus made known the bed maintained an approximate uniformity of thickness. He maintained that the strata now in the basin were once horizontal and that their present inclined position is due to movements involving crushing and faulting subsequent to their deposition. This uniformity of thickness and original horizontality is thought to be evidence of the persistence beneath the main basin of those conditions on which coal depends.

In regard to the parallelism of strata, Newell made the following statements:

> It does not follow from what has been said that any one workable coal is continuous across under the basin to the outcrop on the other side. On the contrary, this is probably not the case. The identification of any one coal seam for a distance of even 1 or 2 miles is a matter of great uncertainty in the thickness both of the coal and accompanying shales, the bending and crushing to which all have been subjected, and the rapid decomposition of the whole series. When the change of thickness of the coal beds and the large number of thin coals—usually overlooked—are given due consideration, strong doubt is thrown upon the identifications that have been attempted between the coal in one mine and that in another mine a mile or more away. The probabilities are that the coal of economic importance in the one mine is represented by some one of the smaller neglected coals in the other.

The Russell view (1892).—Prof. I. C. Russell[2] reviewed the opinions concerning the structure of the basin advanced by Lyell, Fontaine, and Newell, and presented the results of his own observations upon such structures as were visible at the time of a visit made by him to the Richmond area.

His observations warrant the conclusion that faulting has taken place along the eastern and western margins of the area, and that the basin owes its position to downfaulting or else to the relative uplift of the neighboring granitic and gneissic areas, its preservation being due to its position thus attained below the base-level of erosion. The faulting along the margins indicates that the strata were formerly more extensive than now, and it is evident from the amount of erosion that what remains is but the remnant of their original area.

North-and-south faults bounding diversely tilted blocks of strata occur on the western margin. In the faults, as seen in the mines, the

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[1] Geol. Mag , Dec. 3, Vol. VI, 1889, pp. 138-140.

[2] Correlation papers—The Newark system, by I. C. Russell: Bull. U. S. Geol. Survey No. 85, Washington, 1892, pp. 89-94.

coal is pinched out to a mere stringer of comminuted and slickensided fragments. The small basins on the eastern margin are held to be due to downthrown masses with faults on their western border, the double outcrop of coal being accounted for by the drag on these faults.

In discussing drainage modifications and their interpretation, Campbell[1] infers that the double line of Triassic deposits in Virginia outlines depressions on an earlier Triassic peneplained land surface, as a result of which deformation the drainage was concentrated along these troughs. He supposes a maximum submergence in the central portion of the Newark areas along a northwest and southeast axis, as a further result of which the sediments spread over the area as a continuous sheet. This cross-axis is placed on the line of the present Susquehanna River.

SUMMARY OF THE PRECEDING VIEWS.

The authors cited have explained the deposits of the Richmond Basin as being made under the following somewhat different geographic conditions:

1. A lake formed behind a rock barrier in the course of a river. Behind this barrier silt accumulated, forming the present deposits. (Volney.)

2. A river valley of great width and extent, in which the existing strata were deposited in an inclined attitude, simulating cross-bedding on a large scale. (Rogers brothers.)

3. A valley, lying between mountains and studded over with granitic peaks, which became filled up with sediments, at first sloping on the sides of the valley, but becoming horizontal over the middle of the area when the inequalities had been covered up. (Daddow and Bannan, Lesley.)

4. A shallow depression, deepening as filling went on, ending in faulting and folding by lateral compression. (Fontaine.)

5. The strata now in the Richmond basin are to be regarded as a downfaulted remnant of a once more extended series deposited by lakes or rivers. (Russell.)

The authors of this report are led to conclusions similar to those entertained by Russell and Fontaine.

STRUCTURE OF THE BOUNDARIES OF THE BASIN.

The boundaries of the Richmond basin are lines of contact between rock masses traced on the surface of the Piedmont district. The surface within and without the area, a region of shales and sandstones on one hand and a region of granites and gneisses on the other, is at approximately the same level in both fields.

The eastern and the western borders of the several elongated areas of Newark rocks lying on the west of the Richmond area and of those found northward, as far as Connecticut and Massachusetts, have been

[1] Jour. Geol. (Chicago), Vol. IV, 1896, pp. 676-678.

shown by examination to present an important structural difference. On the eastern side the lowest beds in the area may be seen resting on crystalline and igneous rocks of more ancient date. Dipping inward with more or less regularity to the opposite border of the area, successively higher and higher beds, sometimes repeated by faults, appear, until perhaps the highest beds in the series are found at the surface of the ground closely in contact with the ancient complex on that side of the basin.

In the published sections accompanying the earlier reports on the geology of the basin the Richmond area has usually been represented as an exception to this type of structure. While the general synclinal character of the structure in the portions of the basin upon which the diagrams were based is in a great degree true, a more extended examination of the area shows the monoclinal structure so pronounced in other Newark areas. The evidence for this conclusion will be apparent from the following account of the boundaries of the area and description of the interior, so far as that is known from visible outcrops.

THE EASTERN BORDER.

The eastern border of the Richmond Basin is roughly outlined by small stream valleys. Fully 20 miles of this line, the total length being about 34 miles, is followed by these streams. Their location in this position is determined by the outcrop of soft coal-bearing shales at the base of the Newark formation. Although the eastern border is thus broadly marked out by streams, the precise limits of the formations at contact along this line show frequent discordance with the configuration of the ground. This imperfect adjustment of the streams to the structure of the Newark beds is due to the fact that the granites and gneisses of the Piedmont district are to the depth of several yards softened by decomposition and disintegration to the low resistance of muds and shales. As a rule, the streams which follow the border line lie within the coal-measure area, and the sandstones and arkose beds at the base of the formation are to be found, along with granites and gneisses, on their eastern banks. The valleys thus formed frequently leave the granitic and gneissic terrane at an elevation varying from 50 to 75 feet above the immediately adjacent coal-bearing region.

The eastern margin of the Richmond area has an approximately straight course in a north-northeast and south-southwest direction. With reference to the basin as a whole, this border corresponds to the uplifted base of a westward tilted series of strata, and is thus in contrast with the western margin, which represents, in a general way the down-faulted side of the monoclinal block. Nevertheless this eastern margin is not without minor irregularities, as the tracing of the outcrops and the exploitation of mines has shown. In the following notes some of the details of this line, the faults which affect it, and the interpretation of its general character, will be set forth.

BETWEEN NAMOZINE AND COALBORO.

Beginning on the south side of the Appomattox, at the southernmost point in the Richmond area, at a place about 1½ miles southwest of Namozine, the eastern border of the area extends in a nearly straight line to Coalboro, a distance of 9 miles. Throughout this extension no deflections from the general course can be made out on the ground. Since this line is formed by the intersection of the even surface of the Piedmont region with the tilted plane separating the Newark rocks above from the granites and gneisses below, its straightness for this distance can be interpreted only as the result of the intersection of two essentially plane surfaces. From the nature of this boundary line, therefore, important inferences may be drawn in regard to the form of the surface on which the Newark beds repose. This matter is discussed elsewhere in this report.

FROM COALBORO TO NUTTREE CREEK.

Near Coalboro the boundary turns sharply eastward to the vicinity of Nuttree Creek, whence it resumes its meridional course, which is maintained, with some minor deflections, hereafter to be noted, past Midlothian to the James River.

From their southern point of beginning to Coalboro the coal measures have been traced almost continuously, and throughout this distance the Newark strata appear to rest in a little disturbed condition upon their original base, the granites and gneisses. But from Coalboro to Nuttree Creek the coal beds which occur near the base have not been discovered. Associated with this circumstance, the truth of which rests largely upon the testimony of miners in this district, is the occurrence of strata in a more highly inclined altitude than is exhibited immediately north and south of this portion of the boundary. Too little, however, is known concerning the structure of the beds in this region to state positively the nature of this deflection in the boundary. It may be that the basement rocks are warped along this line, and that the coal measures follow in due sequence upon this surface. Analogy with similar irregularities in the Connecticut area, as shown by Davis and Griswold, would suggest that the boundary between Coalboro and Nuttree Creek is determined by a northeast-southwest fault, along which the Newark rocks and underlying granites on the northwest side have dropped down, according to the best estimate that the scanty data afford, as much as 6,000 feet. The occurrence of shales in a vertical attitude along the boundary line on the south side of Tomahawk Creek, reported by Mr. G. B. Richardson, is favorable to the view that a fault exists there; but since there are no other structures known on the extended course of this line which require faulting for their explanation, the hypothesis appears at present to be unsupported.

IN THE MIDLOTHIAN DISTRICT.

In the vicinity of Midlothian the border of the basin and that of the detached areas adjacent to the eastern edge of the main coal field has been, at one time or another in the history of the mines, carefully determined. In large measure this knowledge has been lost. In part the facts have been recorded, and in part the nature of the boundary may still be ascertained from the outcrops. Reserving for another section of this report the account of the deposits in the detached basins, their structure, so far as it throws light on the boundary of the main basin, may here be described. The two areas lying south of the turnpike at Midlothian appear not to be associated with any irregularities in the boundary of the main basin. The boundaries of these small areas, as described by Russell,[1] on what appears on the ground to be the best evidence obtainable, are determined by the intersection of the tilted plane of deposition with the present surface on their eastern side and by faults on their western margin. Transverse faults also occur, but their effect on the outline of the margin of these basins and that of the main area is not definitely known. Russell mentions an offset in the mines in the vicinity of Midlothian, which is probably due to a fault of this east and west series. The ends of the detached areas, it is to be suspected, are determined by such faults.

According to Mr. John Peal, a miner of Midlothian, the main coal bed makes a loop to the eastward at the intersection of the boundary with the turnpike near that place, but this feature is not traceable at the present time. According to the same informant, the strata are "on end" along the eastern border near the track of the Southern Railway, the coal beds having been found in a vertical position in the Bonanza, Etna, and the old Gowrie shafts. Just east of the Etna shaft, in the railway cut, the shales underlying the coals may be seen in a horizontal attitude overlying the granite which crops out on the opposite side of the track. From all that can be learned the strata pass without faulting from this attitude steeply downward for about 100 feet. They then dip westward at the usual angle of 25° on this margin. The bottom of the Etna shaft is in the porphyritic granitite of the Midlothian district. The general relations appear to be those sketched in the annexed diagram (fig. 96).

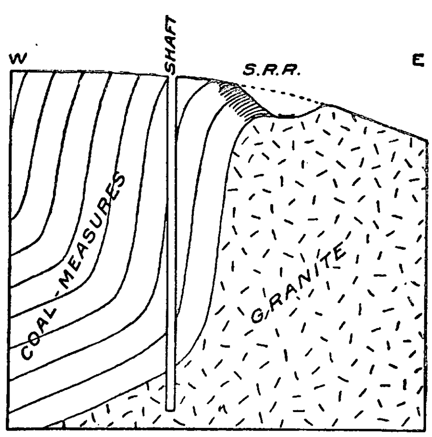


FIG. 96.—Supposed structure of the margin in the Etna shaft, Midlothian, Virginia.

[1] Bull. U. S. Geol. Survey No. 85.

The flexure which is indicated by the reports from this portion of the boundary is like those which, near Winterpock (Clover Hill), occur in the slopes of several mines, attributed by some of the earlier writers on this basin to the deposition of the strata over and around hillocks or islands of granite. It seems most probable, in view of the slickensides exhibited in the beds, that the present structures, as elsewhere indicated in this report, are wholly secondary, and in most cases due to faults in the brittle granitic terrane which pass into flexures in the overlying yielding sediments.

North of the old Gowrie shaft several features render the tracing of the main boundary difficult. Falling Creek has eroded a valley at the point where the small detached areas on the north side of the Southern Railway approach nearest the main basin. On some old mining maps the boundary is indicated as definitely shown between the Gowrie and the site of Jewett's coke shaft, but there is no evidence at present of granite coming to the surface between the Cunliffe and the main basin, nor between the Cunliffe Basin and the Blackheath tract on the east of it. So far as the present shape of the ground indicates anything at all, it points to the conclusion that the basal beds of the main basin extended, if they do not now extend, over the Cunliffe and Blackheath tracts, in the manner indicated in the accompanying cross section, drawn east

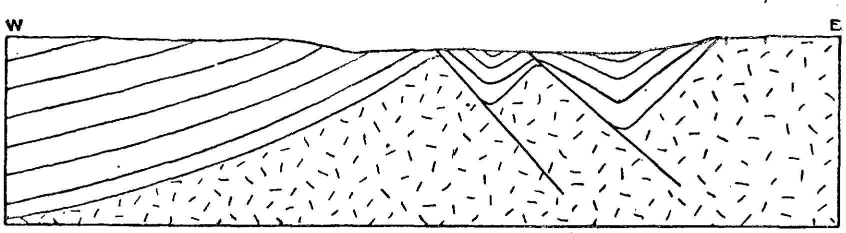


FIG. 97.—Cross section through Blackheath and Cunliffe areas, showing supposed connection with main basin

and west through these small areas. For this reason the boundary has been drawn as a loop around these abandoned workings. Similar indentations in the border occur again on the western side of the basin where the structure is more clearly associated with faulting.

From the vicinity of Falling Creek northward to the James River the boundary maintains its course of a few degrees east of north. Some of the old maps show the position of the granite on the east throughout the entire distance, but the line can not at present be distinctly traced by surface indications in the region south of the river road. On the long slope of the south bank of the James, in the region of the Sallé and Burfoot coal tracts, the boundary was fully explored in the days when mining was carried on. There appears to be the same simple depositional plane intersecting the present surface which characterizes the eastern border south of this field.

NORTH OF THE JAMES RIVER.

On the north side of the James River the eastern border begins opposite the point to which it has been traced on the south bank without evidence of displacement in the intervening valley. The line is followed closely by a branch railroad from Lorraine to the vicinity of the confluence of Deep Run with Tuckahoe Creek. Thence for about a mile the boundary takes a northwest course, at the end of which it straightens out and runs nearly north to the northern end of the basin. This deflection in the boundary is marked by an offset in the coal shafts between James River and Gayton (Carbon Hill). The evidence of a northwest and southeast fault along this line appears to be complete. The extension of such a fault into the basin is not, however, shown by any visible structures. It is to be noted that on the western border, where such a fault extended in a direct line would intersect the pre-Newark rocks, there is a marked indentation of the boundary. The structure of this indent, however, does not demand the occurrence of the fault on the eastern margin. It appears unreasonable, therefore, to assume that this fault extends over a great distance.

The eastern border at Gayton has been somewhat differently placed by different observers. This disagreement is largely owing to the difficulty of distinguishing the unaltered granite from the arkose, which everywhere along the eastern border in the granitic region obscures the contact. In fact, there is probably a gradation in certain portions of this region from clastic materials above to igneous below through the products of disintegration. Along this portion of the line the granite is recognizable on the surface by the large rounded blocks produced by its disintegration. The boundary lies on the eastern side of the small brook east of the mines. All the granitic-looking fragments on the surface on the west of this brook and in the outcrops in its bed show upon close examination the arkose structure with waterworn pebbles. On the east of this brook is a small tract in which the Newark sandstones appear with a dip to the east as high as 80°. Granite bowlders appear to the east of this line of outcrop. The entire boundary of this eastward prolongation of the basin can not be clearly made out. The scanty facts observed point to a tongue or detached area of the coal measures like the Cunliffe and Blackheath tracts.

From Gayton northward the nature of the boundary is but little known. Granites give way to gneiss, the former being probably intruded into the latter, since there is a gradual increase of fineness of texture in the granite as one approaches the gneiss. Where the Three Chop road crosses the boundary, the Newark and the underlying crystalline rocks were not seen in contact.

The precise mode of termination of the Newark rocks on the north is not known. Faulting rather than folding would be inferred as controlling their structure. This appears from the character of the western border in its vicinity, the nature of which line it will now be our task to describe.

THE WESTERN BORDER.

The observed cross section of the Richmond Basin in the valley of the James River has afforded a reasonable basis for interpreting the structure as synclinal. This view is in part right and in part wrong. There are many sections across the basin which repeat the structure so well shown in the James River bank, but there are others which exhibit a western dip of the strata almost continuously from the eastern margin to the western border. Even where the marginal beds dip eastward on that border they are usually much more broken by faults than the strata on the eastern margin. In other words, it appears that the strata along the western border have been abruptly thrown or flexed down to variable depths. The basin therefore shows to a large degree that dominant structure of the Newark areas in the Piedmont district by which the beds are made to dip mainly westward. The nature of these faults, first made out by Russell in the vicinity of the James River, will now be described, so far as they are at present known.

As a preliminary to understanding the detailed statements which follow, it should be said that the observed and inferred faults on this margin are not strictly parallel to the border, but usually exhibit a northwest and southeast course, while the boundary line trends to the east of north. As a result of this arrangement, and as a consequence of the level of denudation in this region in relation to the structures of the basin, it often happens that the basal beds of the Newark occur along the boundary, that part of the line being determined by the outcrop of the deposition plane, as on the eastern border. These facts are best shown in the Turkey Branch section (see p. 478).

SOUTH OF THE APPOMATTOX RIVER.

Beginning the tracing of the border, as before, on the south in the Winticomack Creek prolongation of the Newark rocks, we note that the precise extension of these beds on the south side of the river can not be accurately fixed. From a few decomposed sandy exposures it appears likely that the beds underlie the low grounds of the Appomattox River in the manner in which they are represented on most of the older maps. There has been found no evidence, however, of the existence of another finger-like projection of the series such as occurs in the lower course of Winticomack Creek. Gneiss appears, in fact, in the bottom of Horsepen Branch, fixing the limits in that part of the line.

THE BEVIL BRIDGE ROAD SECTION.

It is to be noted that there are beds of recent geological date in this area, the lithological characters of which closely resemble the typical Newark sediments. In fixing the boundary care has been exercised to exclude wherever possible these patches of rock. At no point has the task of dealing with these discriminations been more difficult than along the western margin in the region which is now to be described.

Not only does the boundary line depend upon the determinations which are here made, but an important question regarding the physical history of the Richmond Basin hinges upon the view which is taken of the structures which the presence of these beds indicate. The problem is first encountered at Bevil Bridge, on the east bank of the Appomattox River. The river has here cut a valley about 150 feet below the general level of the Piedmont district. Gneiss crops out on the eastern bank and continues to be exposed in the road for a distance of about one-third of a mile to the east of the river. At this point the pre-Newark rock is capped by horizontal strata of clays and argillaceous sands in an advanced state of decomposition from weathering. The unconformity with the gneiss is obvious, although it is not marked by a basal conglomerate. Fossils are also lacking as aids in the determination of the age of the stratified rocks.

About half a mile eastward from the point of beginning of the above-mentioned section and 50 feet higher up a white vein-quartz pebble conglomerate comes into view, overlain by reddish mottled sandstone. A quarter of a mile farther east and still higher up red and white clayey sands, probably decomposed sandstone, in distinct bands dipping 45° west, appear. This last exposure indicates that the area of horizontal beds resting upon the gneiss near the river has been passed and that the Newark beds which exhibit the tilt of post-Triassic dislocation are near their western margin. The evidence now to be set forth concerning a fault in this vicinity will make this relation clearer.

The Spout Spring boundary fault.—The high ground north of the Bevil Bridge road and east of the Appomattox, known locally as Gravelly Hill, is capped by a deposit of white and reddish quartz and quartzite pebbles varying in size up to 3 inches in diameter. This deposit, though not shown in natural sections to be a part of the Newark or later deposits, may for the present be neglected, it being sufficient to note that it is like many other gravelly areas capping high ground in this area and occurring usually near the larger rivers (see p. 505).

A ravine on the northern slope of Gravelly Hill, on the Condrey place, exposes a contact between the Newark rocks and the gneiss of the western border. The Newark shales are at this locality at a lower level than the surface of the gneiss on which the horizontal strata rest in the locality described, near Bevil Bridge, on the western slope of the hill. At the base of the hill, in this ravine, there is a perennial outflow of water known locally as "Spout Spring." The water issues from broken-up blocks of Newark red shale, the gneiss at the spring not being exposed. About 150 feet northwest of Spout Spring, downstream, there is an exposure of schistose rocks, much decayed, flanked by a remnant of the Newark shale. The schists strike N. 63° W., with a dip nearly vertical. The exposed surface of contact between the gneiss and the Newark is too small to afford a definite determination of its inclination. At the point where the contact was observed its plane showed a hade of 40° west. Its strike was northwest to southeast, agreeing in direction and hade with several observed faults elsewhere along the western border. The shale and the gneiss are clearly brecciated along the plane of contact. These circumstances, together with the phenomena at Spout Spring, afford good evidence of a fault at this locality.

The attitude of the Newark strata immediately in contact with the fault is not determinable. One-eighth of a mile up the little stream and about 200 feet east of the probable position of the fault plane, a thin quartz pebble conglomerate is seen resting on a clay (decomposed shale) stratum. This small exposure gives a strike of N. 28° W., and a steep dip to the northeast, an attitude which accords with the expectation that the Newark sediments should show a drag along the fault plane.

These details, unimportant in themselves, have been thus explicitly set forth in order that the nature of the evidence on which faulting is inferred along this western boundary may be thoroughly understood.

It now remains to consider whether the Newark strata overlap the Spout Spring fault, having been deposited subsequent to its formation. Two exposures of sediments—that just named, near Bevil Bridge, and one which will now be briefly mentioned—bear on this question.

Nearly due west from Spout Spring, on the bank of the Appomattox River, some test pits have been sunk into black shales, carrying traces of coal. These shales are said to have been traced across the river at this point. Brownish sandstones with plant stems were found in the débris from the pits. These members of the Newark system lie on the west side of the projected line of the Spout Spring fault, and at a lower level than the gneiss at the spring. The Newark rocks, therefore, clearly extend beyond the fault to the west.

The elucidation of the stratigraphy and structure in this Bevil Bridge section is so important from the point of view of an understanding of the faults which occur to the northward that it seems well to discuss the matter somewhat at length in this place.

First, we may suppose, what other observers apparently have assumed, as their maps would go to show, that the boundary line in this district is to be drawn to include in the Newark system the horizontal

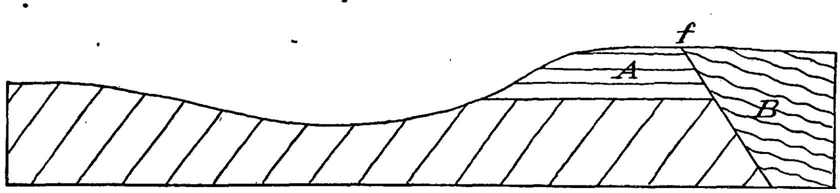


FIG. 98.—(Case I.) Newark strata on both sides of the fault along the Bevil Bridge road, the fault (*f*) coming to or near the present surface. *A*, basal Newark strata; *B*, upper downthrown Newark beds.

strata in the valley of the Appomattox. (See fig. 98.) In this supposition (which may be called Case I) the fault comes to the present surface; the beds on the gneiss are at the local base of the Newark system, and the throw on the fault is probably great, but less than the thickness of the whole section.

It is shown elsewhere in this report (see p. 505) that there are considerable patches of post-Newark sediments capping certain ridges and hills in the Richmond area. The deposits on Gravelly Hill and eastward require us to consider the possibility that the entire section extending beyond the Spout Spring fault along the Bevil Bridge road is post-Newark, and, therefore, not cut by the fault; in other words, presenting the cross-section shown in the accompanying diagram (fig. 99). If this hypothesis (Case II) be true, the Newark boundary should be drawn no farther west than the position of the fault-plane.

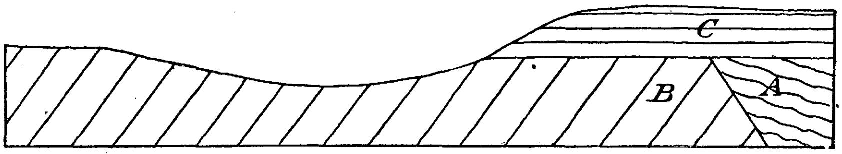


FIG. 99.—(Case II.) Downthrown Newark (*A*) and adjacent gneiss (*B*) eroded and covered by newer strata (*C*).

Yet, another hypothesis needs consideration before a conclusion concerning this matter is reached. It is imaginable that after a part of the Newark sediments was laid down in a subsiding trough a fault developed along this line, so that the beds east of it were thrown down, giving the minor foldings which they now exhibit; or, what is equally probable, if not a necessary postulate in this view, the western block rose up, being stripped of the sediments already laid down west of the fault-plane. After the dislocation, sedimentation was renewed, horizontal strata being laid down over the region adjacent to the fault, giving the Bevil Bridge section the hypothetical structure shown in fig. 100 (Case III). In this view, the horizontal strata on the west of the fault are late Newark, though they lie here upon the gneiss.

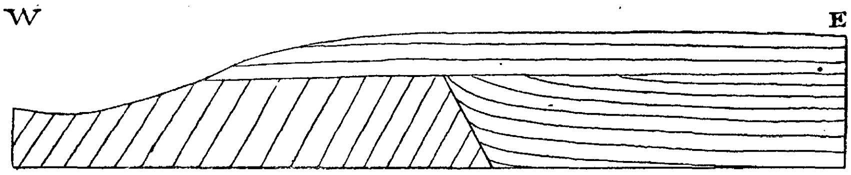


FIG. 100.—Case III, in which it is supposed that the beds on the west of the fault are late Newark rocks, deposition to the eastward having been continuous during Newark time.

Without lithological characters of determinative value and without fossils, the evidence derivable from structure, even where a fault is definitely known to affect a portion of the section, must leave us in doubt as to the relations of the horizontal beds in question to the main mass of Newark in the Richmond Basin. But there is another possibility which remains for consideration. If the second and third hypotheses are to be preferred to the first, the horizontal beds should originally have extended across the fault, which would thus be of earlier date than their deposition. It is conceivable that movements may have been renewed on the old fault subsequent to the deposition of the horizontal beds. We are thus brought to a fourth hypothesis (Case IV), which admits the possibility of the second and third cases as preceding alternative conditions and leaves us without criteria for choosing between the first and this last hypothesis by the use of any local criteria as yet discovered.

Such is the argument by which the conclusion is reached that the age of these horizontal beds can not be definitely determined by direct methods. It has seemed necessary to be thus explicit in regard to these slight structures in order to set forth the difficulties which attend the interpretation of portions of this basin. There is left to the geologist, however, the argument based upon probability of recurrence of a type of structure known to exist in the immediate vicinity. At this point the knowledge gained from the patch of coal-bearing rocks lying in the Appomattox Valley west of the Spout Spring fault becomes of significance in showing that the Newark sediments extend west of the fault, as postulated in Case I. It is only necessary to suppose that the area of Newark in which the pits lie has been thrown down below the level of the horizontal strata seen resting on the gneiss to make it seem more probable that they are basal members of the Newark rather than beds belonging to a higher horizon. This line of argument, it will be shown, is confirmed from step to step as one goes northward along the western boundary. Therefore the boundary line has been drawn so as to include the horizontal strata whose occurrence without other similar known Newark blocks would remain without definite proof of a Newark age.

THE GOODE BRIDGE ROAD SECTION.

The rocks in the vicinity of Goode Bridge repeat all the essential features described for the Bevil Bridge section. About three-fourths of a mile east from the river horizontal strata appear unconformably overlying the gneiss at an elevation about 200 feet above the river. At the brow of the hill a mottled conglomerate, overlain by sandstone, crops out, dipping gently eastward. Half a mile eastward, along the road near the Zoar crossroads, a gently flexed bed of mottled conglomerate makes its appearance, recalling the post-Newark conglomerate at Midlothian. Immediately north of this locality, where the road running northwest from Zoar crosses a small brook, the gneiss is exposed. The boundary of the Newark is, therefore, here in the same complicated position in which it exists at Bevil Bridge. Faulting is a probable explanation of the relations.

BETWEEN ZOAR AND MOSLEY JUNCTION.

The boundary is not clearly revealed from the vicinity of Zoar northward until the road passing west from Skinquarter is reached. At the distance of about 1½ miles west from this place, the Newark strata are exposed for several hundred feet eastward from the boundary, the position of which can be fixed with approximate certainty.

The contact of the Newark with the gneiss at this point is not seen; but the faulted reddish shales of the basin may be seen dipping westward within a few rods of the boundary. The continuous westward dips as we approach this boundary require us to suppose that a considerable thickness of the Newark beds are thrown down against the gneiss.

For a mile and a half northward from Zoar, the boundary line is believed to lie on the west side of Skinquarter Creek. At a point about 1 mile south-southeast from Clayville, in Powhatan County, the line turns abruptly toward the east, recrossing Skinquarter Creek and holding that course for nearly half a mile, whereupon it again turns northeastward, passing to the east of Mosley Junction station.

The angle south of Mosley Junction.—The abrupt indentation in the outline of the basin which is thus produced about 1½ miles south of Mosley Junction is not represented on the older maps. The extension of the Newark system west of Skinquarter Creek is based upon the occurrence of decomposed sandstones found within the field adjacent to that stream and in line with the westerly strike of the Newark strata on the Irwin Bass place. The contact of the red shales and sandy beds of the Newark with the underlying gneisses at this latter locality, near a barn, is shown in Pl. XXXIII, a photographic view which illustrates the indifferent way in which these two types of rocks weather and erode.

In its general structure, this indentation recalls the Blackheath and Cunliffe basins on the eastern margin. While clear evidence of faulting, either on the western margin beyond Skinquarter Creek or on the east-west line passing through the Bass place, has not been found, it seems probable that faulting may exist on the western side. The question is of some importance, for upon its determination depends the position assigned to the excellent exposures of Newark sandstones, grits, and shales upon the Irwin Bass place, previously described in some detail (see p. 440). As will be seen from Dr. Knowlton's report on the silicified wood of the Richmond Basin, a specimen found in this section is identical with one found in the upper beds. This identity of species does not at present, however, appear to be conclusive as to the identity of horizon. Until faulting can be proved along this east and west line it seems inadmissible to suppose, upon the evidence from a single fragment of a wide-ranging species of tree, that the beds resting here on the gneiss are other than basal sediments.

Boundary fault at Mosley Junction.—In the vicinity of Mosley Junction, there is evidence of a profound fault, for on the south side of the Southern Railway, the Newark sandstones and shales are in a vertical position, striking nearly east and west against the boundary. This structure, so closely associated with the east and west strikes on the Irwin Bass place, together with adjacent tracts in which the Newark appears to lie in a horizontal attitude near the boundary—though it may be downthrown against the gneiss even in this case—points clearly to the sagging of the beds along the western faulted boundary. That synclines of this origin pervade the Newark strata toward the interior of the basin will be brought out in the sequel, the whole evidence strongly confirming the view of a faulted western boundary.

Between the railway exposures at Mosley Junction and the Irwin Bass place, lies the instructive section disclosed whenever the bed of Turkey Branch is swept free of sand. The stratigraphic details of this section are presented elsewhere in this report. It is of importance here to note, however, the two faults which occur in this short section, since they throw light on the method of folding and faulting along the margin and confirm by one additional case the view that the Newark strata may rest locally upon the gneiss west of a fault essentially at the boundary in the existing relation of the Piedmont peneplain to the sediments in the basin. In Turkey Branch of Swift Creek, the Newark beds rest upon the gneisses very much as they do on the eastern border, but at a distance of 650 feet from the boundary the strata having been at this point profoundly folded by compressive movements, were subsequently faulted. This fault is of the reversed type, dipping steeply west. The amount of the throw is not ascertainable. At the distance of 1,400 feet from the boundary, the section is traversed by another fault dipping steeply east, but there seems no way of determining the direction of the throw. The conditions of compression indicated by the first-named fault would point to the existence of a reverse fault here also (see Pl. XXXVIII).

FROM MOSLEY JUNCTION TO THE JAMES RIVER.

Northward from Mosley Junction, the boundary is ill defined. The Newark crops out in the north bank of Swift Creek three-fourths of a mile northwest, or upstream, from the point where the creek crosses the Powhatan-Chesterfield county line.

From Swift Creek to the James River the boundary, except in the vicinity of the river, is not well shown. Widely separated outcrops of gneiss on one hand and sandstones on the other show that it follows the general course of Dutoy (or Dittoway) Creek to its union with Jones Creek. At one or two points in the vicinity of the Old Dominion pits, where the lower coal-bearing rocks are brought to the surface, the strata are in nearly vertical attitudes. Russell's studies of the Norwood tract at the time the mines were opened show clearly the nature of the faulting along this part of the boundary and the disturbances which affect the strata at a distance from it. The fault-block of pre-Newark, crystalline rock which enters the Norwood estate from the northwest in the form of a wedge will be described in connection with the better exposures of the structure on the north side of the river. It is only necessary to note in this connection that the sandstones and shales in the river road on the west side of Jones Creek, resting apparently on the tilted surface of the fault-block mentioned, dip west at an angle of 20° or more toward the main terrane of gneiss beyond.

Enough has already been stated concerning the relation of the Newark to its western border in this basin to make it probable that a very marked downthrow of the strata occurs from the Appomattox River northward to the James. This evidence becomes indubitable and its interpretation as to the manner of faulting plain, when the facts cited by Russell and our own observations concerning the western margin of the basin at Manakin and Boscabel Ferry are given their due weight.

The Cornwallis Hill fault-block.—It is clear, from an examination of the neighboring exposures, that Cornwallis Hill, between Manakin and Boscabel Ferry, is a fault-block of the pre-Newark crystalline rocks, left standing up in the crushed and broken sediments of the Richmond basin. This block wedges out south of the river, disappearing beneath the surface of the Newark beds. It appears to have been tilted westward, the coal shales having been thrown down on its eastern face (see fig. 102, p. 467, and Pl. XXXV).

In the quarry opened on the bank of the James River faults may be seen dipping steeply east in the block (see Pl. XXXIV).

NORTH OF MANAKIN.

North of the river road at Manakin the boundary is traceable by occasional outcrops of the white gneisses and the reddish shales, generally following closely the east side of the Manakintown road. At a few points offsets occur by which the Newark sediments overstep the general line and appear as downthrown blocks in the pre-Newark rocks.

At the elbow in the Manakintown road, 2½ miles north of the village of Manakin the Newark beds may be seen a little east of the highway, dipping eastward into the basin. Small exposures in the old fields north of this locality give similar indications of this attitude of the strata, but there is not enough of the structure shown to enable one to affirm or deny faulting along this portion of the boundary.

Transverse fault block.—From the corner of the Manakintown road and the road running southeastward to Gayton the boundary is deflected sharply westward for about one-third of a mile, forming one of the shoulders above mentioned. This indentation has a north and south extension exceeding 1 mile in length. The supposition that this apparent depression in the now inclined floor of the Richmond basin may be an original valley filled with the Newark sediments is negatived by the fact that on the northern edge of the depression these beds clearly bend down into it, though they lie nearly horizontal in the middle of its

CONTACT OF NEWARK SHALES AND GNEISS ON THE WESTERN BORDER, SOUTH OF MOSLEY JUNCTION. LOOKING WEST.

Shales on left of bush, gneiss on right.

extent. It seems more likely to arise from the settling down of a block of the gneiss between nearly east and west faults, with probably a meridional fault on its western limit, in the manner indicated in the annexed diagram, in which the floor of gneiss is shown without the cover of overlying sediments. At the southeastern corner of this indentation the Newark shales appear to be faulted, but the precise nature of the disturbance can not be made out.

Northern end of the basin.—Northward, to the end of the Richmond basin, the boundary is not clearly revealed. A projection of the gneiss into the basin, mentioned by Russell and shown on his map, can be made out by the distribution of soils derived from the gneiss on one hand and the Newark beds on the other, reinforced by a few outcrops of both groups of rocks. It is probable, as that geologist suggests, that the structural features at Cornwallis Hill are repeated here.

The westward dip of the strata along the Three Chop road, quite up

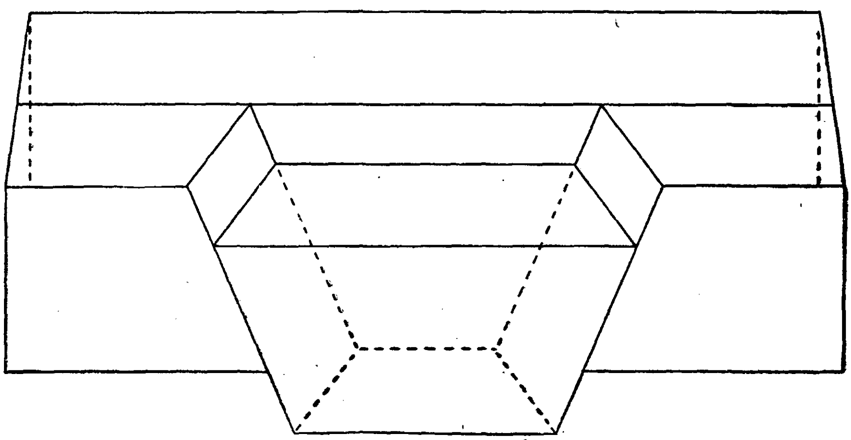


FIG. 101.—Diagram showing supposed system of faults in the gneissic base of the Newark system giving rise to a quadrangular indentation with downflexed strata.

to the gneiss on the western border, is in accordance with the occurrence of a strong fault with a downthrow on the east. The structure of even this narrow portion of the basin is too complex, involving as it does the granitic tongue and the diverse attitude of the strata in the middle of the area, to permit the use of dips in determining the probable amount of throw along the fault at the western border.

From the locality above mentioned to the northernmost point of the basin the structure, as on the eastern border opposite, is not well shown, and the boundary line as mapped may be somewhat out of place.

SUMMARY CONCERNING THE BOUNDARY OF THE BASIN.

From the preceding notes upon the nature and interpretation of the boundary of the Richmond Basin on the east and west it will be seen that a detailed study has confirmed and extended the views of the structure of the basin advanced by Russell[1] in 1885. In general terms, the eastern border is mainly characterized by the horizontal truncation, through base leveling, of a tilted set of terranes, the boundary line marking the appearance at the Piedmont surface of the plane of contact between them. Faults are not wanting, but those which have been detected do not dominate the direction or structure of the beds along this margin. In a very uniform way, the strata dip westward toward the middle of the basin.

The western boundary, on the contrary, is characterized by faults. These faults are more generally oblique to the boundary than parallel with it. Their course is mainly west of north, while the trend of the boundary line is east of north for the major part of the distance. On the southwest the trend of the faults and the boundary is more nearly in accord. Accompanying the numerous faults along this western border is the feature of diverse attitudes assumed by the strata. The strata in some places dip inward away from the margin, and in other localities they dip toward it or lie flat against it, affording by this evidence alone satisfactory proof of the dislocations which occur along this line. The irregular occurrence of the coal beds along the western margin, viewed in the light of the variable structures just mentioned, points to the same conclusion. In addition to this local evidence, there is that derived from the analysis of the dip of the strata over the basin as a whole. Despite the apparently synclinal structure in the James River section and elsewhere south of that region, it is a recognizable fact that there is a westward tilt to the strata in the basin without effectively compensating eastward dips along the western margin. This difference of level between the eastern and western sides of a basin, the strata of which were probably once more nearly horizontal than they now are, can be satisfactorily explained only by the dropping down of the basin step by step along faults or flexures or by heavy faulting on the downthrown side.

Viewed in this way, the Richmond Basin exhibits, in unmistakable characters, the dominant type of structure of the several Newark basins west and south of the Hudson, viz., a westward tilt accomplished by a series of faults arising in the pre-Newark gneissic terrane, with downthrows on the west.

STRUCTURE OF THE INTERIOR OF THE RICHMOND BASIN.

THE AREA NORTH OF THE JAMES RIVER.

JAMES RIVER SECTION.

The structure of the Richmond area on the north side of the James River is roughly synclinal along the river bank, changing to a westward-dipping fault block at the northern narrowed end of the basin. This change may be conceived as having been accomplished by the erosion

[1] Bull. U. S. Geol. Survey No. 85.

FAULTS IN GNEISS AT CORNWALLIS HILL, BOSCABEL. LOOKING NORTH.

of the upturned western margin in the northern part of the field, or, since the floor of the basin rises from the James River to the northern end, the result may be said to have been effected by the denudation of the western flank of the faulted syncline, or "graben," which flank probably originally lay over the western margin. The synclinal structure, so called, finds its best expression in the section exposed along the north bank of the James. In the sense that a syncline is a part of a system of folded strata, however, this cross section deserves another name. It is rather a series of westward-dipping monoclines or flexures extending from the eastern margin westward to a zone of faulted and folded structure, the dip of which is mainly eastward. It is the "flexurgraben" of the German geologists,[1] complicated with faults, which latter structures, owing to the relation of the Piedmont plateau to the depressed sediments, appear mainly as boundary faults.

The great flexures, now much broken, which bring the coal measures up on the margins of the basin may be interpreted as the expression in the soft Newark strata of fractures in the underlying granitic and gneissic terrane. From them we infer a large downsunk block of the

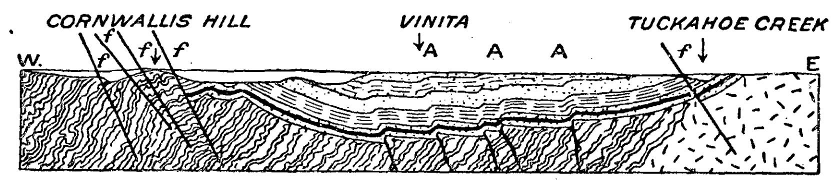


FIG. 102.—Structure of the James River section. A, minor flexures; f, f, faults. The superficial portion of this section is based on observation and reliable information; the deeper portion is hypothetical. The heavy black band represents the supposed position of the coal beds.

pre-Newark terrane. In the middle of the basin this block is traversed by minor fractures, along which it is downthrown to the west. Wherever we see the Newark strata immediately overlying the broken surface of the pre-Newark terrane, as we do along the upturned margins of the basin in the coal-bearing shales, we find abundant evidence of the extension of the fractures into the sediments overlying the crushed granite and gneiss. The fractures frequently die out upward as flexures. It is for this reason that only the greater faults affect the higher-lying sediments found within the central tract of the Richmond area. The faults and flexures are thus related phenomena, expressing, in materials of different resistance to stress, the effects of a common orogenic movement—the fracturing of the buried pre-Newark land mass.

The gradual dropping of the strata in the middle after passing the down-bent eastern margin of the area shows that the deepest part of the basin, on the assumption that the strata are uniformly thick from

[1] De Margerie et Heim: Les dislocations de l'écorce terrestre, Zurich, 1888, pp. 27, 37.

east to west, is near the western margin, at the "lower bend"[1] of the flexure on that side of the basin. The flexures by which this successive lowering of the strata in platforms is accomplished vary in throw and in the dip of the strata involved. The dips vary from 5° to 25° west in the James River bluff. From a rough estimate, based on the scanty data afforded by exposed flexures, it seems highly probable that the western side of the flat tract must be lower than the eastern by an amount equal to the height of the bluff, or about 150 feet.

The faulted structure of the eastern margin was revealed in a small shaft sunk on the western bank of Tuckahoe Creek by Mr. Robert Snead, of Richmond, Virginia. According to his verbal account a shaft was sunk to the depth of 412 feet and a bore hole was put down 75 feet farther. The sole bed of coal was met about 100 feet above the bottom of the shaft. This bed was "6 feet tall"; it was worked upward on the dip, or eastwards toward the surface, until a "trouble", evidently a fault, was encountered. The so-called Scott pit was sunk at the base of the hill, in the valley, on apparently the same layer of coal, until the "trouble" was encountered. Mr. Snead states that "whin rock", the diabase of this field, was found in the dislocation, and that the coal was thrown down on the east side of the fault. The structure at this locality is not perfectly clear.

About 2,000 feet west of Tuckahoe, along the river bluff, horizontal sandstones with shale bands succeed to the inclined strata on the east. On the east side of the stream there is a width of outcrop of inclined beds probably as great as that on the west, making in all less than 4,000 feet. The uncertainty regarding the structure in this belt makes any calculation upon the thickness almost worthless, although an estimate varying between 500 and 1,000 feet would probably include the beds.

About 450 feet west of the exposure of horizontal strata above mentioned a bed of sandstone dips 20° westward, affording an example of one of those flexures which characterize the interior of the Richmond Basin. Gentle westerly dips continue for about 500 feet; thence the strata are nearly flat to the Tuckahoe siding of the Chesapeake and Ohio Railway. From this point westward to Goat Hill, beyond Vinita station, occasional flexures appear in the bank, by which the thick sandstone bands and intercalated shale beds drop down to the west and continue flat at a lower level. There is no appearance of faulting in these minor flexures at the level of the ground.

Between Goat Hill and Cornwallis Hill (the gneissic fault block before alluded to) the coal shales and Estheria beds come to the surface and occupy the western margin of the area. Their softness, dependent on the larger proportion of shale beds and their broken condition, have made them give way to erosion, so that the river valley has widened out in the vicinity of Manakin station, giving local topographic expression to the region they occupy (see Pl. XXXV).

[1] De Margerie et Heim: Dislocations de l'écorce terrestre, p. 26.

CORNWALLIS HILL, LOOKING UP THE JAMES RIVER, ACROSS THE AREA OF TILTED SHALES OF THE WESTERN BORDER.

Upper sandstones in the foreground.

The tilted beds on the western border have a greater breadth of outcrop than those of the same horizon on the eastern margin, for the reason that the strata are repeated by folds and faults. This greater complexity of structure is marked by steeper dips and overthrown folds, which are almost unknown along the eastern margin of the main field.

Near the old brick church at Manakin a fault of a few inches of throw dips 45° east, with a downthrow on the west side. The shales are crumpled along the fault as if by compression. Some additional structures bearing on the type of dislocations in the basin are given below in the matter concerning the details of the strata in this section.

Stratigraphy of the James River section.—The strata in the James River bluff, by far the longest natural section in the basin, are fairly well exposed in the old road passing by the ruined brick stable at Tuckahoe. At this place there is, below, a dark drab argillaceous sandstone, cut by ragged-edged joints into irregular quadrangles (see Pl. XXXVI). Above this comes a coarse granitic sandstone of the arkose type, nearly white in color, but locally marked by gigantic spherical shells of iron-oxide stains surrounding a white center (see Pl. XXXVII). The light color of this stone appears to be the natural color of the granitic sandstones in this basin, as the deep boring at Midlothian goes to show. These iron stains appear to be effects of the weathering of the rocks and the oxidation of the iron which they contain. The concretionary arrangement of the stains shows clearly that the iron oxides have been distributed in this manner since the deposition of the rock. East of the station, in the first ravine on the west of Tuckahoe, Estheria shales crop out in a bed, which is probably between the drab beds and the coarse sandstones above noted. At a few points the thick-bedded sandstones have been quarried to a limited extent.

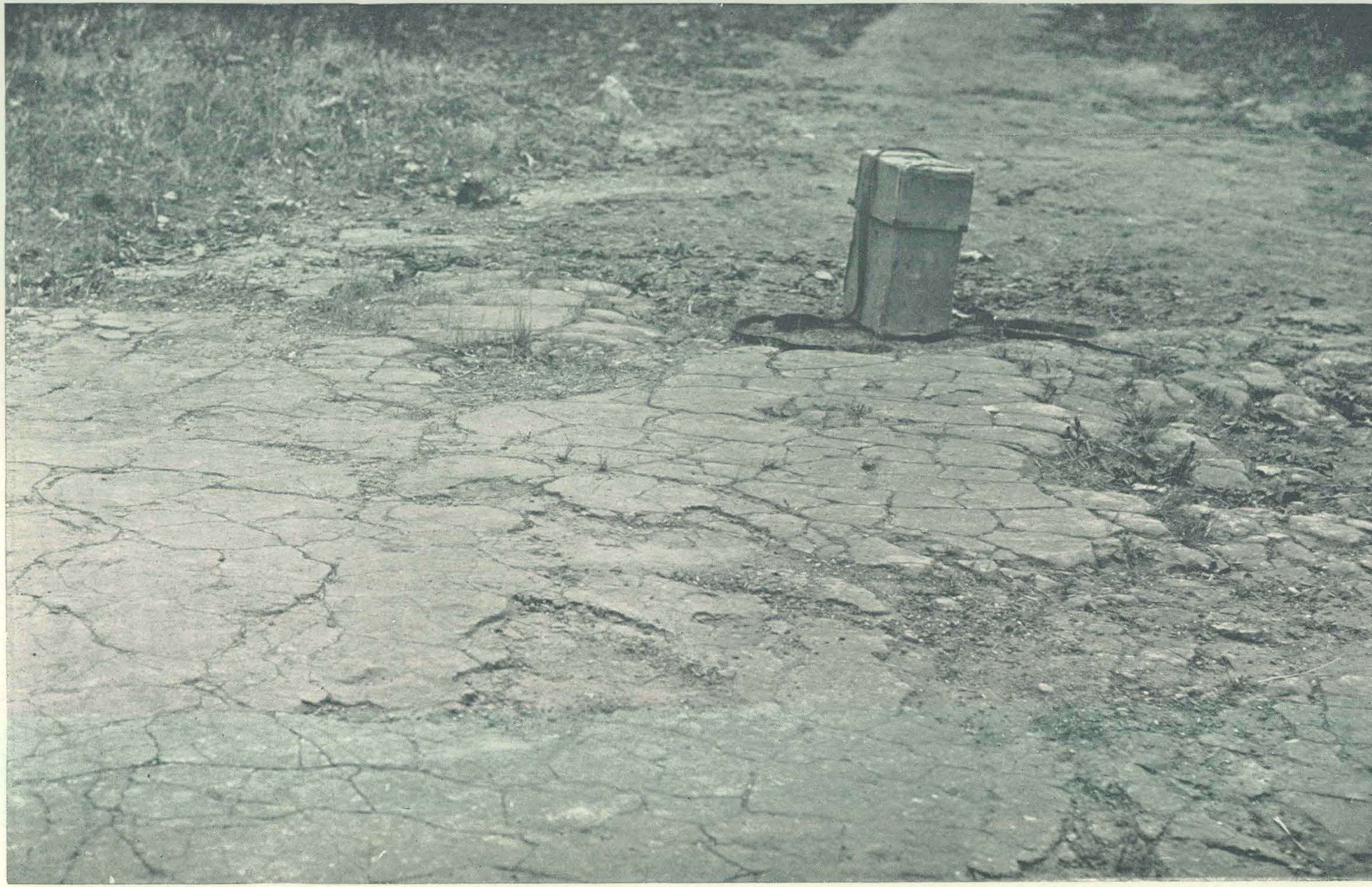
Beneath these strata, at the western base of Goat Hill, sandy shales crop out, with numerous bands of black shales, containing abundant flattened casts of Estheria. While shales predominate, there are a few thick sandstone beds, making small spurs on the river bank. The smudging of the outcrops by the creep of the decomposed shales makes the delineation of the section very uncertain.

A typical exposure of the coal-bearing strata occurs near the western edge of the main basin. The following detailed section was there measured for the purpose of illustrating the type of sedimentation and the structure of a limited portion of the western margin.

Details of a natural section near Manakin, Virginia.—A gully just east of the brook coming down the east side of Cornwallis Hill exposes the following stratigraphic and structural features:

Section in gully near Manakin, Virginia, beginning at the upper (north) end of gully and top of section. Direction of gully, N. 17° W.

Strata.	Thickness.	
	Ft.	*in.*
Shales, sandy	10	0
Shales, reddish	3	0
Sandstone, thin bedded	42	0
Shales, reddish	1	0
Sandstone	3	0
Shales	6	0
Sandstone	3	0
Shales with sandstone partings	6	0
Sandstone, brown at surface	3	0
Shales, reddish purple, with local faulting	3	0
Shales, brown and sandy	3	0
Sandstone	4	0
Shales	1	0
Sandstone	0	8
Shales	0	1
Sandstone	0	6
Shales	0	4
Sandstone	5	0
Shales, reddish purple, carbonaceous in seams	4	0
Sandstone	15	0
Shales, brownish red	3	0
Sandstones with shaly partings	2	0
Sandstone	3	0
Shales, black	6	0
Shales, sandy, laminated, faulted	6	0
Sandstone	3	0
Shales, brown mud at surface	0	2
Shales, black, with Estheria	6	0
Shales, brown, sandy, and slickensided	24	0
Shales, carbonaceous	0	6
Shales, sandy, brown, laminated	5	0
Shales, with joints stained by iron oxide, light brown	1	1
Shales, black, thin-laminated, and carbonaceous, with 1-inch sill of decayed trap. The shale below the sill is concretionary with iron oxide at contact. Ganoid fish scales abundant in upper part of the shale. *Estheria ovata;* small variety, also, present	1	6



RAGGED JOINTS IN ARGILLACEOUS STRATA, TUCKAHOE.

Section in gully near Manakin, Virginia, etc.—Continued.

Strata.	Thickness.	
	Ft.	*in.*
Shales, brown, sandy	0	5
Shales, grayish, with bits of plants and molds of ganoid scales, and blackish concretionary stains	0	3
Shales, brown, sandy	0	6
Shales, carbonaceous, 1 inch to	0	3
Shales, laminated, sandy	5	0
Shales, with ironstone concretions	1	0
Coal, 6 inches to	1	6
Shale, carbonaceous	3	0
Shale, brown, sandy	1	0
Sandstone	1	6
Shale, brown	0	6
Shale, blue, with a 1-inch layer of coal near top	1	0
Sandstone with rolled and broken shale	10+	
Shale, brownish	0	3
Coal, 3 inches to	0	6
Shales, laminated, separated from rocks above by a fault, amount of throw unknown	10	0
Coal, with shale partings, 6 inches to	0	8
Shale, ferruginous	0	8
Coal, 1 inch to	0	2
Shales, mottled	6	0
Coal, shaly	0	6
Shale	7	0
Sandstone	1	0
Shale	1	0
Sandstone, probably	2	0
Shale	0	3
Sandstone, red brown	5	0
Shale, brown	4	0
Sandstone, brown, shaly, 6 inches to	0	8
Shale, grayish	1	0
Shale, dark gray	0	4
Coal	0	2
Shales, brown	1	0
Sandstone, red brown	5	0
Shales, bluish gray, 3 inches to	0	6
Sandstone, gritty, brown	1	6
Sandstone, brown	1	0
Shales, brown, laminated; faulted, downthrow to the east	3	0

Section in gully near Manakin, Virginia, etc.—Continued.

Strata.	Thickness.	
	Ft.	*in.*
Sandstone, fine brown	0	6
Shale, with carbonaceous traces	0	3
Sandstone	2	0
Shales, brown and red	0	2
Sandstones, feldspathic with smoky quartz veins.	0	2
Shales	1	0
Sandstone	3	0
Shales, with carbonaceous layer near top	1	6
Sandstone	2	0
Shale, cut by red-clay(?) dikes	1	0
Sandstone, veined with small smoky quartz crystals and cut by a small fault	1	0
Shale, light-brown	3	0
Sandstone, fine. brown, micaceous	1	0
Shale	0	3
Sandstone, gritty	0	4
Shale, in red and yellow bands	1	6
Sandstone; arkose with smoky quartz crystals; strike of veins N. 38° E. in bottom of bed	2	0
Shale, with thin seams of arkose; 3 inches to	0	4
Sandstone, brown	0	9
Shales, laminated to sandy	1	6
Sandstone, gritty	0	9
Shales, red-brown, sandy	0	6
Sandstone, fine, brown	2	0
Shales, passing upward into next above	0	9
Sandstone, with red pasty dikes, dip 60° W. 1 foot to about	2	0
Shales, fine, sandy	9	0
Sandstone, brown, micaceous, gritty and faulted.	1	0
Shales	0	3
Sandstone, brown, micaceous	0	4
Shales, brown	0	9
Sandstone, fine, with shaly partings	3	0
Shales, sandy	1	0
Coal; strike N. 24° E. A lens from 0 inch to	0	0.5
Shales, with sandstone lenses. The shales weather with red faces. Numerous small slips occur with the downthrow on the east. There are a few minute veins of smoky quartz at base of the bed in an arkose layer	12	0
Sandstone	1	6

LARGE FERRUGINOUS CONCRETIONARY STAINS IN LIGHT-COLORED SANDSTONE, TUCKAHOE.

Section in gully near Manakin, Virginia, etc.—Continued.

Strata.	Thickness.	
	Ft.	*in.*
Shales	0	2
Sandstone	4	0
Shales, coarse, red and brown	1	6
Sandstone, brown	3	0
Shales	0	6
Sandstone	3	0
Sandstone, grit with granitic detritus	0	6
Shales, cut by small faults	0	9
Sandstone	2	0
Shales, sandy and laminated	0	4
Sandstone, brown, micaceous	1	0
Shales, purple with small faults; 1 inch to	0	3
Sandstone, fine, brown	1	0
Shales, mottled red and white		
Sandstone with ferruginous concretions; brown yellow; thickness at least	3	0
Shale, with ferruginous concretions	3	0
Sandstone, strike N. 24° E	1	0
Shales, brown, thickness unknown. The sandstone above named now reappears, bending around the shales so as to strike N. 48° W. The following-named beds are the continuations, in reverse order, of the beds above the shale. These thicknesses are given for the sake of comparison; they should not, of course, be added to the preceding in obtaining a total for the section		
Sandstone, just mentioned	0	6
Shales, brown	2	0
Sandstone, light-brown, micaceous, pinching out from 3 feet to	0	6
Shales, brown; strike N. 41° W., dip 45° S	3	0
Sandstone, brown, micaceous, with concretions at base	8	0
Shales, brownish and micaceous	14	0
Sandstone, vertical	2	3

It is not now ascertainable whether this section lies above or below the main coal horizon on the western margin. It serves, however, to give an idea of the sedimentary conditions along the present western margin during the coal-making time. There was a frequent alternation of sands and muds, with occasional importations of arkose, but pebbles are in this section entirely wanting. The coals are lenticular seams, beginning and ending with shale-making conditions.

THE GAYTON SECTION.

The mines at Gayton (Carbon Hill of the old reports) afford a view of the structure a few hundred feet from the margin on the east. The general structure is essentially unchanged from mine to mine. Exploitation of the ground has shown, however, that the coal beds are not parallel in going from north to south. The coal beds are three in number, the upper workable layers varying from 4 to 9 feet in thickness, including coke. The coal beds are underlain by a considerable thickness of sandstones and arkose beds. The latter beds are shown in the stream east of the mines.

The strata dip westward at the usual angle along the eastern margin. A small fault with a downthrow of a few feet on the east was encountered in the Saunders slope in 1896. The strata probably do not lie flat for any great distance west of the present workings at Gayton. On the western bank of Tuckahoe Creek, at a point about seven-eighths of a mile due west from the mines, the Newark shales dip steeply westward, apparently along the line of a strong flexure or fault, which can be traced from the James River to this point. It is almost inconceivable, when the structure of the basin as a whole is considered, that so marked a disturbance of the strata shown at the present surface should not influence the attitude of the underlying coal measures. If the general conclusion reached in this report—that the displacement in the Newark rocks increases with the depth—be true, the underlying coals at that point should be much disturbed. On the western border, opposite Gayton, sandstones and shales dip eastward, in the manner described in the account of this portion of the boundary, giving to the Gayton section a synclinal aspect.

THREE CHOP ROAD SECTION.

Owing to heavy rains the gullies of this road were, in the month of June, 1897, in a condition to expose a fairly continuous section across the northern extremity of the basin. In September of the same year most of this interesting section was obscured by the shifting of sands and by the repair of the highway. As a whole, the section exhibits westerly dips, with angles varying from 15° to 30°. The occurrence of these westerly dips toward the gneiss of the western border has already been adverted to as sufficient reason for believing that this line is determined by faulting.

Beginning on the east, compound conglomerates, with pebbles of granite and gneiss up to 6 inches in diameter, are scattered through about 100 feet of sandy strata near the base, the actual position of which is not seen. These beds dip from 25° to 30° west. They are succeeded by sandstones and more conglomerates, and it is reported that coal has been found in the vicinity of Coal Hill. At a distance of about 2,000 feet west of the margin sandstones with whitened layers and

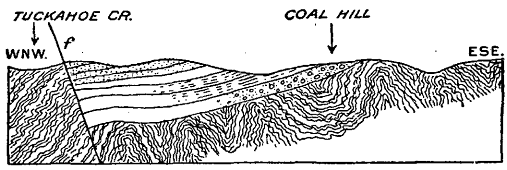


FIG. 103.—The Three Chop road section; f, boundary fault. This section is wholly ideal so far as the structure of the underlying gneiss is concerned. The Newark rocks are made to represent observed structures and strata at surface extended underground.

veins occur, recalling very similar strata which are found west of Winterpock along the roadside at Mantua. Toward the west the dips locally flatten, but return quickly to the western dip. In this portion of the section there is also a limited exposure of quartz pebble beds.

THE AREA SOUTH OF THE JAMES RIVER.

The southern bank of the James is more gentle and sloping than the northern wall, and fewer opportunities are offered for the examination of the attitude of the strata. Enough is shown, however, to warrant the statement that the same beds which appear in the bluff in Goochland County cross the river without faulting or disturbance marking the site of the river. The fact that the coal beds have been followed beneath the river in the Burfoot tract on the eastern margin is sufficient evidence of the continuity of the coals in that direction on a line with those of the northern side of the river.

The principal available lines for sections in this area are as follows:

1. Through Midlothian, along the line of the Buckingham turnpike.
2. Through Otterdale, in the Swift Creek region, following the Genito road.
3. Through Winterpock (Clover Hill of the old reports), across the area to the vicinity of Goode Bridge.

GEOLOGIC SECTION THROUGH MIDLOTHIAN ALONG THE TURNPIKE.

A geologic section constructed upon the data afforded by the natural exposures within a mile or two north and south of the turnpike passing through Midlothian, while it must fall short of certainty as regards the depth of the basin and the thickness and number of the strata, can not fail to throw some helpful light on the general geologic structure of the region, particularly since no attempt has heretofore been made to represent the surface aspect of the bed rocks along this line. Only the extreme eastern and western portions of this line are at present definitely known by explorations in mines or drill holes.

According to the best evidence now obtainable from the old workings, i. e., the published writings of Heinrich and Clifford and the small visible outcrops in the vicinity of Midlothian, the general section is in that part of the field essentially as represented in the accompanying diagram (fig. 104).

The attitude of the beds in the detached basins near Midlothian may reasonably be explained in accordance with Russell's suggestion by the faulting and dragging of the strata on the fault planes. If we conceive of these faults as arising in the granitic basement, and of the overlying strata as flexing and stretching over the uplifted areas in the granitic floor, some of the peculiarities of the strata as the beds now exist may be better understood. Russell supposes that the beds in these detached areas rest in original sedimentation contact on the tilted granite on their eastern margin, are cut off by eastward-dipping faults

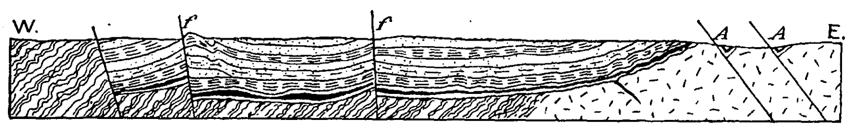


FIG. 104.—Section through Midlothian, showing, A, A, outlying basins and the main coal measures; f f, places of observed faults. The deeper parts of this section are hypothetical. The heavy black band represents the supposed position of the coal beds.

along their western margins, and that the drag in these faults has thrown the beds up so that there is a double line of outcrop of the coal in each basin.

From what can be learned of the general structure of the coal measures along this border of the field and of the surface of the granitic floor, faulting in the basement rocks has taken place so as to produce heaved and downthrown blocks or "horsts" and "graben," respectively. The soft shales and coals have thickened in the flexure graben or depressed areas, and the same layers have thinned out over the horsts or upheaved areas. Thus, while faulting may have actually broken the rigid granitic base, the overlying sediments may have simply yielded interstitially or by the slipping of the comminuted beds. The slickensided shales afford evidence of this creeping movement.

This modification of Russell's view makes it possible to account for the excessive drag on the western margin of these detached basins. The general structure of the Blackheath and Cunliffe basins thus conforms with the flexure type as above explained.

In the main basin the strata exposed at the surface dip strongly westward as far as the vicinity of the Midlothian railway station. The average dip is about 25°. At this point the beds flatten and a small broad anticline appears in the railroad cut. This structure appears to have a north-and-south axis. The so-called "Sinking shaft," the most western of the shafts and bore holes on the south side of the turnpike in Midlothian, was probably sunk upon the axis of this uplift.

The Salisbury drill hole.—The section obtained in a boring on the Salisbury property revealed an alternation of sandstone of the arkose type, generally gray in color, with shales. Beginning with nearly horizontal strata at the surface, the drill at a depth of 900 feet passed through beds with a marked westerly dip, which increased rather than diminished toward the bottom of the drill hole. Boring was stopped in shales underlying a bed of coke at a depth of 2,380 feet. The coke is traversed by a gray decomposed dike and one of apparently fresh diabase of later date. The basal granite was not reached.

The structure of the middle of the basin, where traversed by this section, is best shown on the south side of the line in the cuts of the Southern Railway between Dry Bridge and Hallsboro. Near Dry Bridge the steep western dips of the eastern margin reappear, disprov-

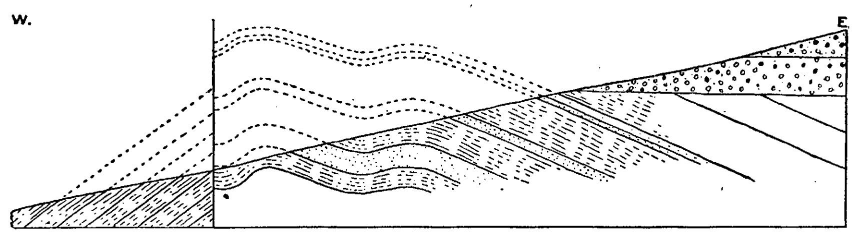


FIG. 105.—Section of beds on west slope of High Hill. The conglomerate above the folded Newark beds is the supposed Lafayette. The surface exposures along this line west of High Hill show mainly westerly dips.

ing the belief that the middle of the basin is relatively flat throughout, with less disturbance than on the margin. A dike of diabase 20 feet wide traverses this section on a north-northwest course. North of the turnpike, in Manakintown Creek, the Newark beds lie in a less disturbed position. On the Le Prade place, a washout in the turnpike exposes beds dipping 25° west, cut off by a fault from strata on the east lying at a less angle. The amount of throw on this fault has not been determined.

Farther west, in Powhatan County, the Newark strata are exposed on the sides of High Hill, a prominence traversed by the turnpike. The eastern slope of this hill exhibits brownish and light-colored sandstone beds thrown into contortions which are not readily diagnosed. The dips vary from vertical to horizontal, broad stretches of outcrop dipping from 45° to 30° west. The High Hill dislocations are in line with the Cornwallis Hill fault block.

On the west slope of this hill the section is composed of sandstone and shales. These beds are thrown into gentle folds (see fig. 105).

THE SWIFT CREEK DISTRICT.

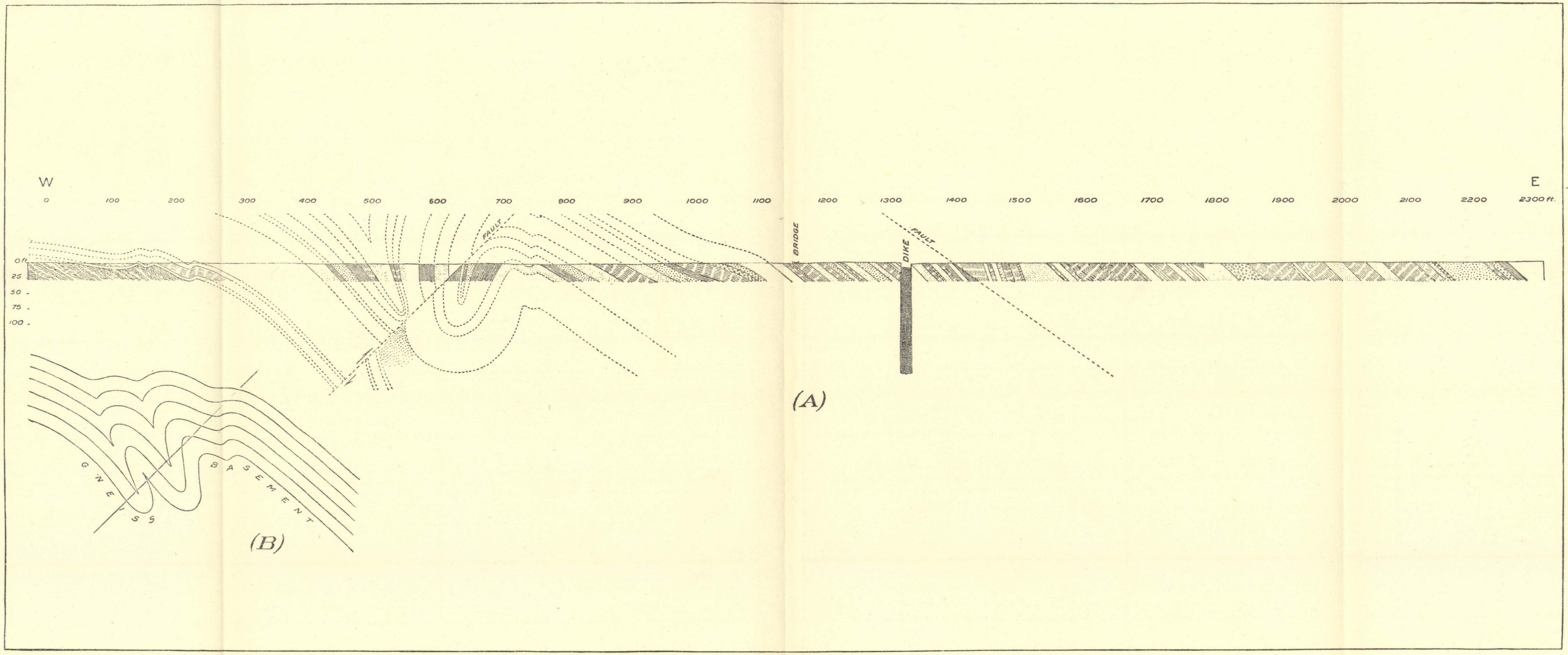
Throughout this region, the broadest part of the Richmond area, there is a marked departure of the strata from the horizontal attitude. Following the Genito road into the area from the eastern border the strata at the surface show westward inclinations, varying from 30° near the margin to angles of from 5° to 10° at a distance of 2 miles. On the west bank of Swift Creek the strata are almost flat, but the same beds traced around the bank of the creek to the westward assume a high dip to the southwest. Swift Creek appears to have sought out soft strata thus turned up by a fold or a fault.

About 2 miles west of Otterdale, northeast and southwest strikes, with easterly dips, appear, and this structure continues to within a mile and a half of the western border, where the strikes becomes more nearly north and south.

Section on the Turkey Branch of Swift Creek.—One of the most complete natural exposures of the lower members of the Newark group in the Richmond Basin occurs on the western margin, near Mosley Junction, in the headwaters of Turkey Branch of Swift Creek (see Pl. XXXVIII). In the summer of 1896 heavy rains had washed down the sand in the bed of this stream, so that the bottom was unusually free from detritus, and the following section, giving a record of over 1,000 feet in thickness of strata from the base up, was observed:

Turkey Branch section. (In descending order.)

Strata.	Exposures (measured).	Thickness (computed).
	Feet.	*Feet.*
Clay, sandy, dip 45° E	15	10.60
Conglomerate	12	8.48
Clay, white	8	5.65
Sandstone, pebbly, dip steep east	72	50.90
Conglomerate	5	3.53
Sandstone, coarse, gray	8	5.65
Shale, green	16	11.31
Shale, red with green streaks, dip 90°	48	33.93
Sandstone	20	14.14
Shales, green	32	22.62
Sandstone, pebbly near top, dip 45° E	27	19.08
Shales, green and red	38	26.86
Shales, sandy, red and green	5	3.53
Conglomerate, with quartz pebbles from 3 to 5 inches long	6	4.24
Shale, red	36	25.45
Shale, green	20	14.14
Conglomerate, dip 45° E	36	25.45



GEOLOGIC SECTION IN TURKEY BRANCH OF SWIFT CREEK.

A, Section of Richmond Basin exposed in Turkey Branch; *B*, Theoretical form of Turkey Branch fold before faulting.

Turkey Branch section. (In descending order)—Continued.

Strata.	Exposures (measured).	Thickness (computed).
	Feet.	*Feet.*
Sandstone	30	21.21
Sandstone, with cross bedding or local unconformity at east end of an 18-foot bed; overlying the pebbly sands, dip 15° E, and the underlying layers are nearly vertical, indicating probably an overthrust. (See Pl. XXXVIII, station 1,800.)		
This exposure extends in the creek	18	12.72
No exposures	6	4.24
Sandstone, pebbly	6	4.24
Clay, greenish	9	6.36
Sandstone, fine-grained, dip about 45° E	15	10.60
Clay, sandy, light greenish to brown	18	12.72
Sandstone, brown	6	4.24
Clay, greenish	1	.70
Sandstone	2	1.41
Clay, green	6	4.24
Sandstone, dip 45° E	18	12.72
Shales, green, dip 60° or more E	3	2.12
Shales, red and brown	44	31.10
Sandstone	6	4.24
Shales, red, dip 45° E	50	35.35
Clay, light green	8	5.65
Sandstone, with pebbly bands	15	10.60
Clay, red and green	6	4.24
Sandstone, dip 45° E	41	28.98
Shales, bituminous, 6 inches thick, with Shales, light-colored, 12 inches	1.5	1.06
Sandstone, dip 70° E	4	3.76
Shale, greenish	10	9.40
Shale, red	15	14.10
Sandstone, greenish, dip 80° E	4	3.92
Sandstone, brown	10	9.40
Shales, greenish	8	7.52
Sandstone	6	5.64
Shale, red and green, dip about 70° E	37	34.78
Sandstone	6	5.64
Shale, red	2	1.73
Shale, green	2	1.73
Shale, red	3	2.59
(Here a fault, dip 60° E, cutting out this red shale bed. See section, Pl. XXXVIII, at station 1,400.)		

Turkey Branch section. (In descending order)—Continued.

Strata.	Exposures (measured).	Thickness (computed).
	Feet.	*Feet.*
Sandstone	10	8.66
Shale, red	6	4.24
Clay, green	7	5.65
Sandstone, containing a local seam of coal one-half inch thick	12	8.48
Conglomerate	4	2.82
Shale, brown and green, exposed on south bank facing the trap on north bank	5	3.53
Sandstone	12	8.48
Diabase dike, exposed in branch; at locality 1,300.		
Sandstone, brown and soft	5	3.53
Sandstone, fine red	9	6.36
Sandstone (?), brown and soft	3	2.12
Sandstone, dip 55° E	4	3.27
Shales	14	9.89
Sandstone, 35° E	12	6.88
Conglomerate, with quartz pebbles 3 inches long	18	12.72
Sandstone, gritty	18	12.72
Turkey branch diabase dike exposed here; dike 12 feet wide, nearly vertical, with ball weathering; strikes N. 87° E., and is partly excavated by the stream.		
Clay, green, 35° E	6	4.24
Grit	3	2.12
Clay, light-green, dip 45° E	2	1.41
Sandstone	4	2.82
Clay, light-green	3	2.12
Conglomerate, with quartz pebbles	9	6.36
Clay, greenish and reddish	11	7.77
Sandstone, greenish-brown, dip 50° E	18	12.72
Shales, red and green, under bridge, dip 45° E., strike NNE	24	16.96
Sandstone	....	4.00
Shales, red	....	10.00
No exposures for about 80 feet, equivalent to (?)	....	40.00
Sandstone, gritty, dip 15° E	16	4.14
Conglomerate, fine	14	3.62
Clay or light-colored fine sand	4	1.03
Clay, sandy and pebbly	3	.87
Clay, light-colored	16	4.14
No exposure, but probably clay	18	6.19

Turkey Branch section. (In descending order)—Continued.

Strata.	Exposures (measured).	Thickness (computed).
	Feet.	*Feet.*
Clays, light-colored	15	6.34
Sandstones, brown	18	9.00
Sandstone, coarse, gritty, light-brown	27	15.49
Sandstone, fine brown, dip 40° E	33	21.54
Clays, light-colored, dip 40° E.; strike N. 12° E	25	16.40
Sandstone, slate-green color	5	3.28
Sandstone, bed C, coarse brown, marked by small fall in bed of stream; joints, N. 32° E., N. 35° E., N. 37° E., a few scattered pebbles up to 2 inches in diameter	27	6.99
Clay, bed B, light-green, with sand partings, dip 15° E	13	3.36
Sandstone, bed A, brown; anticlinal exposure, base not seen	9	(?)
Clay, bed B, slate-colored, top not seen, synclinal exposure	16	(?)
Sandstone, bed A; fine brown; anticlinal exposure, low and flat fold; the bed here carries nodules up to 6 inches in diameter. The bed is overlain in the bank of the brook by the light-green clay, bed B	51	(?)
Clays, bed B, with sand partings, dip 25° W	40	19.03
Sandstone, bed C, coarse brown, dip 30° W	9	4.50
Shale, red, bed D, dip 60° W	4	3.00
Sandstone, bed C, brown	3	3.00
(For a fault at this point see Pl. XXXVIII, locality 700, and fig. B, restoration of folds before overthrusting occurred.)		
Clay, brownish-green, bed B, partly cut out by fault on south side of brook, but from 10 to 12 feet thick in north bank	12	10.00
Sandstone, varying from fine to coarse pebbly near contact with clay	23	....
Clay, bed B, light-green, dip 90°, 20 feet	....	20.00
Unexposed; probably clay, becoming sandy, near next	....	24.00
Shales, bed D, red, intersected by greenish walled joints, dip vertical	8	8.00
Clays, light-colored, sandy and pebbly, with bands of light-green clay	7	....
Sandstone, brownish and greenish	33	....
Clays	15	....
Shales, red and green, dip 60° E	3	....

Turkey Branch section. (*In descending order*)—Continued.

Strata.	Exposures (measured).	Thickness (computed).
	Feet.	*Feet.*
Clays interstratified with red shales	16	....
Sandstone, bed C, coarse brown	22	....
Clays, light-green, wedging out at north bank	25	....
Sandstone, bed A, fine brown, dip 45° E., strike N. 2° E	32	....
Unexposed, but probably clays	80	....
Clays, bed C, unsatisfactory exposures, whitish beds with quartz pebbles	85	....
Sandstones, bed B, anticlinal exposure	13	....
Clays, bed C	10	....
Sandstones, bed B; anticlinal exposure	20	....
Clays, bed C, dip 10° E	30	....
Sandstone, bed B; low, flat anticline, tops not seen	6	
Clays, bed C, top not seen	20	....
Sandstone, bed B; low, flat anticline, with schist breccia	30	....
Clays, bed C, dipping gently E., with quartz pebbles	4	....
Unexposed, probably some white clays with the sandstone, bed B	60	....
Pre-Newark gneisses; surface dipping gently E	....	....

Such was the exceptionally complete section of strata exposed in this creek in 1896. In 1897 the shifting of the sands downstream had concealed the greater part of the outcrops.

There is, as will be seen by a study of the table, an alternation of clays, sands, and conglomerates, the texture of the beds generally increasing in coarseness toward the upper portion of the section. There is, strictly speaking, no basal conglomerate. In its place we find light-colored clays with a few scattered quartz pebbles and a single layer of brecciated gneiss.

The colors at the base, mainly those of rocks bleached of their iron contents, show an association of red and green shales, with brown sandstones. The thickness of the individual beds increases toward the top of the section.

The absence of coal in this section is evidence against the view that the coal beds extend everywhere under the basin. Their failure to appear on the western margin in Turkey Branch can not here be due to faulting, unless they have been entirely cut out in the part of the section which is traversed by the eastern fault. The western fault appears to be bridged by the strata, as shown in Pl. XXXVIII, and no coals there occur. It is possible that some coal may occur in that part of the section near the base in which rock is not exposed in Turkey Branch. In Pl. XXXVIII, *B*, the relations of the contorted strata to the fault are worked out in the diagram. It is thought that movements in the underlying gneiss first produced folds in the overlying strata; then faulting took place in the lower zone so as to cut sharply through the folded rocks above.

THE WINTERPOCK SECTION.

The Clover Hill mines repeat the essential features of the more northern sections of the eastern border. Here are exhibited, perhaps better than elsewhere, the phenomena known as "rolls," by which the coals locally disappear by the arching up of the floor. These structures extend nearly parallel with the border and are undoubtedly associated with the monoclinal attitude of the strata. The beds generally dip westward at an angle of about 25°. The approach to one of the ridges above noted in the floor of a slope or incline is indicated by the lessening of the dip, which may become horizontal, giving way in a few yards to an inclination back toward the east. These flat stretches of strata have frequently led to the belief that the horizontal bedding of the middle of the basin had been reached. Experience in the Clover Hill mines has shown that driving through these ridges on the same inclined plane as the coal on the "rise" brings the miner again into the coal on the western side of the fold.

In some of the mines in the Midlothian district granite has been encountered in these pinches. It is probably the case that most of these arches are due to the A-shaped horsts or uplifted blocks of the faulted basement rocks.

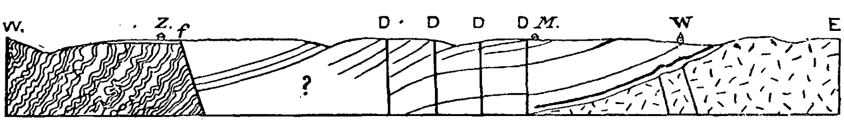


FIG. 106.—The Winterpock section. D, D, dikes of diabase; f, western fault; W, Winterpock; M, Mantua; Z, Zoar.

The strata are not well exposed between Winterpock and the Mantua estate, where weathered sandstones, red shales, and whitish clays are found in a nearly horizontal position. On the western margin of this estate westerly dips set in; and, so far as observations go, alternating strata of sandstone, for the most part brown and red shales, continue to the western border, where the flat beds described in the account of the boundary appear resting horizontally for a short distance on the gneiss. The greatest uncertainty must exist concerning the depth and thickness of the strata in this part of the field until it is examined by means of the diamond drill. The section given in fig. 106 is merely intended to show the attitude of the beds as exposed on the surface.

In the area south of that above noted there are too few outcrops to afford a satisfactory idea of the succession of strata. The data obtained from roadsides and streams indicate westerly dips. A noteworthy ledge of sandy conglomerate occurs south of the Bevil Bridge road, on the Blankinship estate, east of Cedar Creek. The beds of this rock ridge, which is covered with a luxuriant growth of the creeping cactus or prickly pear (Opuntia) of the eastern United States, have a marked westerly dip.

AREAS OF SPECIAL STRUCTURE.

An examination of the scanty surface exposures of the strata in the Richmond basin is sufficient to show that the strata lie in diverse attitudes in different parts of the area. In general it may be stated that the northern and southern ends of the basin have a monoclinal structure, with mainly westerly dips.

The central part of the area south of the Midlothian turnpike, in the drainage area of Swift Creek, shows a roughly outlined system of transverse folds, the axes of which lie athwart the general direction of the basin. A broad synclinal area or trough is marked out by these dips between the Genito road and the Southern Railway and west of Otterdale. A rude arch of the strata is less satisfactorily indicated on the south side of this structure. Throughout this region northeast and northwest strikes occur, often in such juxtaposition as to call for faulting as a feasible explanation of the discordant structures.

There is a roughly indicated synclinal area south of the James River, between Bernard Creek and the eastern border. Along the eastern border the dips are quite uniformly westward toward the center of the basin. Dips in this direction have been observed nearly 1 mile west of the boundary, indicating the general width of the upturned border rocks. In the drainage region of Bernard's Creek and its tributaries, on the east of the main stream, an area lying in the middle of the basin, the observed dips are eastward and southeastward at low angles. In Michaux Branch dips as high as 30° may be seen. On the "river road," where, going westward, it descends the south bank of the James River Valley, horizontal sandstones and Estheria-bearing shales occur in the axial area of the trough thus structurally outlined. It is to be suspected from the structures observed at Midlothian that minor flexures of the strata are also to be found within this shallow syncline.

West of the westernmost exposures thus defined the strata lie nearly horizontal. A notable example of this series may be seen on the western bank of Bernard's Creek, at the river-road crossing, where sandstones overlie one of the Newark conglomerates.

Between the synclinal trough thus outlined and the western boundary of the basin, observations upon the attitude of the strata are limited to a few exposures along the south bank of the James River and to the old mines. The diverse structure of the western border has in general an eastward dip. Between these structures and the outcrops marking the western side of the trough above outlined a few westerly dips may be seen, enough to indicate the existence of a low anticline near the middle of the basin.

Between Hallsboro and Mosley Junction the Newark sandstones and shales strike northeast and southwest, and dip from southeast near the former place to vertical dips near the western border. This structure points to a downthrown or downfolded area south of the Southern Railway. Southeasterly dips occur as far south as near the junction of the Genito road and Otter Branch. This belt of southeastward dipping strata flanks the broad central tract in which the Otterdale sandstones occur.

In the area between the upper part of Deep Creek and Horsepen Branch mainly easterly dips occur. Contrary dips indicative of numerous small folds or faults succeed to the south and east. Owing to the imperfection of the exposures it can not be stated definitely whether these structures pertain to folds or faults.

FAULTS IN THE INTERIOR OF THE RICHMOND AREA.

It has already been shown, in the account of the boundaries of this area, that abundant evidence of faulting is to be seen from point to point on both its eastern and its western side. Where these faults appear in the Newark rocks they, in many cases, affect the lower parts of the section only.

The apparent horizontality of the broad area of strata in the central

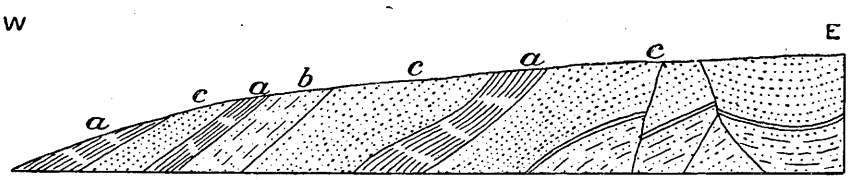


FIG. 107.—Fault on the Le Prade place, Buckingham turnpike, 1½ miles north of Dry Bridge, Chesterfield County, Virginia. *a a*, slate-colored clays; *b*, reddish sandy clays; *c c*, sandstones.

part of the basin and the lack of knowledge concerning faults in that part of the field has for a long time led to the hope that not only the upper part of this great central section, but also the lower and basal beds in that field would prove on further examination free from those faults and disturbances which are so manifest on the margins. The present survey, while it has confirmed the view of maximum tilting and faulting of the strata along the borders of the Richmond area, has found evidence that the middle of the basin is not without faults, and has led the writers to the opinion that the lower parts of the strata are more disturbed than the upper beds.

The indications of faulting in the interior of the area are of different values. These values may be expressed as demonstrable, probable, and possible evidences of faults.

Demonstrable or visible faults have been seen at the following localities remote from the margin of the basin: On the Le Prade place, at a point 5 miles west of the eastern margin, a fault crosses the Buckingham turnpike, its presence being disclosed by a washout in the road at that place. The structure of the Newark beds at this locality is as represented in fig. 107.

The amount of throw on this fault is indeterminable, but is probably small, as the beds are not dissimilar on the opposite sides of the plane of rupture. The attitudes of the beds on the sides of the break are, however, diverse, as is indicated in the diagram. The direction of the fault, as nearly as it could be ascertained from the limited exposure, is west of north, the strike of the tilted strata being N. 13° W. The extension of this fault would carry the dislocation into the Cornwallis Hill fault block on the western margin. Its extension in the opposite direction would intersect the strata in the Dry Bridge railroad cut (see Pl. XXXIX). A small fault observed there west of the road bridge shows that this is a line of disturbance. Another small fault may be detected in the roadside on the western slope of High Hill, in Powhatan County (see fig 105, p. 477).

Probable faults affecting the interior of the area are indicated by the marginal structures. The absence of hard and resistant masses of rock at the present surface within the basin and the deep weathering of the strata render the recognition of faults well-nigh impossible. The work of Davis and his assistants in the Connecticut area has shown that the faults which produce jogs in the boundary line of one of these Newark areas may traverse the interior sections. Faulting is strongly indicated in the angularity of the boundary in the vicinity of the Appomattox River. Some of these northwest and southeast faults may appear in the section, though an examination of the long Skinquarter dike has shown us no measurable offsets.

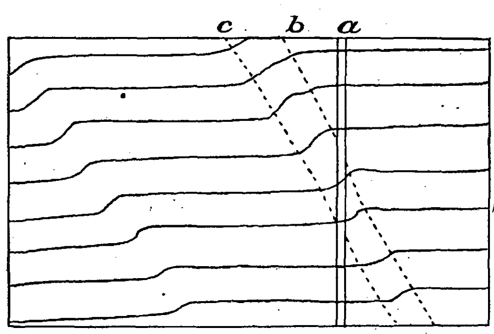


FIG. 108.—Diagram showing drill hole (*a*), intersecting a flexure with inclined axial planes *b*, *c*, of upper and lower bends.

Possible faults in the lower part of the section are marked by the flexures which appear in the uppermost layers. The argument for this association of flexures with faults has already been advanced in the discussion of the James River section and of the small detached basins which margin the main area. From all that can be learned in the examination of this basin by ourselves, and from the reports of others, it appears highly probable that these flexures pass into faults as one approaches the granitic or gneissic floor. These faults would have great displacement near and in the basement, dying out downward like the flexures in the upper sections.

WESTWARD-DIPPING NEWARK SANDSTONES AND SHALES, SHOWING CROSS BEDDING AND SMALL FAULTS, SOUTHERN RAILWAY CUT AT DRY BRIDGE. LOOKING NORTH.

It has been noted in the two borings made in the area during the progress of our investigations that there is a marked change of inclination of the strata from low angles or even horizontality near the surface to higher angles at a considerable depth below. Passing still deeper the strata return to a gentle dip. In the boring at Salisbury fragments of core were so brought up by the drill as to show the westward direction of the dip. This phenomenon of alternating high and low dips is, it is believed, a natural consequence of the development of flexures in the section, the axial planes of which are inclined. Thus in the annexed diagram (fig. 108) the lines *a* may be supposed to represent a drill hole sunk through flexed beds; *b* and *c* are respectively the axial planes of the upper and lower bends of a flexure. As a consequence of the inclination of the planes of the flexure the vertical hole *a* passes through beds at high inclinations lying between gently inclined or flat strata. More than one such alternation may be encountered in a deep section.

OUTLYING BASINS.

Along the eastern margin of the Richmond area are several outliers of the Newark strata, of which those near Midlothian and the so-called Deep Run area are coal bearing. Owing to the removal of much of the coal from these areas in former days, they are not now open to examination. That these basins are due to deformation of the underlying granitic terrane by faulting, and perhaps to movements in the granite which are locally expressed by folds in the overlying sediments, seems highly probable. In a general way these basins may be regarded as showing the nature of the granitic floor beneath the basin as a whole. The disturbance of the Newark strata would be at a maximum on the broken granitic and gneissic basement, with faults dying out upward in the central part of the basin in the form of flexures, or disappearing altogether where the throw is small, by the accommodation of the strata in a section from 2,000 to 3,000 feet thick. If this view of the area be accepted, it is probable that drilling in the middle of the basin would reveal greater diversity in the attitude of the beds as the depth increased, and so the depth of the coal beds might vary greatly within short distances. Thus the Blackheath basin is about a quarter of a mile wide, with coal on its two sides sinking to a depth of 800 feet in the middle.

The following notes relate to the areas nearest the main basin.

THE BLACKHEATH TRACT.

Famous in the early mining history of the Richmond coal field is the small area on the eastern margin lying mainly on the north of the line of the Southern Railway (see Pl. XXV). This area appears from the statement of old miners and from such information as can be gleaned at the present time from the materials about old pits to have contained two rather distinct troughs of coal, an eastern one known as the Blackheath Basin, and another one, known as the Cunliffe, lying between this and the main basin.

The Blackheath Basin, so far as is indicated by the outcrop of the coal, is of oval form, elongated in a north-and-south direction, and extends a short distance south of the tracks of the Southern Railway. At its northern end lies the old Bingley slope (see Pl. XL), worked during the civil war by the government of the Confederate States. The coal seam here is thick, locally approaching 40 feet, but thinning southward, being at the railroad not more perhaps than 18 inches thick. Up to as late as 1897 individual miners took out coal from the upper pillars of the old workings. This coal found a market in Richmond. Beneath the upper thick seam of coal there is another bed, reported to be about 2½ feet thick.

The so-called Cunliffe Basin, so far as the outcrop of coal is concerned, appears to be a small trough elongated in an east and west direction. The "Grapevine shaft" was sunk on the western outcrop of this basin. It is not known whether the granite was met between this basin and the areas to the east and west of it. The evidence on the ground appears to indicate that the Newark strata are let down in the area north of the Southern Railway in the manner indicated on the geologic map (see Pls. XXVI and XXXI). This view is favored by the fact that coal has been found just west of Fall Creek, near the railroad embankment, outside of the recognized basins.

The synclinal structure of the Blackheath and Cunliffe Basin shows that flexing of the coal measures over the underlying broken granitic base has taken place.

THE UNION PITS AND STONEHENGE TRACTS.

East of the main basin at Midlothian and south of the turnpike are two outliers of the coal measures well known in the mining history of this district. The eastern one is traversed by Falling Creek. Its north and south length is probably half a mile, but its southern limits are hidden in the alluvium of the creek. In this area are the Union pits. The view shown in Pl. XLI was taken looking north, on the east side of Falling Creek, showing the sandstone and coal-bearing shales below the main coal seams. The shales decompose and run down over the outcrop, forming a mud crust upon them. The steep westerly dip is much higher than is the general rule along the eastern margin. A seam of coal about 4 inches thick is exposed near the point indicated on the picture by the geological hammer.

A shallow pit sunk through the sandstones a few yards south of the first locality revealed a fault striking east and west and dipping about 30° south. Such cross-faults probably also occur at the ends of these small basins (see Pl. XLII).

Between the Union pits and the main basin lies the northern end of a coal-bearing tract, probably 1 mile long. Its boundaries are somewhat uncertain, but it is evidently separated from the main basin by

COAL BED OF THE BINGLEY SLOPE IN THE BLACKHEATH DISTRICT. LOOKING NORTH.

Coal is exposed overlain unconformably (as shown in the upper left-hand corner) by the Lafayette pebble bed and yellow clays.

the granite, which has a breadth of exposure of about 2,000 feet, as mentioned by Russell.

These basins have evidently, as pointed out by Russell and others, been let down by faulting along their western margins and cut by east-west faults at one or both ends in the manner above indicated. The purely diagrammatic conception of the structure which is gained from an examination of the ground and a review of the literature is shown in the accompanying figure (fig. 109). The only apparent objection to the faulting hypothesis is the attitude of the beds on the drag side of the fault, by which the double line of outcrop is produced. It is permissible, in view of the structures encountered in the mines in the main basin, to conceive of the fault proper as limited to the granitic terrane and of the drag in the coal measures as being due to the flexure of the strata over the uplifted edge of the base of the section. The thinning of the beds in this situation is just what would be expected in a flexure.

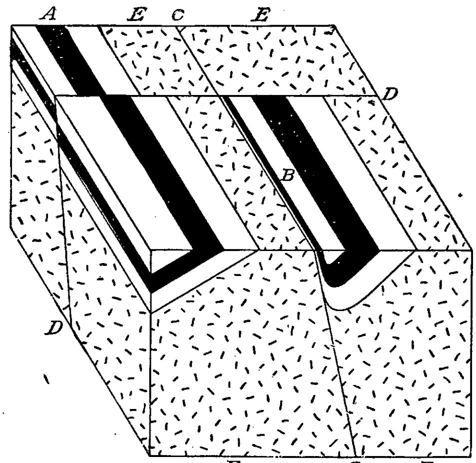


Fig. 109.—Hypothetical structure of one of the detached basins on the eastern margin of the Richmond area. *A*, the coal measures in the main basin, dipping west; *B*, a detached basin; *CC*, fault on the western margin of detached basin; *D*, dip faults, cutting off ends of the detached basins; *EEE*, granitic pre-Newark terrane.

THE FLAT BRANCH AREA.

Between the southern end of the Springfield area (the Deep Run Basin of recent reports, see Pl. XLIII, by Clifford) and the main Richmond area lies the shallow valley of Flat Branch, a stream flowing almost due south into Deep Run at an average distance of 1 mile from the eastern margin of the main coal-field. In the bottom of this valley, both north and south of the Quiocassin road, and particularly along the side of that road for a distance of 300 feet in either direction, inclined strata may be seen, which recall the neighboring Mesozoic beds. On the west side of the stream shales and granitic sandstones dip gently east, while on the east side, about 300 feet beyond the little church, are pebbly arkose deposits dipping 15° to the west, along with beds whose decomposed surface aspect is that of clay. The syncline thus plainly indicated is the only evidence directly obtainable concerning the structure of this small area.

About half a mile north of the Quiocassin road sandstones and shales, dipping westward, crop out along the eastern margin of this area. A shallow pit sunk in the beds failed to reach deposits of coal.

West of this locality granitic sandstones occur in the stream bed. The area has a maximum width of perhaps half a mile and a length north and south of three-fourths of a mile, being continued south of the road above named, where pits have been sunk in the search for coal. Whether or not this area connects southwestward with the main basin can not well be determined on account of alluvium.

On Major Hotchkiss's Geological Map of Virginia and West Virginia[1] the Deep Run Basin (see Clifford's map, Pl. XLIII) is mapped as continuous through this tract, or near its site, into the main basin. Daddow's[2] map carried the Springfield area southwestward nearly to the place of the Flat Branch area; but Russell[3] omits it. As indicated above, no evidence of the present connection of these areas was discovered in this survey.

CONGLOMERATE AREA ON WESTERN BORDER.

The outlying small tracts of Newark rocks on the eastern border have their counterpart on the western edge of the field. How far out upon the surrounding crystalline region these patches may be found to the westward is not known. There is reason for believing that they may be widely distributed between the known Newark areas. One such patch of the Newark beds, composed of a coarse conglomerate (see Pl. XXII), is crossed by the Manakintown road north of the Three Chop road crossing. The bounds of this small area, not heretofore shown on maps, are not precisely ascertainable. Outcrops of gneiss occur between this area and the main Richmond basin on the east and gneiss appears again on the north, so that it seems to be somewhat closely circumscribed. The structure of this area is not revealed.

MINOR STRUCTURE DUE TO STRESS.

Aside from the slickensides which everywhere pervade the shales of this area, there are numerous indications of yielding of the rocks to pressures presumably taking place at the time of faulting.

Cleavage.—Occasional layers of shale from the beds on the eastern margin exhibit secondary structures which closely simulate the metamorphic schists. Layers of shale intersected in the Etna shaft at Midlothian have been crumpled and a cleavage has developed normal to the plane of the stratification at the bends of the folds. This rock needs only mineralization along the planes of fracture and gliding to take on the essential characters of a schist. These layers are noticeably calcareous, and if we may suppose that consolidation set in earlier in them on account of the carbonate of lime present than in the adjacent layers, the difference of behavior under the strains of deformation may be explained.

Cone-in-cone structure.—In the shales at Manakin, on the western border, certain more resistant highly calcareous layers display the

[1] See map in Reprint of the Geology of the Virginias, by W. B. Rogers, New York, 1884.
[2] Daddow and Bannan: Coal, Iron, and Oil, 1866, p. 395.
[3] Russell: Bull. U. S. Geol. Survey No. 85, Pl. V. 1892.

TILTED SANDSTONES AND SHALES IN THE UNION PITS AREA. LOOKING NORTH.

A 4-inch layer of coal is exposed near the hammer.

peculiar arrangement of fractures known as cone-in-cone structure. Here the stress was probably due to crystallization.

Joints.—The deeply decayed condition of the rocks in this region precludes any general study of the system of joints. Not infrequently, however, the existence of joints in decayed sandstones and shales is indicated by the bleaching of the rock on either side of these planes of parting, which have favored the ingress of surface waters. At a few localities the induration of the sandstones at or near contact with the diabase dikes has preserved the joint structure. From a study of the joints associated with dikes alone, it is evident that there was developed in this region a set of joints having a north-northwest course which became the seats of the dikes. Where joints precede dikes and thus guide their course, it has been customary, at least in this country, to regard the joints as the effect of either the contraction of the sediments or the torsion of the mass through unequal tilting. Opinion at present inclines rather to the theory of torsion from deformation. Dr. Hans Reusch has suggested that the joints which guide dikes may be effects of the intrusion, being in the nature of forerunning fractures in the rock bordering the invading magma, a zone in which the explosive action of the magma, the deformation of strata, and volumetric changes dependent on rising temperature combine to afford a complex of causes, any one of which, acting alone, may be regarded as competent to effect the observed result.

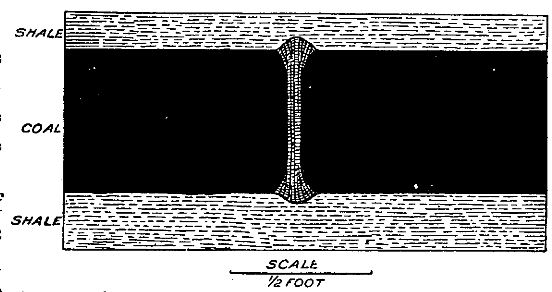


FIG. 110.—Diagram showing cross section of vein of fibrous calcite in coal, Winterpock, Virginia.

The occurrence of well-developed joints in rocks free from intrusive masses is conclusive evidence that dikes are not the necessary antecedents of joints, even where the intrusion of rocks is associated with jointing. In the case of joints in the Richmond basin, there were no evidences found by which to determine the lapse of time between the formation of the joints and the intrusion of the dikes. The cause of the joints in question is, therefore, left open for further investigation.

The bituminous coal is usually much jointed. The interval between the joints is rather short, and small-sized fragments result. On account of these joints the coal breaks up somewhat more readily than that of the Carboniferous section. In good part this greater degree of fragility is due to the stress to which these Mesozoic coals have been subjected in the faulting and flexing of the beds.

Structures associated with veins.—In the old Raccoon mine, south of Winterpock, certain layers of coal exhibit peculiar hour-glass-shaped cross fractures occupied by veins of fibrous calcite. (See fig. 110.) The fractures are perpendicular to the bedding. A single wide vein in the middle of the stratum splits into numerous side branches near the upper and lower limits of the coal seam. The edges of the vein project into the bordering shales by actually displacing the rock rather than by making a gash such as is sometimes filled with the veinstone. The markings described below, sometimes seen on layers, arise in the same way.

Markings on shale due to vein structures.—The thin laminæ of coal in the Midlothian field are sometimes minutely jointed, and these closely-set gaping joints have been filled with veins of calcite. The overlying and underlying layers of shale frequently bear incised lines marking

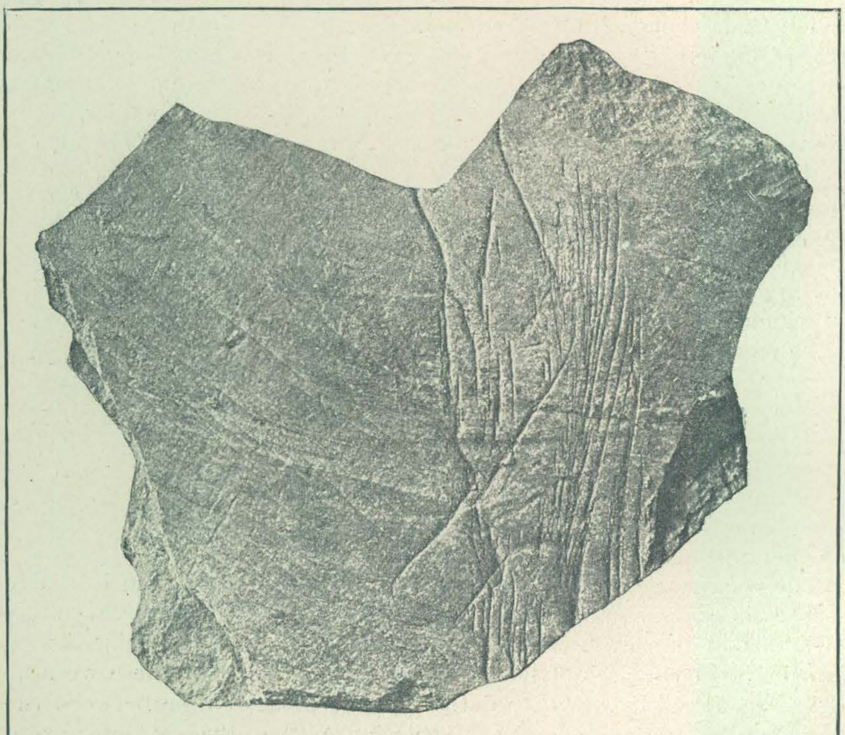
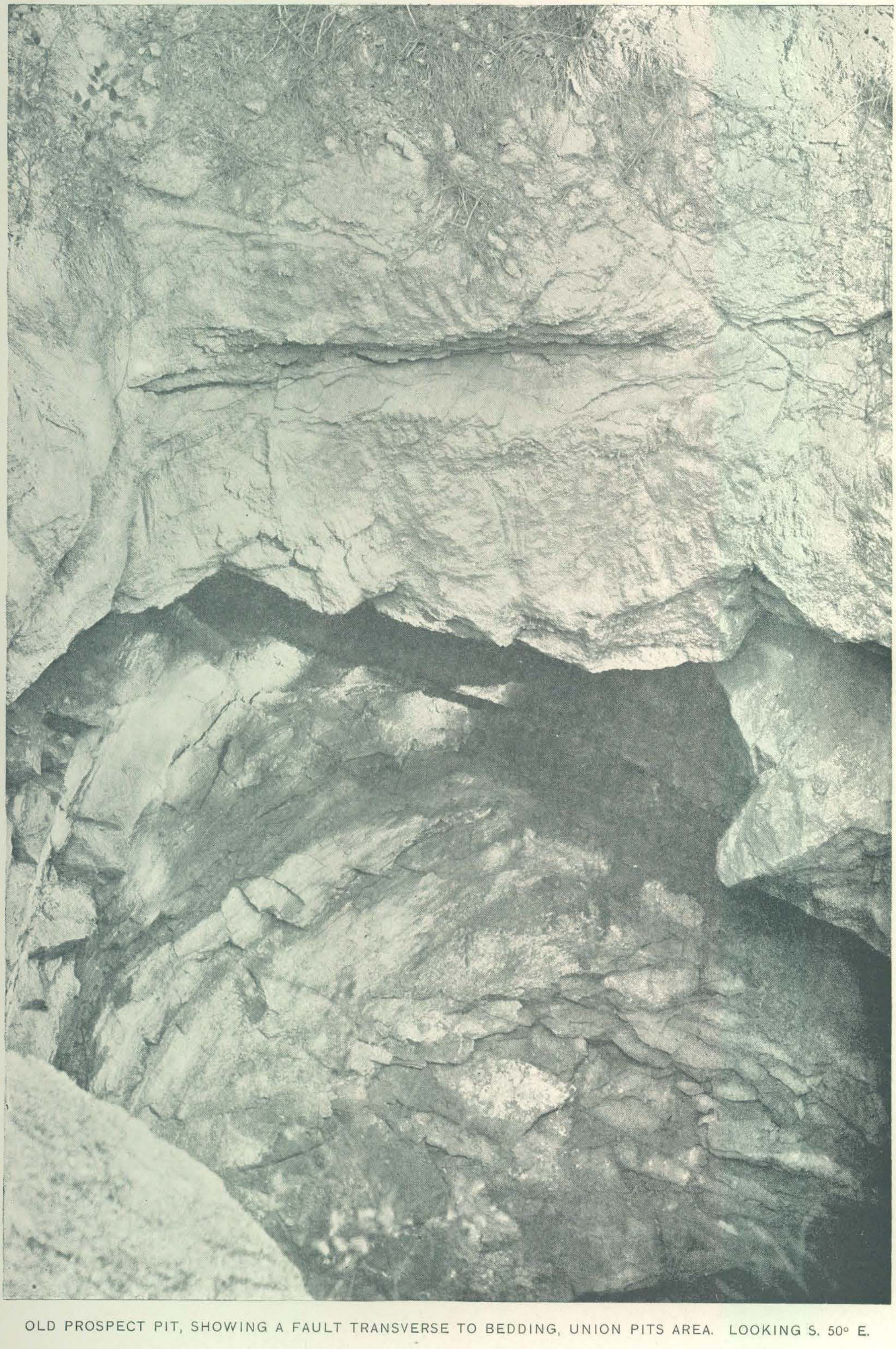


FIG. 111.—Surface of a fragment of shale from Midlothian, after layer of coal with calcite veins has been removed, showing lines of grooves marking edges of the veins.

the sharp edges of these veins, in the manner already described in the case of veins seen in cross section near Winterpock. These markings are creases or grooves rather than fractures in which the veinstone original formed. These creases, which stimulate mud cracks and ice crystal marks, indicate the compression of the shale upon the coal, the sediments yielding, while the veinstone resisted the movement (see fig. 111). The slight compression indicated by these lines may be accounted for by the weight of the overlying beds, though the joints may have been initiated by torsion and displacement.



OLD PROSPECT PIT, SHOWING A FAULT TRANSVERSE TO BEDDING, UNION PITS AREA. LOOKING S. 50° E.

Fault plane dips S. 30°; strike, about E.-W.

SUMMARY OF OBSERVATIONS BEARING ON THE STRUCTURE OF THE RICHMOND AREA.

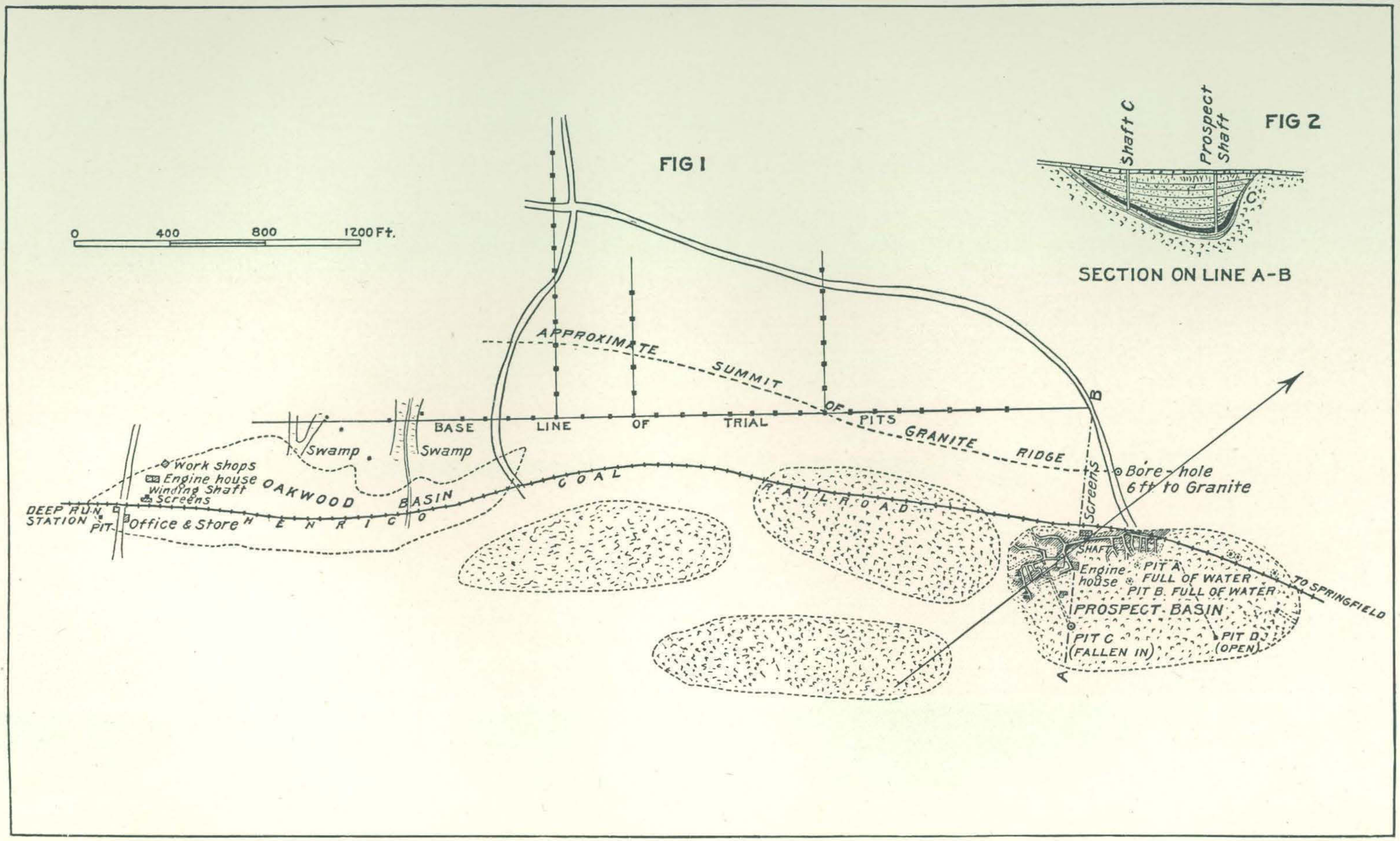
A thorough search for outcrops of the Newark rocks over the interior of the Richmond Basin has shown that the idea of a relatively great central undisturbed area is erroneous. While the interior of the area shows at the surface very little evidence of faulting and folding as compared with the highly tilted attitudes of the strata about the margin of the area, faults, folds, and flexures can be made out, and their relation to the marginal basal sections of the rocks is such as to lead to the supposition that, could we examine the base of the Newark rocks in the middle of the area, we should find there a repetition of the disturbances which are so pronounced a feature on the existing margins. The occurrence of flexures in the central area, as in the James River bluff, and of folds on the margin in the basal section, is what one would expect where considerable displacements in a granitic basement die out upward into a zone of pliable stratified rocks. A correlative of this conclusion is the inference that the disturbances of the Newark strata are due to their adjustment to the broken edges of the underlying metamorphic and igneous terrane, the ancient floor on which they were deposited.

Deposition appears to have begun in the Richmond area on a surface which had been reduced under the atmosphere to a land of little relief. To determine whether this was a peneplain or not can not be undertaken from the study of so small an area as that included in this report. The present inequalities of the basement of the Newark strata are largely if not altogether due to the dislocations above indicated as taking place after the deposition of most if not all of the strata now in the basin.

The sediments first formed in the area show a local origin, and much of them indicate a derivation from the eastward or southeastward. The coal measures show no signs of thinning toward the margin of the present area. After passing the basal beds the sediments give no clear evidence of the proximity of a shore line in any given direction. The nonmarine character of the sediments points to their deposition in a lake or in a river valley with lacustrine episodes, but there is no evidence to show that the present form of the basin is genetically related to such a valley or lake basin. So much faulting has taken place that by this means alone the trough-like character of the basin is probably accounted for.

The cause of the faulting and rearrangement of the blocks of Newark strata is perhaps to be found in the contraction of the globe. While vertical movements are most pronounced in the attitude of the different parts of the basin, evidence of horizontal pressure is thought to be found in certain cases of folding, and in the tendency to form a synclinal structure which is locally exhibited in the area.

When compared with other areas of Newark rocks on the Atlantic slope, the Richmond field shows by the prevailing westerly dips over broad areas south of the James River that it has undergone the general westward tilt common to the several tracts south of the Hudson River. The synclinal structure which has been attributed to it seems to be due mainly to the local downward drag of strata on the western margin, perhaps accented by lateral pressure and folding consequent thereon.



PLAN AND SECTION OF THE DEEP RUN BASIN.

(After Clifford.)

CHAPTER V.

IGNEOUS ROCKS.

As before remarked, the Richmond Basin, in common with the Newark areas northward to Nova Scotia, is intersected with dikes and sills of diabase. These rocks, on the eastern border, have received some attention on account of the association with them of coke in the several coal mines where they have been found. They have never before been mapped, though the more important of them are well known to the inhabitants of Chesterfield County, and the delineation of their course across country is not difficult.

The natural exposures of these dikes are usually in the form of rounded masses lying upon the surface of the outcrop. Rarely does the presence of the dike manifest itself in any topographic peculiarity of the line of outcrop. The bowldery and pebbly bands cross the peneplain and the valleys alike. In a few instances only have streams come upon a dike and excavated the soft, decayed material, but even in these cases, the most notable example of which is Turkey Branch of Swift Creek, on the western margin, the stream follows the dike for a few rods only.

The decomposition blocks or "hardheads" decay altogether on the outside, the decomposed layers washing off rapidly, so that the interior is comparatively hard and fresh. As compared with fragments of similar rocks found upon the surface in glaciated New England, the zone of decay seems to be thinner here than in the northern field, possibly because severe and long-continued frosts are wanting in the South to open up the loosened texture of the rock and favor the penetration of decay to the interior of the block.

Many of these "hardheads" have been carried to the sites of houses and farms, where they find various uses. It is therefore necessary in tracing the dikes, which are often marked only by the bowlders lying on the surface, to make certain that the fragments near habitations have not been transported by human agency.

The dikes, so far as observations go, appear to lie between the inclined strata in the form of sills on the eastern border of the basin, but no natural exposures have been found in which contemporaneous flows appear. There is therefore no positive evidence of volcanic action in this field during the deposition of the strata which remain in the basin. The occurrences are everywhere intrusive. Possible volcanic conduits have been seen in the Bernards Creek region, where an isolated mass of trap may indicate the existence of small pipe or conduit connecting upward with a volcanic vent; and in the case of a similar mass, better exposed, in the road from Skinquarter to Mosley Junction, where the diabase abruptly displaces the sandstones and shales. The sandstones near this locality are indurated. The shales, which have been finely jointed, are purplish at the contact.

The dikes vary in width from mere plates a few inches wide, traceable only for short distances, to masses measuring from 25 to 50 feet across the outcrop. The larger dikes have been traced for 5 or 6 miles, and there is reason to believe that they are continuous over much greater distances within the limits of the basin.

The largest dike has a general northwest and southeast trend, but others run east and west. The prevailing direction, however, is from northwest to southeast. On account of the deep decay of the rocks contact phenomena are seldom observed. The usual effect is an induration of the sandstones and the darkening of the shales, red colors passing to purple, as noted by Russell. Contact minerals have not been observed in the rocks adjacent to known dikes, but minerals have been found along the margin at Midlothian and Manakin, suggesting solfataric action (see pp. 502, 503). The general relations of the more important dikes which have been seen will now be described. It has not been thought necessary to present an account of the petrography of these rocks. So far as known by the microscopic examination of a typical specimen the rock is diabase.

DESCRIPTIONS OF DIKES.

The Skinquarter dike.—This dike may be traced in a north-northwesterly direction from a point about midway between Zoar and Winterpock through Skinquarter to the bank of Skinquarter Creek, 2½ miles south of Dorset. Throughout this extension of 5½ miles there are no obvious horizontal offsets of the dike due to faulting subsequent to its intrusion. The average width of the dike is as much as 20 feet, though in some places the width of outcrop is evidently as great as 50 feet. The contact is here and there shown at surface, but on one side only, so that exact measurements are not easily obtainable.

The coarse granitic sandstones of the Newark where in contact with the dike are light colored and indurated for a distance of from 5 to 6 feet from the igneous rock. Exposures of this nature occur on the land of Mr. J. H. Bailey, in the southern portion of the known extent of the dike. This dike is reported by the inhabitants to be traceable to the James River. Scattered bowlders and outcrops of trap occur east of its line, but a satisfactory tracing of the dike has not proved possible.

The dike usually exhibits joint-plane contacts. It was evidently irrupted in a fissure which followed the dominant joints. Intrusion must, therefore, have come rather late in the history of the basin. These joints, together with the dike, dip very steeply to the east. Columnar structure of the diabase is occasionally shown, the columns, perpendicular to the walls, dipping very gently to the west.

South of Winterpock trap outcrops are rarely found. The small exposure in the tongue of the basin extending southward across the

Appomattox near Namozine appears to have a northerly trend. The course of the Skinquarter dike, extended in this direction, would cut the margin of the basin precisely at the point occupied by this outcrop of a dike. Bowlders of diabase occur on the Scott plantation, between Winticomack Creek and the Appomattox, approximately at the point where the prolonged Skinquarter dike would cross the area.

Dike south of Zoar.—Mr. Geo. B. Richardson found a wide dike of diabase about 1¼ miles south of Zoar, near the western border of the area. It has the north-northwesterly direction of the dikes of this part of the area.

The Winterpock and Mantua dikes.—Mining in the vicinity of the Cox shaft, north of the railroad station at Clover Hill, years ago exposed a "dike" said to extend in a westerly direction. Bowlders may now be seen on the eastern border, indicating the extension of this dike into the granitite. Lyell[1] describes a dike about 20 feet thick occurring on the Johnston tract, about 4 miles north of the Appomattox River, running W. 10° S., and having a thickness of about 20 feet in the vicinity of the Beaver mine. This is probably the dike exposed in old workings, concerning which miners have a memory. Westward, on the line of this intrusion, a large dike makes its appearance on the eastern limits of the Mantua estate, and thence can be traced westward a few degrees south, toward the intersection of the extended course of the Skinquarter dike and another large dike. Beyond this point it has not been traced. On the Mantua estate there is a small dike, about 6 inches thick, extending in an east-and-west direction just north of the house, and another also small with a northwest course is marked by occasional bowlders in the soil north of the Winterpock dike.

Dike on western border in Petersburg road.—A small trap dike about 6 feet wide, dipping 85° E. and striking N. 20° W. crosses the Petersburg road at a point about one-quarter of a mile inside the basin. The western contact of this intrusion is formed by a vein of sand 5 inches thick, the whole intersecting red shales, dipping about 30° W. This dike has not been traced over the surface. The vein of sand is a unique feature which has not been sufficiently investigated to determine the circumstances of its origin.

The Nysons Branch and Dry Bridge dike.—In the railroad cut just west of Dry Bridge, on the Richmond and Danville Railroad, a diabase dike, 21 feet wide, intersects the sandstones and shales, the latter becoming purple at the contact. This dike strikes N. 15° W. in the cutting. East of the dike the rocks are nearly horizontal; west of it they dip as high as 30° W.

Southward, along the banks of Nysons Branch, and particularly on the land of Mr. J. J. Wilkinson, trap outcrops are found. Near the Wilkinson house the trap strikes N. 88° W., the dip of the cross-fracture planes or joints being 30° N.; hence it may be assumed that the dike

[1] Quart. Jour. Geol. Soc. London, Vol. III, 1847, pp. 270-271.

dips 60° S. At one point this dike has a breadth of 27 feet, but for the most part it is about 4 feet wide.

Trap appears along the eastern side of Nysons Branch on a course a little east of south, in the direction of Otterdale cross-roads, and it is reported to occur in this direction on the south side of Swift Creek.

Sill in the Sallé and Burfoot tracts, near the James River.—Sir Charles Lyell[1] described the occurrence of "greenstone" or diabase along the eastern margin of the basin south of the James River, in the tracts above named. On the Sallé tract, he states that the rock was traced to within 120 feet of the coke. On the Burfoot tract, on the James River, three-fourths of a mile above the arsenal, a mass of trap 28 feet thick was seen near "brecciated rock of hardened shale varied by patches of carbonaceous matter resembling impure coke in appearance." The

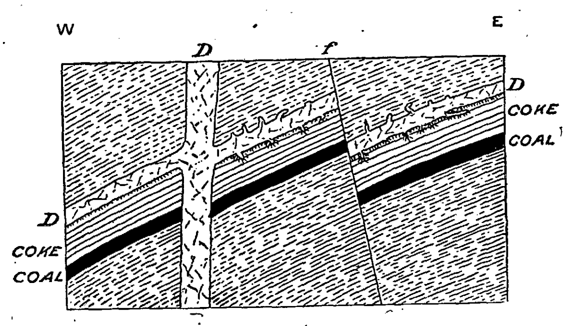


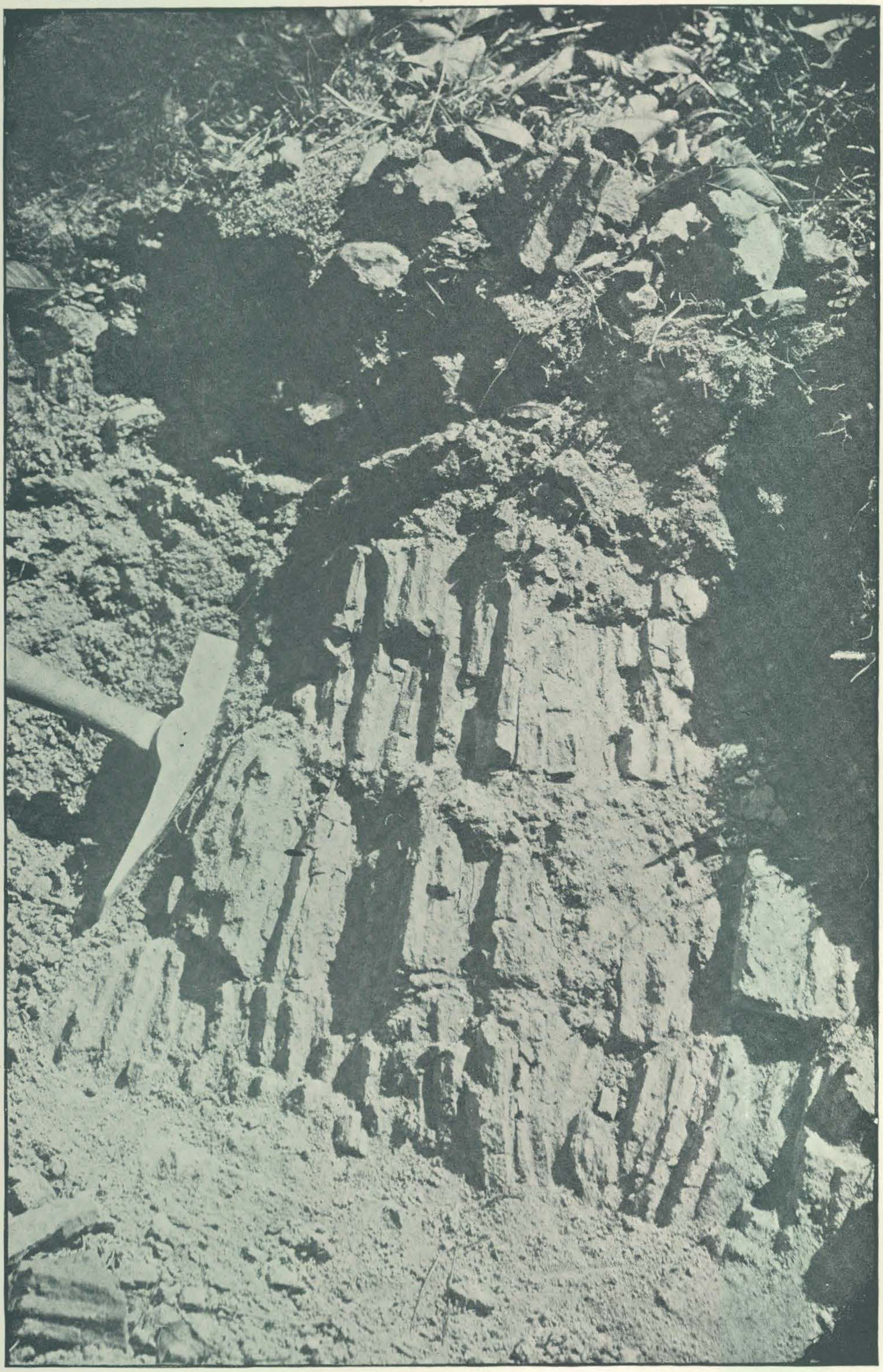
FIG. 112.—Diagram showing relations of dike and sill to coke in Saunders's slope at Gayton, Virginia. *D*, gray altered diabase; *f f*, a fault.

trap is described as overlying the coal in the form of a sill having the same dip as the coal beds.

Sill at Gayton (Edge Hill), on the north side of the James River.—The trap is again seen on the north side of the James, in the Gayton mines, where Lyell described it as a conformable bed of blue basalt 16 feet thick. About 200 yards north of the great coke-pit of his time the trap was 14 feet thick within 26 feet of the surface. Two miles south, at Crouch's pits, the trap was not found.

In 1896–97 the trap was well exposed in the bottom of Saunders's slope at Gayton. It occurs here in the form of a sill, overlying the coke bed and sending small apophyses of gray altered material into the coke, seen from point to point in the roof of the incline. At a depth of about 650 feet from the surface the altered trap forms a dike 4 feet wide, cutting across the coal-measures. The coke is prismatic for a distance of about 3 feet on either side of the dike. The same columnar habit of the coke is observed on a smaller scale surrounding the sides and ends of the little tongues of trap which invade the upper part of the coke bed (see figs. 112, 113). The coke having this structure is said to pop in the fire and is cast aside as worthless.

[1] Quart. Jour. Geol. Soc. London, Vol. III, 1847, p. 271.



OUTCROP OF PRISMATIC COKE, NORTH OF GAYTON.

The alteration of the diabase at this point to a depth so great as 650 feet below the surface in the dike just mentioned is apparently due to solfataric action, and is not to be attributed to atmospheric decay. The same phenomenon is exhibited in the sill in the Jewett's coke shaft at Midlothian and its downward extension in the deep boring at Salisbury. The dike at Gayton exhibits numerous vertical veins of calcite. A like alteration of dark basic dikes to a light gray rock has been observed in the coal-fields of Great Britain.

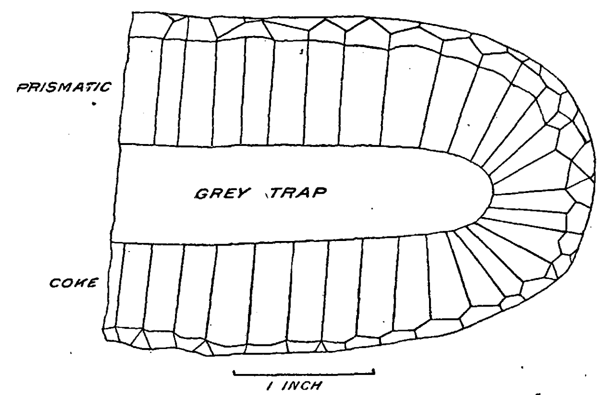


FIG. 113.—Prismatic coke surrounding small apophysis of trap in roof of Saunders's slope.

Dike north of Gayton.—A quarter of a mile north of the Saunders shaft a natural exposure of the prismatic coke is seen. Its appearance is shown in Pl. XLIV. From this locality a dike may be traced northwestward at intervals toward the middle of the basin.

ACTION OF DIABASE DIKES ON THE COAL MEASURES.

The most important change effected in the coals of the Richmond Basin by the action of intrusive rocks has been the driving off of volatile matter, as in the manufacture of coke in gas works. The present openings in the basin do not permit of a satisfactory examination of the relation of the intrusive igneous rocks to the beds of coal which have been thus affected.

According to Sir Charles Lyell,[1] coke occurs in connection with an inclined sill in the northern portion of the field and with a dike, probably the Winterpock dike, at Clover Hill. The upper coal beds exhibit coking, a phenomenon which Lyell explains as due to the intrusion of the trap between the beds and the action of the escaping heat upon the overlying rather than the underlying strata.

In the case of the coke of Towne's and Powell's pits, at Edgehill, now Gayton, Lyell was inclined to refer the origin of the coke only indirectly to the trap. "We may attribute," he says, "the change from coal to coke not so much to the heating agency of the intrusive basalt, as to its mechanical effect in breaking up the integrity of the beds, and

[1] Quart. Jour. Geol. Soc. London, Vol. III, p. 271-272.

rendering them permeable to water or the gases of decomposing coal."

According to our observations, the gray altered trap is closely associated with the altered coal beds or coke. At Gayton the trap overlies the coke, if it does not by intrusion actually lie in the upper part of the bed. At Midlothian the same close relation between the two rocks is observed. In that part of the field where the under contact of the trap has been observed the trap has become fissured after partial or complete cooling and the probably pitchy coke has run into the fractures in the form of miniature dikes. This action was observed in Jewett's coke shaft and again in the deep boring on Salisbury. Above the trap at Gayton and Salisbury there is a variety of the coked coal, high in ash, and having a graphitic appearance. It is relatively soft, gives a brownish black streak on paper, and rubs to a high polish. It is sometimes pulverulent in structure. We may suppose, therefore, that the maximum action of the sills on the coal beds occurred along the upper contact of the sills, and that the lesser degree of change requisite for making natural coke was attained underneath the sill. The thickness of the workable beds of coke, therefore, depends not only on the original thickness of the coal bed, but also on the position in the bed occupied by the invading igneous rock, which along the eastern margin of the area appears to have followed the coal.

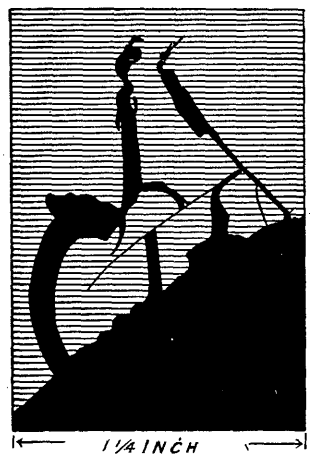


FIG. 114.—Sketch of a portion of the core from the boring on Salisbury, near Midlothian, Virginia, showing coke dikes in lower part of altered gray sill. Vertical and horizontal scale the same. Depth of boring, 2,370 feet.

That the coking of the coals may possibly have arisen from solfataric action going on slowly and coincidently with the intrusion of igneous rocks in this field is shown by the alteration of the granitite in some of the mines on the eastern border. Thus in the Etna shaft at Midlothian the porphyritic granitite was encountered in a bleached state, with here and there veins of fluorite and iron pyrite, indicative of the former presence of volcanic vapors. As already noted, the CO_2 driven off from the coal in the process of coking would afford a powerful agent for the decomposition of the diabase.

APPARENT ABSENCE OF HYDROCARBONS IN THE DIKES.

The well-known fact that the cavities of basic igneous rocks sometimes contain bituminous substances derived from vegetable or animal matter in the rocks through which the igneous rock has passed,[1] sug-

[1] J. D. Dana (Bitumen in trap amygdules): Walks and Drives about New Haven, 1894, p. 106. Also Silvestri: Atti Accademia Gioenia, Series III, Vol. XII, cited by G. F. Rodwell, in Etna, London, 1878, p. 128. R. I. Murchison: Siluria, 3rd ed., London, 1859, p. 25. Abich: Acad. Sci. St. Petersburg, Bull. Phys. Math., Vol. XIV, Nos. 4 and 5.

gested the search for hydrocarbons in the traps of the Richmond Basin, in the hope that some relation might thus be established between this mode of occurrence of hydrocarbons and the existence of coals in the central portion of the area. Either because of the advanced disintegration of the diabase dikes near the surface, or the lack of sufficient material, neither the eye examination of the diabase in the field nor the chemical examination of the rock in the laboratory revealed the existence of the material sought for.

It was thought that the occurrence of a well-developed vesicular structure, as in the deeper-seated portions of diabase, might be regarded, under the assumed conditions, as evidence of coal, particularly if the rock were locally vesicular in the manner of furnace slag about a point in which wood or charcoal has been reduced to gas in its mass. But the investigation of this point, as was the case with that first cited, gave negative results.

DIKES SUITABLE FOR ROAD METAL.

The dikes of the Richmond area afford a possible supply of the best stone for road metal. They form the nearest localities of trap to the city of Richmond. The conditions under which the materials occur, however, make the quarrying of the dikes at present too costly. The decay of the diabase has in most cases proceeded to a point where, perhaps, more than half of the rock near the surface is converted into clay, leaving only the rounded masses, signs of which are found here and there on the surface. Enough trap for the construction of a few miles of road could be obtained by gathering the field stone or bowlders along the line of the Skinquarter dike. By shallow trenching a greater quantity could be procured. On the B. C. Watkins property, in the vicinity of Bernard Creek, a mass of trap lies well above the stream on the west side and in a position to be quarried. The actual extent and condition of the rock beneath the surface remain to be determined by excavation. Except for local purposes, as in the bettering of the turnpikes which cross the coal fields, the distance which the material must be transported precludes its use.

PERIOD OF INTRUSION OF THE DIKES AND SILLS.

All the available evidence thus far obtained from the Richmond area shows that the dikes and sills are somewhat more recent than the Newark strata which now remain in the area. Actual intersections of the dikes have not been observed to show any difference of age in these igneous rocks. At but one point, in the boring at Salisbury, has any evidence been found to favor the idea of successive intrusions. In this instance the drill passed through both gray altered diabase and fresh diabase in close proximity and in distinct sheets in the coal measure section. It is presumed from a study of dikes elsewhere that the altered trap represents an earlier intrusion into the soft wet coal or vegetal beds, by the setting free of the CO_2

of which the trap was altered into a gray clayey mass, and that the unaltered diabase is a later intrusion, coming in after the coking of the coal beds. The interval of time between these intrusions may have been short.

The contact of the larger dikes with the sandstones in the central part of the basin has been shown (p. 496) to have been guided by joint planes, so that the intrusions may be assumed to have come in after the formation of these structures. The joints appear to be due to torsion, which can best be explained as the result of the deformation of the strata during the period of faulting. The dikes on this supposition would be made later than the faults. The failure of dikes which have been traced for some distance to show signs of faulting is also presumptive evidence that the period of faulting preceded the time of igneous intrusion. The behavior of the intrusive sheets on the eastern margin, which follow the coal beds to their outcrop but fail to appear in the detached basins in the old Blackheath and Stonehenge districts, is probably due to the fact that these basins were already formed when the sills came in. The igneous intrusions rising toward the surface would have overshot these depressions, into which the coal beds were locally sunk. From these several considerations it is concluded that in this field the igneous intrusions came later than the observed deformation of the area, though they may have been dependent on the same deep-seated movements.

MINERALS FOUND WITHIN THE BASIN.

The minerals arising from secondary changes within the rocks of the Richmond basin are few in number and, excepting the iron pyrite, exist in very small quanities, at least, in those portions of the strata which are at present open to examination. These are iron pyrite, carbonate of lime, siderite, and wad. These minerals fall into two groups according as they are associated causally with the igneous intrusions of the basin, or with ordinary changes in sediments in which carbon, carbonate of lime, and iron are original components.

Fibrolite.—In the sandstones of the western margin at Manakin veins of quartz occur, inclosing, according to Dr. Palache's determination, long acicular crystals of fibrolite, a mineral usually found in schistose rocks and as a contact mineral.

Iron pyrite.—The association of iron pyrite with some of the coal beds and shales of this basin is probably quite independent of igneous action, this mineral being usually present even in lignites where no trace of volcanic action is seen. There can be little doubt, however, that the distribution of certain iron pyrite bodies has been effected by the action of dikes and hot waters, as is shown by the bleaching of the granitites underlying the coal beds and the veins of pyrite with fluorine which intersect this rock, all of which phenomena point to solfataric action long since the formation of the granitite.

Siderite.—Siderite occurs in the southern portion of the basin in the form of septaria from a few inches to a foot in diameter. Invariably

CALCAREOUS CONCRETIONS FROM NEWARK ROCKS, DININY SLOPE, NEAR TOMAHAWK CHURCH, CHESTERFIELD COUNTY.

the carbonate of lime is in excess and has crystallized out in the contraction gashes of the nodules.

Carbonate of lime.—Calcareous beds overlie the coal measures on the eastern margin, as described by Mr. Heinrich. These are highly nodular. Carbonate of lime also occurs in the central part of the basin north of Swift Creek, filling in the spaces of a brecciated sandstone in the vicinity of the Nyson's Branch dike. This fibrous calcite is probably the result of hot springs coming up through the calcareous beds of the measures, following the intrusion of the dikes. The red shale is here also highly calcareous.

Calcareous concretions.—Calcareous concretions are met with in almost every one of the shafts and slopes of the eastern margin. The general character of these masses as they appear when thrown upon the surface is shown in Pl. XLV, from a photograph taken at the mouth of an incline sunk near Tomahawk Church, on the eastern margin.

The concretions vary in form from nodular to spindle-shaped and in size from nuts to large logs. The exterior of the masses is frequently warty or marked by projections of fantastic shapes. The matrix is usually arenaceous, and the concentric structure of the masses is obvious, particularly in large specimens.

The secondary accumulation of the carbonate of lime in the horizons in which it is found thus seems to be proved. Whether it may not have been deposited along with the grains of sand with which it is associated at the present day is not easily determined, since the opportunity of examining the deposits in situ is rarely found. In the core taken from the drilling at Salisbury, near Midlothian, in 1897, the whitish arenaceous layers, composed of quartz and feldspar, invariably react with dilute hydrochloric acid, showing the presence of lime carbonate. The dark shales interbedded with the sandstones usually give no such reaction except in those sections where calcareous veins occur. At Hallsboro, a borehole intercepted calcareous shales with the fracture of fine-grained limestones.

Carbonate of lime also occurs in sandstones on the western border as in the case of the old shaft at Manakin. Here the carbonate of lime is not concretionary, but forms the cement embedding the sand and fossils. The sandstones referred to contain vertebrate bones, a probable source of the cement.

Hematite ore used for fettling was formerly obtained from the eastern margin in the vicinity of the Sallé and Burfoot tracts.[1]

TEMPERATURE GRADIENT OF THE ROCKS IN THE RICHMOND BASIN.

Prof. W. B. Rogers made a series of observations upon the temperature of the rocks, the air, and the water of the mines at different depths in the vicinity of Midlothian during the progress of his survey of the State. The results of these observations were published in the

[1] Wm. Clifford, op. cit., 1888, p. 349.

Transactions of the Association of American Geologists and Naturalists for 1840–1842.[1] He concluded for this region that from "the invariable plane downward for many hundred feet the temperature augments at the rate of 1° for every 60 feet in depth."

An observation made by the United States Geological Survey in the deep boring of Salisbury tract in February, 1898, at the depth of 2,076 feet gave, according to Mr. Darton's calculation, a rate of augmentation of 1° in 47 feet. It is probable that Professor Rogers assumed too high a mean annual. This and other records, the taking of which is in progress, will be discussed in a forthcoming bulletin of the Survey by Mr. N. H. Darton.

[1] Geology of the Virginias, reprint 1884: Observations of subterranean temperatures in the coal mines of eastern Virginia, pp. 567–574.

GRAVELS OVERLYING NEWARK FORMATION, SOUTHERN RAILWAY CUT, NEAR MIDLOTHIAN.

The spring on the right marks the top of the clayey strata.

CHAPTER VI.

POST-NEWARK CHANGES.

POST-NEWARK DEPOSITS.

Several observers have recognized within the Richmond area the occurrence of patches of strata of more recent date than the Newark system. The discrimination of these sediments from the Newark rocks is not always satisfactory, for the reason that the lithological characters of both formations are similar and the measure of atmospheric decay is the same.

The distinction between Newark and post-Newark formations is best observed about the margins of the Richmond area, where the coal-bearing strata are tilted at high angles and their eroded edges are overlain by the newer sediments. The post-Newark rocks are found in noteworthy masses only in the interstream areas, as in the divide which separates the waters of the James from Swift Creek.

These post-Newark deposits were clearly once more extensive in this basin than they now are. Their occurrence as remnants on divides and high points within the field is explainable only on the supposition that large areas of these rocks have been swept away in the development of the present drainage system of this portion of the Piedmont district. The deposition of at least certain members of this series of deposits was preceded by stream erosion. This feature of the topography is shown by the limited sections in the Blackheath area, near Midlothian. In this small tract excavations have shown the existence of a valley of moderate depth cut into the tilted coal beds, the trench thus formed being subsequently filled with compact yellowish clay having a cobblestone layer at base. The present drainage system has been incised in these superficial deposits along the line of the ancient valley.

The most extensive exhibition of these post-Newark beds in the area, that already mentioned as forming the divide on which the Buckingham or Midlothian turnpike crosses the coal basin, reveals a thickness of strata probably as great as 30 feet. In the vicinity of Midlothian this formation is composed of a yellowish clay stratum below, overlain by a quartz pebble bed, which is in turn surmounted by mottled sandy clays. Fossils have so far not been found in this group, except those included in pebbles of older date.

The pebble beds are well exposed in the Southern Railway cut between Nyson's Branch and the public road crossing the railroad about 1 mile east of Dry Bridge Station (see Pl. XLVI). The beds here consist of the usual conglomerate of quartzite and quartz pebbles, mainly if not altogether materials derived from the Paleozoic strata in the region of the Blue Ridge and the Great Valley of Virginia. Some of the quartzite pebbles contain casts of a Scolithus or vertical worm burrow. In a fine-grained, white, decomposed hornstone was found the internal cast of *Spirifera cumberlandiæ* Hall, as determined by Dr. R. T. Jackson. A fragment of a tabulate coral was also found in this gravel.

Prof. W. B. Rogers[1] described these and similar deposits in the vicinity of Richmond, Virginia, and Washington, D. C., in 1875. He mentions the occurrence of numerous cobbles of quartzite with *Scolithus linearis*, and he referred this group of pebbles to the sandstones west of the Blue Ridge. He also noted the limitation of the materials to the lines of the great river valleys, and attributed the transportation of the detritus to water, aided by ice, working probably at a higher level than the present.

Later Mr. W J McGee reviewed the evidence concerning the superficial deposits of the Atlantic coast and recognized two important groups newer than the fossiliferous Tertiary strata, the Lafayette and the Columbia beds.

Horizontal beds of clay and sand resting on granite are seen in the railway cut at Bon Air, east of Midlothian (see Pl. XLVII). These strata are provisionally classed with those of post-Newark age.

WEATHERING OF ROCKS IN THE AREA.

WEATHERING OF GRANITE AND GNEISS.

The complex processes of leaching and redeposition of mineral matter in the decomposition of granite under atmospheric decay is illustrated by an instance revealed in the softened rock east of Midlothian. The granite where the decayed zone has not been removed by erosion, as in the stream bottoms, is so soft as to be readily pared with a knife. The concentric structure of the decomposed joint blocks is clearly marked by the deposition of black oxide of manganese in the joints formed during the period when the rock still possessed the property of yielding as a mass to strain. The rock is colored deep yellow by the oxide of iron, and mottled with white patches which marked the kaolinized porphyritic feldspars of the original granitite. Bordering the concentric fractures, which have been charged with veinlets of black oxide of manganese, is a bleached zone from which the iron oxides have disappeared (see fig. 115).

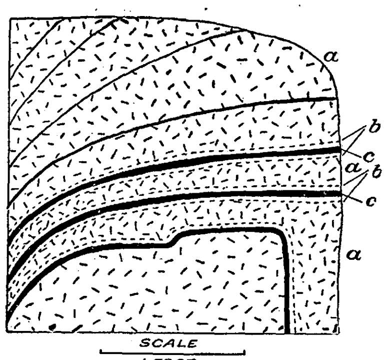


FIG. 115.—Portion of a section of soft, decomposed granitite exposed in a washout near Midlothian, Virginia. *a*, yellow decomposed granitite porphyry; *b*, white kaolinized bands; *c*, black oxide of manganese bands.

[1] Proc. Boston Soc. Nat. Hist., Vol. XVIII, 1875, pp. 101-106. Also in reprint Geology of the Virginias, 1884, pp. 709-713.

POST-NEWARK BEDS, RESTING ON GRANITE AND SCHIST, AT BON AIR, CHESTERFIELD COUNTY. LOOKING N. 20° E.

The gneisses of the western border weather rather less readily than the coarse granites of the eastern margin, mainly because the gneiss contains more quartz. A part of these gneisses appears to be an ancient sheared quartz-porphyry, a group of rocks which resist weathering longer than granite. Notwithstanding this relative resistance to weathering, there are bands of deeply decayed gneisses, and the rains have carved in these fields channels and miniature river systems imitative of bad-land sculpture. Such a piece of topography is shown in Pl. XLVIII, reproduced from a photograph taken from a point south of Mosley Junction.

WEATHERED GRANITE BLOCKS ON THE EASTERN MARGIN.

A striking feature of the eastern boundary of the Richmond area, where that is formed by the granitite previously described, is the occurrence of a narrow belt of land, next the Newark margin, more or less encumbered with granitic bowlders varying in size from cobbles up to rounded masses 10 feet or more in diameter (see Pl. XLIX). These weathered blocks, of the same lithological structure as the underlying

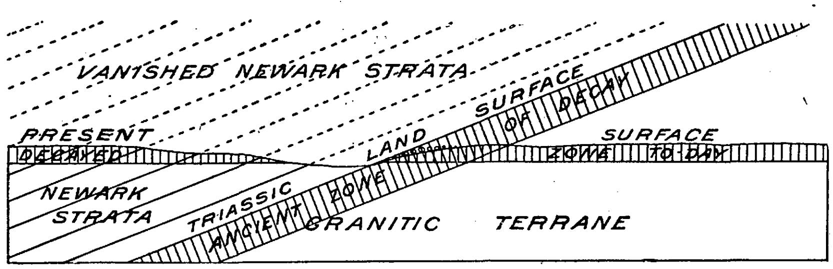


FIG. 116.—Diagrammatic section showing position of weathered blocks in reference to Newark and Recent zones of weathering.

rock where that can be seen, for some reason are singularly limited to the margin of the basin, or if they occur over the granite areas to the eastward seldom give rise to such large bowlders as those common along the line designated. In the present period of atmospheric decay the granites in the two fields have been exposed to like conditions. The belt of weathered blocks along the border of the Richmond Basin becomes thus in some way connected causally with that geologic feature.

As has been shown in the description of the basal members of the Newark system, the principal mineral constituents of the granitite, viz., the quartz and feldspar, occur as mineralogically separate particles, pointing to the disintegration of the granitite in pre-Newark times. When the ancient weathered surface was buried by the Newark sediments a zone of decay must have remained unattacked by erosion. Under the conditions of deep burial, this zone, shut off from the oxygen of the air and the acids which promote decay, would have experienced an arrest of the ordinary atmospheric processes of decomposition and disintegration. The weathering would already have penetrated downward along the master joints, outlining blocks with unweathered centers. When, after the dislocation of the Triassic beds and the tilting of the old land surface to its present attitude, the new land surface was imposed by denudation on this ancient structure, the following results would take place: Atmospheric decay attacking all parts of the surface alike, on either side of the border in question, would advance most rapidly in the weakest rocks. The granitite just below the ancient Newark land surface, having been once partly weathered, would first give way and leave decomposition blocks (see fig. 116).

In the deep boring south of Midlothian "granite bowlders" were reported.[1] The conditions of sedimentation at the base of the Newark along the eastern margin were, as is indicated by the arkose beds, such as to lead us to suppose that these fragments were ancient weathered blocks rather than members of a true basal conglomerate, as that formation is commonly understood.

We are fully warranted in distinguishing a fundamental layer of blocks, however much rounded by decay, reposing at the base of a system of sediments on an ancient land surface, such as the Newark affords, from a true basal conglomerate representing a succession of overlapping beaches or torrent cones. The basal conglomerate may contain rocks of diverse kinds, derived from several terranes. By reason of the transportation of the materials, the fragments are apt to repose on unlike rocks. They are, in a word, prevailingly exotic. On the other hand, by the process of weathering, with the deportation of dissolved materials by water and the blowing away of dust by the winds, there may be left behind the insoluble or undissolved remnants, to form autochthonous deposits which simulate basal conglomerates. By slight redeposition, through the transgression of the sea or the rejuvenation of streams, this sedentary débris may pass into a true basal conglomerate.

The abundant signs of long continued atmospheric decay in the tract about the Newark area makes it probable that the basal conglomerates, where not composed of weathered blocks unaffected by subsequent water action, at least originally strewed the land surface precisely as such blocks and fragments occur on the desert tracts of South Africa, India, or Argentina.

WEATHERING OF QUARTZITE PEBBLES.

It is a well-known fact that the disintegration of angular and subangular masses of rocks first becomes visible upon their corners and edges. This is because the decomposition, penetrating inward on intersecting faces, produces in the region of their intersection a double attack where two planes intersect and a triple attack on a corner where three planes form the salient of the mass. Certain of the

[1] Heinrich, op. cit.

GULLIES IN DECOMPOSED GNEISS ERODED BY RAINS, WESTERN BORDER, NEAR MOSLEY JUNCTION, CHESTERFIELD COUNTY.

quartzite pebbles lying upon the ridge on the north bank of the James near Tuckahoe Creek, in Goochland County, illustrate this feature. These pebbles are relatively rare. Similar pebbles exhibit no signs of this disintegration and falling away of grains. The undisintegrated portion of the pebbles has a hard smooth surface, frequently concave, as if the pebbles had escaped from a conglomerate where they were compressed.

CONCENTRIC SHELLS OF COLOR BANDING.

The weathered sandstones on the south bank of the James River, as for instance along the private road northward from Moss's store, are marked by concentric bands of iron oxides simulating alternating bands of differently colored layers of sandstone on so large a scale and so closely as to make it difficult to distinguish this secondary banding from the original stratification. Some large concretions of this character occur at about the same horizon in the sandstones on the north bank of the river at Tuckahoe (see Pl. XXXVII).

CHAPTER VII.

ECONOMIC GEOLOGY OF THE BASIN.

All the important facts which have been ascertained concerning the deposits of the Richmond Basin have been stated in the preceding pages of this report. It is desirable, however, that they should now be considered from the economic point of view. The value of these materials other than the coals is so small that they may be dismissed with a brief statement.

Soils.—As to the soils of this area, it may be said that with the exception of the alluvial plains (see Pl. L), some of which form a fringe along the James River and other considerable streams above the present level of the flood waters, the tillable layer is composed of residual deposits arising from the decay of the Newark beds. Owing to this origin they are sandy clays, or occasionally nearly pure sands. At the best they are of a rather low order of natural fertility, though they would respond quickly to systematic culture with the use of fertilizing materials. The fact that the area underlain by the Newark beds has been less stripped of its forests than the surrounding country, where the underlying rock is granite or mica-schist, shows that the present methods of agriculture are relatively unprofitable in this field.

Building stones.—None of the rocks in the Newark section are suitable for use as building stones. The subjacent granitic rocks have no commercial value, as like materials are more conveniently accessible at other points in this district. Some of the beds of shale lying over or under the coals may be found suitable for making road-paving, or perhaps fire brick. If this should prove to be the case, the culm from the coal mines might well be used in the process of burning the clay. In case this clay, made by grinding the shales, were used for road-paving brick, it would probably be found advantageous to coke the dust, using the waste gas in the kilns.

Ores.—There are no ores known to occur in the basin in economically valuable quantities. There are reports that sulphur has been found in small quantities near the surface, but inquiry has failed to verify these statements. It is in the coals and the related natural coke and jet that the economically important earth products of the area are found.

Jet.—Beginning with the least important of these, the jet, it may be said that the conditions of its occurrence are little known. They are such as to indicate that it is worth while to make explorations that may better determine the nature and extent of the deposits. The senior author has examined the localities in northern England where the principal supply of this material is mined from two Triassic strata. There

WEATHERED GRANITIC BLOCKS, EASTERN BORDER, SOUTH OF GAYTON, HENRICO COUNTY.

the material of best quality is found at considerable depths beneath the surface, in masses rarely of more than a few pounds in weight. As jet is used only for personal ornaments in the form of beads, etc., the demand for it, owing to the variations of fashion, is very irregular. Of late it has, to a great extent, been replaced by black glass, which is much more cheaply shaped.

Coke.—The natural coke of this field varies much in quality and texture, ranging from a dense, amorphous, graphitic-looking material to that which in general aspect, especially in the prismatic form of the masses, resembles the non-compact varieties produced in modern ovens. As the coking has evidently been due to the intrusion of somewhat localized masses of trap, the distribution of these cokes is irregular and their quality is variable, because of the differences in the original composition of the coal and in the heat which has been applied to them. As to the proportion of the coal of the basin which has been coked by the traps, no sufficient data for a reckoning can be obtained. Judging from the experience afforded by the mining along the outcrop edges of the field, probably less than one-fifth of the coal has undergone this change.

Although the natural coke of the Richmond Basin has been long in use, there appear to be no sufficient tests of its economic value. As a domestic fuel it is well esteemed in the neighborhood and in towns of the vicinity. It is in one feature evidently superior to artificial coke in that it is denser, having more nearly the quality of anthracite. So far as has been learned no adequate trial has been given it to ascertain its fitness for metallurgical work. This inquiry appears to be worth making. Should the material prove serviceable, it would afford a much cheaper fuel for ore smelting than any now available in this district. Should experiments in smelting furnaces be made with the natural coke, it is important to recognize the fact that the material varies considerably in quality according to the nature of the original coal and the conditions in which the coking was brought about. In some varieties, where the original coal contained a good deal of lime carbonate in the form of small veins, the coke carries a share of lime which may advantageously affect its action in the furnace. Much variation in the amount of ash is to be expected. At some points the share of earthy matter will be found so large as to make the material unfit for use.

Bituminous coal.—The coals of this field are quite sharply parted from the cokes. In most, if not all, instances the evident effects arising from the heat brought in by the traps stops rather suddenly, so that there is but a small amount of material intermediate between coke and coal. The character of the true coals is quite variable, as the diversity of the analyses shows. The range in ash is greater than is commonly found in neighboring beds or in different portions of the same bed in rocks of the Carboniferous period.

As regards the amount of fixed carbon and volatile matter which they contain, these coals are satisfactory. At some points where the beds have been subjected to much shearing there are infiltrations of lime carbonate in the form of numerous small veins. Where this condition exists it is desirable that the coal be broken and "washed" by some of the well-known methods, as by the use of jigs. In certain portions of the coal beds there is a notable quantity of iron pyrite, in amount sufficient to fire the old dumps. This substance is, as is usual in bituminous coals, disseminated through the body of the seams. As it is to a great extent gathered in the joint planes, it may be in large part removed by washing, by which treatment an excellent fuel should be obtained.

It is commonly believed that the ash of the coal and coke of the Richmond basin is more likely to flux, and thereby to clog grate bars, than is the case with the products of the western Appalachian mines. This evil would probably be diminished by washing, which would remove the lime contained in the small veins. So far as this lime is a component of the ashy matter which is interstitially diffused in the coal, washing would, of course, not remove it. It does not seem likely that the inconvenience arising from this source would prove serious, provided the product of the mines were marketed in such quantities and in a sufficiently steady manner to induce a proper adaptation of furnaces and practice in firing to its peculiarities. In this connection it is to be noted that it requires patient management to bring into general use a fuel which differs in quality from that to which consumers have been accustomed. Even if it be quite as good as that in use, the inconvenience of having to change the conditions of firing so as to win the value from the new source may hinder its introduction. The relatively small cost of transporting the coal of the Richmond basin to tide water should go far to counterbalance the difficulties which arise from the above-noted features of the material.

Extent of the coal beds.—As to the area of the basin underlain by the coal beds, the evidence may be stated as follows: On the eastern margin, where the beds are best placed to be exposed in natural sections (see Pl. LI), and where they have been most extensively worked in former years, there is a fair presumption that the deposits are substantially continuous. Where, as is shown on the map, the coal beds have not been found, as is the case in two considerable sections of the eastern border, the failure of the slight explorations to disclose them may be fairly explained by the existence of faults which have thrown the beds down or up, so that the shallow pits which were sunk did not pass through the deep surface rubble. So far as has been learned, there were no indications in the old workings that the coals were fading out in the directions of these portions or the margin where they have not yet been found. In the blank north of the Clover Hill mines the streams run so near the position of the outcrop that exploration has been discouraged by the difficulty which would evidently be encountered from surface water.

ALLUVIAL PLAIN OF THE JAMES RIVER, IN POWHATAN COUNTY, NEAR VINITA. LOOKING SOUTH.

Alluvial land in foreground; Newark terrane in rising ground on the horizon.

On the western margin the coals are practically unknown from a point about 2 miles south of the James River, at the Old Dominion pits, to the southern extremity of the basin, though there are traces of the dark shales which are probably associated with it. In this part of the border the failure to discover the beds may well be due to the abrupt downfaulting which is known to exist along this line. At only one point, viz. in the stream bed of Turkey Branch, has it been possible to obtain a tolerably continuous section of the beds on the western margin of the field. This failed to reveal the coal-bearing beds, but there is reason to believe that they may have been thrown down by an unobserved fault traversing a portion of the line where the strata were not disclosed, or that they are to be found under a slight cover of alluvium.

As to the extension of the coal beds beneath the central parts of the area, the evidence in hand is insufficient to warrant a definite statement. The conditions may be briefly set forth as follows: The tolerably complete if not perfect continuity of the beds on the eastern margin and at either end of the basin appears to afford fair evidence that the coal beds have a continuous habit. It has been suggested that the coals, though continuous along the margin of the basin, may be lacking in the central parts of its area. But it should be noted that the present outcrop line is not to be regarded as the original border of the coal-bearing strata. That line was probably miles east of its present position. The existing face is, in effect, a chance north-and-south section of the deposits. There is no evident reason based on the character of this outcrop why a like exhibition of coal beds should not be had if the face were carried 1, 2, or 3 miles westward.

The failure to find the coal beds in the Sinking shaft and in the drill hole in its bottom has been considered as evidence that these beds were lacking at a point about 1 mile from its margin. This failure to attain the coal is to be explained in the light of the information obtained in the Salisbury boring. The depth at the Sinking shaft was altogether insufficient to traverse the barren strata, the drill most likely not penetrating to within 200 feet of the level where the coal beds might be looked for. The Salisbury drill hole, on the other hand, has shown the coal-bearing rocks at a distance of a mile from the eastern main outcrop, at a depth of about 2,350 feet below the surface.

When all the evidence is weighed, it leads to the conclusion that the central portions of the area most likely contain coal beds in something like the measure that they are exhibited in the margin. The measure of the probability of such occurrence is rather greater as regards that portion of the field which lies to the east of a line drawn from the Clover Hill pits, near the southern end of the basin, to the Old Dominion mines, on the western margin about 2 miles south of the James River, than it is concerning the field west of that line. This is for the reason that outcrops have not been found along the western margin south of the Old Dominion property, though, as before noted, their failure to occur may be accounted for by accidents of faulting. Leaving out of the reckoning the southwestern portion as possibly lacking the coal-bearing beds, there remains an area of about 150 square miles where the deposits may reasonably be expected to occur.

Although the information obtained from the existing and the old workings show the coal to vary greatly in thickness, and some of the beds much in quality, it is a not unreasonable estimate that the average thickness of the workable material is 12 feet. Allowing for occasional strips of coal which have been crushed by faulting and for loss in treatment in the breaker, the yield per acre may be roughly estimated at 1,000 tons per foot in depth, or a total of 12,000 tons. The total area which is reckoned as most probably coal bearing (150 square miles by 640 acres) equals 96,000 acres, which, on the basis of yield above adopted, would give a total content of 1,152,000,000 tons. This reckoning, it should be said, rests altogether on probabilities. It can not be taken as an estimate such as would warrant an account of values. It is merely the best that can at present be done toward elucidating a very obscure and difficult economic problem. It should be understood that in no part of the field would it be judicious to undertake mining estimates or operations without careful preliminary explorations by means of the drill.

The variation in the number and thickness of the coal beds, as will be seen from the sections given in this report, is considerably greater than is encountered in the other coal fields of this country east of the Mississippi River. In none of the mines does it appear that less than two beds of workable thickness are encountered. In other instances there is reason to believe that three, four, and at Clover Hill even five beds of economic value were found. Although all these beds thicken here and thin there and probably at points unite or separate, the coal-bearing character of the section in which they lie is probably maintained in a tolerably continuous manner.

Depth of the coal.—The question as to the depth at which the coals lie in the central parts of the basin or even at the distance of a mile from the margin can not, for lack of information, as yet be satisfactorily dealt with. The fact that the beds near the surface in the central portions of the field show much less dip than those on the margin has been taken as evidence that the deep-lying coal measures are likewise in an approximately horizontal position. One of the results of the survey discussed in this report is to show that the lower strata are probably more disturbed than those near the top of the series. All the considerable body of evidence which has been gathered leads to the supposition that while the interior of the basin may be somewhat less faulted than the parts which have been explored, the difference will be only in degree, irregularly faulted blocks, each dipping but little, and broken seams, with their several areas separated from one another by "troubled ground," extending throughout the field. The broken condition of the basement rocks makes it very difficult to reckon the depth

METHOD OF WORKING MINE AT SMALL DEPTH BY USE OF MULE GIN, BINGLEY SLOPE, BLACKHEATH AREA.

of the section above the coals at any considerable distance from the margin.

In the present condition of our knowledge of the basin it will be safe to assume that at the distance of a mile from the eastern outcrop the coal-bearing section lies at a depth of about 2,500 feet below the surface. Farther toward the interior of the field the depth at which it will be found will probably be somewhat greater. It is not impossible that at some points the faulting has carried these deposits more than 4,000 feet below the present surface. From what has been learned of the conditions, it seems unlikely that the section in which the coals belong is at any point as deep as 5,000 feet.

In the present condition of the art of mining the cost of working coal seams at the greatest depth above mentioned would not be prohibitive, provided there were no other elements of expense than those due to the construction of the shafts and the charges for hoisting. In this field, however, there are certain important hindrances to be reckoned with. Much of the rock to be passed through by the shafts is penetrated by very numerous minute faults, the faces of the fractures not having been cemented together since their formation. These ruptures will be likely to cause the material to creep under the pressure to which it will be subjected at great depths, thus requiring care and increasing the cost of lining shafts. The same evil is to be anticipated in greater measure in working the coal under deep cover. Much of the coal is already divided by the above-mentioned small faults into bits a fraction of a cubic inch in size. Such portions of the beds may be expected to creep in a troublesome manner. A like motion may be expected in the overlying and underlying clays. There will also be certain risks arising from the spontaneous combustion of the coals, and from mine explosions, such as have occurred in the past history of the pits in this district.

All the above-noted difficulties can probably be met by a proper system of mining. All sinkings and drivings on such ground need to be swiftly done. The coal faces should be worked back as rapidly as possible, and thorough ventilation provided for the openings. The plan of allowing the roof to descend upon the floor as soon as possible, thus avoiding the retention of large spaces for the storage of gas and dust, should be considered. In mines operated with such precautions, there appears to be no evident reason why the coals of this basin may not be won at depths as great as they are likely to be found. The cost of the mining and the relative advantage of the fuel, as compared with that of other districts, needs be the matter of a special reckoning. All that can be said on those points in this report is that hitherto there has been no well-devised mining work on a large scale done in the field. The coal has been often marketed without due attention to its condition, or to processes of bettering its quality, so that the commercial results thus far attained afford no fair measure of the possible value of the fuel resources of this field.

APPENDIX.

REPORT ON SOME FOSSIL WOOD FROM THE RICHMOND BASIN, VIRGINIA.

By F. H. Knowlton.

Mr. J. B. Woodworth recently submitted to me for examination a small collection of fossil wood made by himself during the season of 1896 from the Richmond coal field, in Chesterfield County, Virginia. The material consists of three small pieces of silicified wood and a number of fragments of lignite. The silicified specimens are evidently small fragments broken from large trunks, and on this point Mr. Woodworth writes as follows: "These are examples of prostrate trees 20 feet and over in length, and upward of 4 feet in diameter at the base. They sometimes appear in the roads, with both extremities concealed in the banks."

Following are the exact localities for the three specimens:

Near Skinquarter Station, Chesterfield County, Virginia; from the upper sandstone measures of the Richmond Basin [1535].

Near Otterdale, Chesterfield County, Virginia; in the upper sandstone measures of the Richmond Basin [1537].

South of Mosley Junction, in Chesterfield County, Virginia; on the western border of the Richmond Basin, near the base of the Trias [1536].

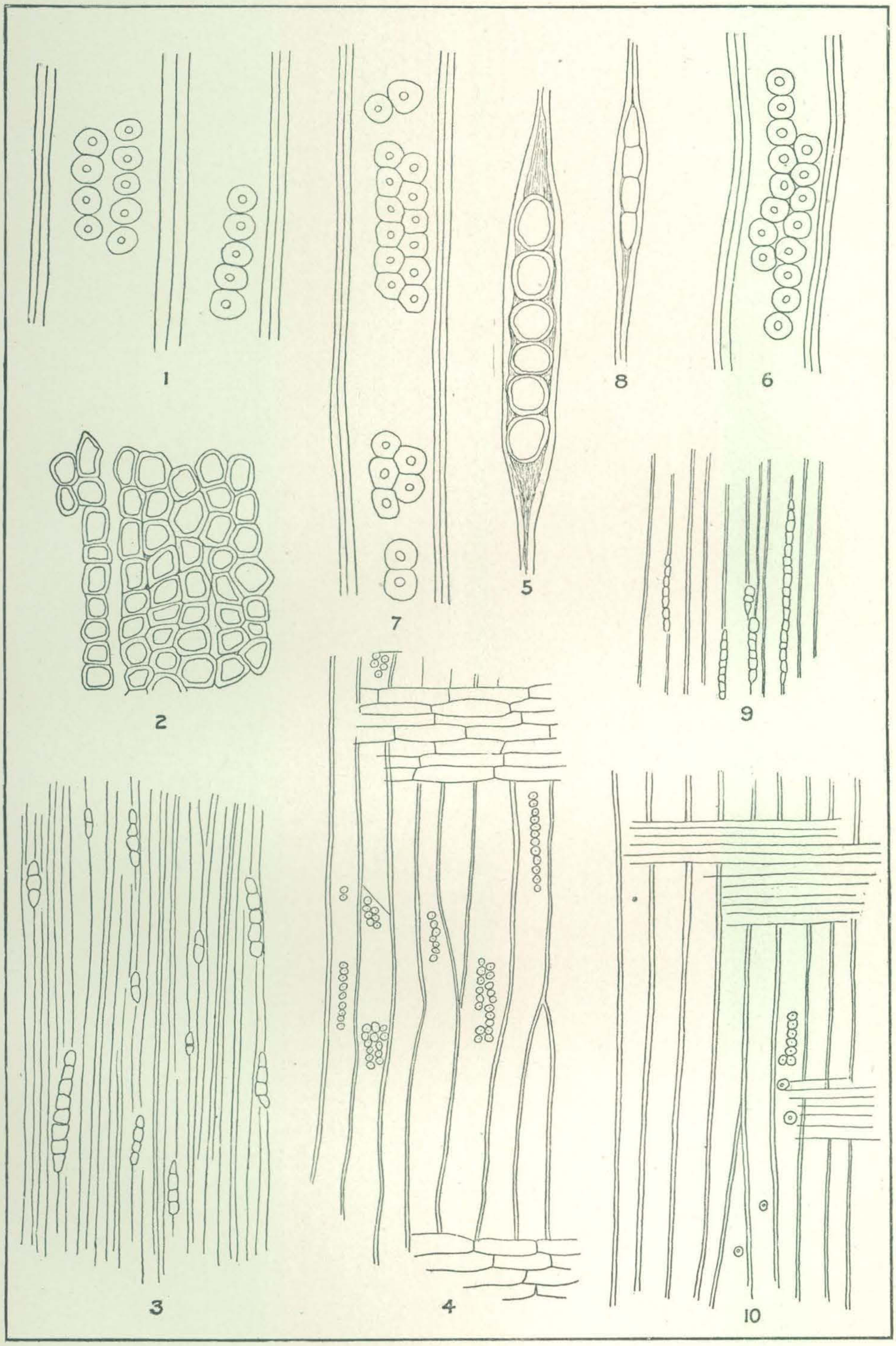
An examination of thin sections cut from these specimens proves them all to be coniferous. The one from the first of the above-mentioned localities proves to have been so metamorphosed by the process of silicification that it is impossible to make out the intimate structure. The wood cells were evidently large, but it is impossible to determine the character of the bordered pits or markings. The other specimens are much better preserved, and represent two species, as follows:

ARAUCARIOXYLON VIRGINIANUM Kn.

Pl. LII, figs. 7-10.

Araucarioxylon virginianum Kn.: Bull. U. S. Geol. Survey, No. 56, p. 50, Pl. VII, figs. 2-5, 1889.

When this species was described it was supposed to have come from a locality within the Potomac formation, at Taylorsville, Virginia, but



ARAUCARIOXYLON, RICHMOND BASIN.

Figs. 1–6. Araucarioxylon Woodworthi n. sp.

Fig. 1. Radial section showing bordered pits × 310.
Fig. 2. Transverse section. × 90.
Fig. 3. Tangential section showing medullary rays. × 90.
Fig. 4. Radial section showing bordered pits and medullary rays. × 90.
Fig. 5. Tangential section of single medullary ray. × 310.
Fig. 6. Radial section showing bordered pits in two rows, somewhat compressed. × 310.

Figs. 7–10. Araucarioxylon Virginianum Kn.

Fig. 7. Radial section showing hexagonal bordered pits. × 310.
Fig. 8. Tangential section of single medullary ray. × 310.
Fig. 9. Tangential section showing wood cells and ends of medullary rays. × 90.
Fig. 10. Radial section showing bordered pits and medullary rays. × 90.

subsequent investigation[1] has shown that it was undoubtedly from the Trias or "Older Mesozoic." The error regarding its horizon arose from the fact that this is almost the only known locality at which the older Potomac rests directly upon the Trias, and up to that time fossil wood was known to be abundant in the Potomac, but had not been reported from the Trias. A reexamination of the locality was made by Ward, McGee, and Fontaine, with the result of fixing the horizon. Of this later examination Professor Ward writes[2] as follows:

> A subsequent investigation of this locality by Mr. McGee, Professor Fontaine, and myself has proved that the fossil forest bed from which this specimen was taken really belongs to the Older Mesozoic or Upper Trias. This is one of the few regions in which the Trias and the Potomac formation are in contact, and without such a careful investigation as we made on that occasion it might be easy to confound these deposits, as the locality for the fossil wood lies close to the line of contact.

The specimen that I now refer to this species is from south of Mosley Junction, and according to Mr. Woodworth is from near the base of the Trias. It will be seen on comparing the figures in this report with those of the original publication that they agree in all essential particulars. The important characters of the medullary rays and the wood cells and their one or two series of more or less hexagonal pits are indistinguishable, the only difference being in the size and relative number of superimposed cells in the medullary rays. This difference, however, is not marked, and the two specimens are regarded as belonging to the same species.

The finding of this species in another part of the Richmond basin is of interest, and shows that the study of internal structure may be relied upon to furnish recognizable stratigraphic marks.

ARAUCARIOXYLON WOODWORTHI n. sp.

Pl. LII, figs. 1-6.

Diagnosis.—Annual ring very obscure, not visible to the naked eye; wood cells broad, long, sharp-pointed, moderately thick-walled, provided with 1 to 3 (usually 2) rows of contiguous, faintly hexagonal bordered pits; medullary rays moderately numerous, short-celled, and in a single super-imposed series of 1 to 12, usually 3 to 4, cells; resin ducts, none.

Transverse section.—The annual ring is not visible to the naked eye, but on examination under the microscope it is found to be present and to consist of only two or three slightly smaller and thicker walled cells. The wood cells are only moderately thick-walled and are quite uniform in size.

Radial section.—This section shows to the best advantage the character of the wood. The wood cells are shown to be long, sharp-pointed, and to be provided with, usually, two rows of bordered pits, although cells are common on which there is but a single series. Cells on which

[1] Ward, Am. Jour. Sci., 3d series, Vol. XL, 1890, p. 257.
[2] Sixteenth Ann. Rept. U. S. Geol. Survey, 1896, p. 499.

there are three rows of pits are much rarer. When in a single row the pits are contiguous and but slightly modified in shape by pressure, as may be seen in Pl. LII, fig. 1. When the pits are in two rows they usually occupy the center of the cells and are contiguous and slightly hexagonal, as in fig. 7; but occasionally, as shown in fig. 6, the two rows may be slightly separated and then may have the characters of the single rows. When there are three rows of pits they are close together and markedly hexagonal. The average diameter of the pits is about 0.015 mm. and that of the inner pore about 0.003 or 0.004 mm.

The medullary rays, as seen in this section, are short-celled, each cell being about as long as the width of 2½ of the wood cells. They are without markings or pits of any kind, so far as can be made out.

Tangential section.—Owing to pressure in this direction the section is somewhat distorted and does not show clearly the relative abundance of the rays. The number of cells entering into the composition of the rays, however, shows satisfactorily. It is found that they are in a single vertical series of from 1 to 12 cells, the usual number being 3 or 4. The two figures given (Pl. LII, figs. 5, 8) show very well the character of the rays and their arrangement.

The hexagonal form of the bordered pits settles at once its generic affinities, and it is consequently referred to the genus *Araucarioxylon.* It differs at once from *A. virginianum* in the character of the bordered pits and the short-celled medullary rays.

This species is very closely allied to, if not indeed identical with, *Araucarioxylon arizonicum* Kn., first described[1] from the Triassic or Lower Jurassic of New Mexico and Arizona, and since detected in the Triassic of North Carolina.[2] It differs from the New Mexican specimens in the absence of bordered pits on the tangential walls of the wood cells, and from both the New Mexican and North Carolina specimens in having two, or rarely three, rows of bordered pits on the radial walls. The short cells of the medullary rays are the same in all these specimens, and it is possible that the increase in the number of rows of bordered pits may be only an individual variation, or possibly due to the tree from which they came being larger or more mature. With a larger series of specimens from the Richmond basin for comparison, it is possible that some variation would be found in this respect, but until this can be obtained it seems better to describe the specimens as new to science. I have given it a name in honor of Mr. J. B. Woodworth, the collector.

The bearing of these species of plants on the question of the age of the deposits in which they occur is of importance. The Araucarian type of structure in conifers was of very early introduction, originating in the Devonian, and attaining, perhaps, its maximum development in the Upper Carboniferous and Permian. Wood showing this Araucarian

[1] Proc. U. S. Nat. Mus., Vol. XI, 1888, p. 3, Pl. I.

[2] The Newark system, by I. C. Russell: Bull. U. S. Geol. Survey No. 85, 1892, p. 29.

type, from the Devonian to and including the Permian, is known under the names of Cordaites and Dadoxylon. The former is characterized by the possession of an Artisia pith and numerous hexagonal pits, in which the inner pore is elliptical instead of circular. In the genus Dadoxylon are included certain of these Paleozoic woods, of which the complete history, for some cause or other, can not be fully made out. It is therefore in the nature of a provisional grouping, and, should more perfect material be obtained, it is likely that most, if not all, of its species will ultimately be relegated to Cordaites. The more modern structure, which approaches closely to that of the living Araucaria, appears to have been inaugurated with the beginning of the Mesozoic. To this the name Araucarioxylon is now restricted. It embraces about twenty species, most of which are found in the Juratrias, with three or four in the Cretaceous and one or two in the Tertiary.

Of the two species mentioned in this report, *A. virginianum* is now reported for the second time, having been described as from the Lower Potomac, but now known to be from the Trias. The species described as new is very closely allied to a well-marked Triassic species (*A. arizonicum*), and, as already pointed out, may be identical. The evidence, therefore, would indicate the Triassic age of the Richmond beds, from which they came.

THE CRETACEOUS FORMATION OF THE BLACK HILLS AS INDICATED BY THE FOSSIL PLANTS

BY

LESTER F. WARD

WITH THE COLLABORATION OF

WALTER P. JENNEY, WM. M. FONTAINE, AND F. H. KNOWLTON

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THE CRETACEOUS FORMATION OF THE BLACK HILLS AS INDICATED BY THE FOSSIL PLANTS.

By Lester F. Ward.

GENERAL REMARK.

The Black Hills are an object lesson in geology. An isolated spur or outlier of the Rocky Mountains, but separated from the main range by valleys and plains of considerable width, they seem to stand alone as a landmark of the Great Plains, presenting from a distance a dark and frowning aspect, which has given them their name. Their elliptical form, the granitic nucleus of the central portion, and the series of successively higher formations that concentrically surround this nucleus, imbricated over one another and stretching away in all directions with diminishing dip, have been too often described to require redescription here.

The history of the discovery of the Black Hills has also often been written and need not be repeated, and we are therefore in condition to proceed directly to the consideration of the specific problems in hand, and may confine our attention almost exclusively to the one formation named in the title of this paper, viz, the Cretaceous. Indeed, the limitations of our subject enable us to leave out of account that part of the Cretaceous formation itself which has received the largest amount of attention from other writers, viz, the marine shell-bearing deposits which occupy its upper portion. These, not having thus far yielded any fossil plants, will be treated in this paper only in relation to the lower beds, and we are restricted to those deposits which lie between the Fort Benton shales above and the marine shell-bearing Jurassic formation below.

I. HISTORY OF OUR KNOWLEDGE OF THE CRETACEOUS OF THE BLACK HILLS.

The great exploring expeditions of Lewis and Clark, 1804–1806; of Maximilian, Prince of Neuwied, 1832; of Nicollet, 1839; and of Audubon, 1843, which so enriched our knowledge of the Great Northwest, all followed the valley of the Missouri River so closely as not to penetrate the Black Hills, and only vague mentions are to be found in the reports of these expeditions of a dark object looming up in the distance. But it was otherwise with the important expedition with which the name of John Jacob Astor is so intimately connected and which has been made famous by the eloquent pen of Washington Irving.[1] This expedition was made in 1811, under the immediate direction of Mr. Wilson P. Hunt. Its object was entirely mercantile and not at all scientific, yet many of the facts that were recorded in Mr. Hunt's notebook and by other members of the party and worked into the narrative twenty-five years afterwards, have a true scientific value—even to some extent a geological value. It is at least true that the exploring party left the Missouri River at the mouth of the Cheyenne, followed that river up some distance, crossed over to the valley of the Little Missouri, and from there skirted the northern limits of the Black Hills proper, and passed on to the Big Horn region. The greater part of the narative is taken up with descriptions of the mountains, the native Indians, and the wild animals that were met with. But soon after leaving the Missouri River the party encountered a fossil forest, which is described in the following terms:

These plains, however, had not always been equally destitute of wood, as was evident from the trunks of trees which the travellers repeatedly met with, some still standing, others lying about in broken fragments, but all in a fossil state, having flourished in times long past. In these singular remains the original grain of the wood was still so distinct that they could be ascertained to be the ruins of oak trees. Several pieces of the fossil wood were selected by the men to serve as whetstones.[2]

There is no probability that these fossil trunks belonged to the Cretaceous formation, certainly not to the Lower Cretaceous, and they were probably the same as those now known to exist in the valley of the Little Missouri, especially in the vicinity of Gladstone, which are usually referred to the Fort Union group.

The approach of the party to the Black Hills is graphically described, but there is so much that is fanciful in the description that the scientific man must depend upon his own judgment as to what the facts were upon which these high-sounding accounts were based. To those who are acquainted with that country now it is not difficult to do this, and therefore the following description, perhaps the first that was ever made of the Black Hills, still possesses a scientific interest independent of the classic language in which it is couched:

The Black Hills are chiefly composed of sandstone, and in many places are broken into savage cliffs and precipices, and present the most singular and fantastic forms; sometimes resembling towns and castellated fortresses. The ignorant inhabitants of plains are prone to clothe the mountains that bound their horizon with fanciful and superstitious attributes. Thus the wandering tribes of the prairies, who often behold clouds gathering round the summits of these hills, and lightning flashing, and thunder pealing from them, when all the neighboring plains are serene and sunny, consider them the abode of the genii or thunder spirits, who fabricate storms and

[1] Astoria, or Anecodotes of an Enterprise beyond the Rocky Mountains, by Washington Irving, in two volumes, Philadelphia, 1836.

[2] Loc. cit., Vol. I., p. 246.

tempests. On entering their defiles, therefore, they often hang offerings on the trees or place them on the rocks, to propitiate the invisible "lords of the mountains," and procure good weather and successful hunting; and they attach unusual significance to the echoes which haunt the precipices. This superstition may also have arisen, in part, from a natural phenomenon of a singular nature. In the most calm and serene weather, and at all times of the day or night, successive reports are now and then heard among these mountains resembling the discharge of several pieces of artillery. Similar reports were heard by Messrs. Lewis and Clarke in the Rocky Mountains, which they say were attributed by the Indians to the bursting of the rich mines of silver contained in the bosom of the mountains.[1]

There is probably considerable literature relating to the Black Hills which antedates the middle of the present century, resulting from various hunting and trapping expeditions and to some extent from early attempts at settlement of the country around their base; also from occasional gold hunting and prospecting parties that penetrated some distance into the interior. But such literature, if it exists, must be contained in the popular journals and newspapers and could scarcely be found by the most systematic search. The only mention that I have met with belonging to this class is one which very intimately concerns the subject of this paper, and is, upon the whole, somewhat remarkable. It is contained in the prose writings of Edgar Allen Poe, and occurs in The Thousand-and-Second Tale of Scheherazade. The poet, as all know, was in the habit of supporting much of his imagery by means of footnotes, purporting to be drawn from facts, and often embodying true scientific information. In this characteristic production occurs the following paragraph:

Leaving this island, we came to another where the forests were of solid stone, and so hard that they shivered to pieces the finest-tempered axes with which we endeavored to cut them down.

To this statement he appends a somewhat elaborate footnote, describing three fossil forests. One of these is in Texas, and the description is credited to Kennedy; another is the celebrated fossil forest near Cairo, in Egypt, of which he takes a rather extended account from the Asiatic Magazine. Following the first of these accounts by Kennedy and preceding the longer one relative to the Egyptian forest, he interpolates the following brief but highly significant paragraph:

This account, at first discredited, has since been corroborated by the discovery of a completely petrified forest near the head waters of the Chayenne, or Chienne River, which has its source in the Black Hills of the Rocky chain.[2]

It may never be known when, where, or how Poe came into possession of the data for this statement, but it seems altogether certain that the fossil forest referred to is none other than the one that I visited in 1893, in company with Professor and Mrs. Jenney, and from which the specimens of wood were collected which are further mentioned in this paper (infra, pp. 552, 642).

[1] Loc. cit., Vol. I., p. 253.

[2] The Works of the late Edgar Allan Poe, with Notices of His Life and Genius, by N. P. Willis, J. R. Lowell, and R. W. Griswold; in two volumes; Vol. I, Tales, New York, 1850, p. 139.

Our knowledge of the Black Hills, in so far as it is based on scientific reports, all bears a later date than any hitherto quoted. The important expedition of Lieutenant Warren, made in the year 1855, did not reach the Hills proper, for, as he says, "The routes traversed led over the Great Plains between the Missouri, the Platte, and the Shyenne, and nowhere entered the mountains." But the party was in full view of the Black Hills, and Lieutenant Warren makes the following remark with regard to them: "The Black Hills of Nebraska are believed to be composed of primitive rock, and are the eastern portion of the great mountain belt." Dr. Hayden accompanied this expedition, and his report follows that of Lieutenant Warren.[1] A map accompanies the report, showing much more fully than had any earlier map the numerous streams that have their origin in the Black Hills. Many fossils were collected on this expedition, some of them Cretaceous, which were fully described by Hall and Meek.[2]

This was the first of a series of similiar expeditions conducted by the United States Army, each of which made new inroads into the unexplored country. The report of the Secretary of War in 1858 contains Lieutenant Warren's later results, including expeditions in 1856 and 1857.[3] In these reports Lieutenant Warren gives a historical account of the whole country explored. The Black Hills were penetrated from the south as far as Inyankara, where the expedition was obliged to return on account of hostile Indians and insufficient force. Besides giving a tolerably clear description of the geographical position of the Black Hills, Lieutenant Warren makes a number of allusions to the geology, in which the Cretaceous formation is recognized.

Dr. Hayden accompanied each of the expeditions, and his report (pp. 676–747) constitutes the first really scientific contribution to the geology and natural history of the Black Hills. The section of the Cretaceous, however, given on page 681, does not come from the Black Hills, but from points near the Missouri River. Nevertheless, in view of its early date, it may be worth while to quote so much of it as refers to formation No. 1, afterwards known as the Dakota group:

> Yellowish and reddish friable sandstone, with alternations of dark and whitish clays. Seams and beds of impure lignite, fossil wood, impressions of dicotyledonous leaves; *Solen, Pectunculus, Cyprina*, etc., Lower Cretaceous.

The reference to fossil wood and lignite is significant, as is also the expression "Lower Cretaceous."

Fossil plants were collected from this horizon and referred to Dr. Newberry, who did not, however, determine them specifically, but referred them to thirteen genera, several of which are extinct. Two

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[1] Explorations in the Dacota Country in the Year 1855, by Lieut. G. K. Warren; Washington, 1856. Senate Ex. Doc. No. 76, Thirty-fourth Congress, first session.

[2] Mem. Am. Acad. Arts and Sci., new series, Vol. V, 1853, pp. 379ff.

[3] Message from the President of the United States to the two Houses of Congress at the Commencement of the Second Session of the Thirty-fifth Congress; Vol. II; Washington, 1858. House of Representatives, Ex. Doc. No. 2, pp. 620ff, 671ff.

of these genera, Credneria and Ettingshausenia, are characteristic of the Cenomanian of Europe, and from these and other facts Dr. Newberry argues that the beds can not be Triassic, but must be Cretaceous (see pp. 683–684).

These several reports were republished verbatim in 1875.[1]

By permission of the Secretary of War Dr. Hayden published certain of these results in the Proceedings of the Academy of Natural Sciences of Philadelphia for 1857,[2] and with the assistance of Mr. F. B. Meek, who determined the molluscan remains, he considerably extended these observations in a paper immediately following the last.[3]

In the first of these papers, speaking of formation No. 1, as seen near the mouth of the Judith River, Dr. Hayden says:

> Although the formation of which I am about to speak has already revealed many important facts, the organic contents of its strata differ so materially from those of any other with which I am acquainted in the Northwest, that we are unable to fix with certainty its position in the geological scale (p. 116).

The second paper contains considerable introductory matter of a geological character, with sections of the various strata in which the fossils were found. On page 128 is given a vertical section of the entire region, from the Carboniferous to the Miocene. The description of Cretaceous No. 1 is identical with the one already quoted, except that in place of the words "Lower Cretaceous" the following is substituted: "This bed is not positively known to belong to the Cretaceous system."

On page 125 the authors make the following important statement relative to their formation No. 1:

> The deposits above alluded to (at the mouth of Judith River) as probably on a parallel with beds seen near the mouth of Big Sioux River on the Missouri—forming No. 1 of the Nebraska section—are characterized, as stated in one of our former papers, by a group of fossils remarkably distinct from those occurring in any of the higher Northwestern formations, and there remains some doubt as to whether or not they are older than Cretaceous. The presence of the genus *Baculites* would seem to establish the fact that they belong to the Cretaceous epoch; while the occurrence in the same hand specimens with these remains of *Baculites*, of a species of *Hettangia*—a genus of bivalves, not known to occur in the Old World in newer formations than the Lias—would, on the other hand, indicate that these beds are older than Cretaceous. For the present, however, we express no decided opinion on this point, but content ourselves with the remark that we are inclined to think that they hold a position near the base of the Cretaceous system and are probably on a parallel with the Neocomian of the Old World, though they may be older.

[1] Engineer Department, U. S. Army. Preliminary Report of Explorations in Nebraska and Dakota, in the Years 1855–'56–'57, by Lieut. G. K. Warren. Reprint. Washington, 1875, pp. 1–125, 1 map.

[2] Explorations under the War Department; notes explanatory of a map and section illustrating the geological structure of the country bordering on the Missouri River, from the mouth of the Platte River to Fort Benton, in lat. 47° 30′ N., long. 110° 30′ W., by F. V. Hayden: Proc. Acad. Nat. Sci., Phil., Vol. IX, 1857, Philadelphia, 1858, pp. 109–116.

[3] Descriptions of New Species and Genera of Fossils, collected by Dr. F. V. Hayden in Nebraska Territory, under the direction of Lieut. G. K. Warren, U. S. topographical engineer; with some remarks on the Tertiary and Cretaceous formations of the Northwest, and the parallelism of the latter with those of other portions of the United States and Territories, by F. B. Meek and F. V. Hayden; loc. cit., pp. 117–148.

Furthermore, under the head of "Conclusions," on page 133, they say:

Although the weight of evidence thus far favors the conclusion that this lower series is of the age of the lower Green Sand, or Neocomian of the Old World, we yet want *positive* evidence that portions of it may not be older than any part of the Cretaceous system.

In a subsequent paper, published one year later,[1] the same authors extend these considerations to include their researches in the Black Hills, and this may be regarded as the first scientific treatment of the geology of the Black Hills. Relative to their formation No. 1, they say in this paper:

It will be remembered, we have in all our published papers, when speaking of that portion of the Nebraska section composing No. 1, expressed doubts respecting its age. We placed it provisionally as the basis formation of the Cretaceous series, but at the same time stated it was not positively known to belong to the Cretaceous system (p. 44).

They proceed to reproduce the passage last quoted, and add:

Although we have little direct additional evidence at this time in regard to the age of this series, as we have always understood it, we now know that from beneath its lower beds, around the base of the Black Hills, there rises a series of very similar strata, as may be seen by the foregoing section, separated from its base by no well-marked line of demarcation, and containing many fossils closely similar to those considered characteristic of the Jurassic system of the Old World. At the same time we have failed to recognize amongst these fossils any forms peculiar to the Cretaceous epoch, or even very nearly analogous to species common in rocks of that age. . . .

Inasmuch, however, as numerous leaves beyond a doubt belonging to dicotyledonous trees, closely analogous to the oaks, willows, and other existing forest trees, are known to occur in No. 1 along the Missouri, near the Big Sioux, and in northeastern Kansas, and we have a *Baculite* from similar beds, apparently of the same age, near the mouth of Judith River, on the upper Missouri—while we also learn from the letters and notes of our deceased friend, Mr. Henry Pratten, that he saw a species of *Baculite* in formations presenting the same characters, and seeming to occupy the same position, along the Platte above Fort Laramie, we think we hazard little in viewing at least a considerable portion of No. 1 as belonging to the Cretaceous system.

Another fact favoring the opinion that No. 1, even down as low as we have provisionally carried it in the Black Hills section, probably belongs to the Lower Cretaceous, is the occurrence at its base of a bed containing *Ammonites* and *Ostrea*, along with *Unio*, *Planorbis*, and *Paludina*; an association of fossils which, in that position, carries the mind rather to the Wealden than to older formations.

The occurrence of these forms at this horizon also leads us to suspect that a considerable portion of the estuary beds at the mouth of Judith River, above Fort Union, in regard to the age of which we have been so much puzzled, may be, as first suggested by Dr. Leidy, a representative of the Wealden, and, as we were then inclined to suppose, belong to our No. 1. . . .

Since we know that there is a similar group of beds at the base of No. 1, as we

[1] Descriptions of New Organic Remains collected in Nebraska Territory in the year 1857, by Dr. F. V. Hayden, Geologist to the Exploring Expedition under the command of Lieut. G. K. Warren, Top. Eng. U. S. Army, together with some remarks on the Geology of the Black Hills and portions of the surrounding country, by F. B. Meek and F. V. Hayden, ibid., Vol. X, Philadelphia, 1859, pp. 41-59.

now understand it, near the Black Hills, containing a mingling of fresh-water and marine fossils, although we are not sure any of them are specifically identical with those found near the Judith, we are inclined to think our first views in regard to these Judith River formations will prove to be correct, or in other words, the beds from which the saurian remains described by Dr. Leidy were obtained, will yet prove to be a part of the series we include in No. 1 of the Black Hills section. This view receives additional support, too, from the fact that the Judith River fresh-water or estuary formations were often seen much upheaved and distorted, while around the Black Hills the Tertiary deposits appear to lie undisturbed upon the upheaved older rocks, in such a manner as to indicate that the last period of disturbance among the strata of this region occurred after the close of the Cretaceous epoch, but previous to the deposition of the Tertiary (pp. 45, 46).

From all this it is perfectly clear that both Meek and Hayden originally regarded the Dakota group as true Lower Cretaceous, i. e., as lying below the Cenomanian of Europe. Their argument seems to have been in the main in the direction of proving that it could not be lower than Cretaceous, i. e., that it could not be Jurassic or Triassic. It is true that the fossil plants, as already indicated by Newberry, pointed to a Middle Cretaceous age, and not long afterwards quite large collections of plants were made and studied by Heer and others, who were disposed to place the beds still higher.

But it is also true that the determinations of Meek, Hayden, and Leidy, based entirely on the scanty animal remains, and pointing to the Lower Cretaceous, Neocomian, or Wealden, related to beds in which there were very few if any vegetable remains, and which lay below the plant-bearing horizon. The plant beds consist of dark brown, highly ferruginous sandstone, often becoming clay ironstone, and these still constitute the typical Dakota sandstone. Now the lower beds holding the animal remains do not conform to this description, but are rather light colored, coarse sandstones with only occasional yellow ferruginous bands. They have a considerable thickness, and there is no antecedent improbability in their belonging to a lower horizon.

The next important paper was published four years later by Dr. Hayden,[1] but was read July 19, 1861, and is little more than a reëlaboration of the subjects treated in the papers already quoted from. In this paper Dr. Hayden continues to refer to No. 1 as Lower Cretaceous.

Dr. Hayden accompanied, as geologist, the expedition in charge of Col. William F. Raynolds to explore the head waters of the Yellowstone and Missouri rivers, in the years 1859 and 1860. His report was long delayed, but appeared in 1869.[2] This expedition did not, of course, purport to explore the Black Hills, nevertheless they were entered at various points and are dealt with more or less extensively in this report.

[1] On the Geology and Natural History of the Upper Missouri: Trans. Am. Phil. Soc., Vol. XII, new series; Philadelphia, 1863, pp. 1-218, 1 map.

[2] Geological Report of the Exploration of the Yellowstone and Missouri rivers, by Dr. F. V. Hayden, assistant, under the direction of Capt. (now Lieut. Col. and Bvt. Brig. Gen.) W. F. Raynolds, Corps of Engineers, 1859-'60; Washington, 1869.

One paragraph relates exclusively to Dakota No. 1, and has more than usual interest in the present connection:

In the vicinity of the Black Hills, as well as in several other localities, which will be alluded to hereafter in their proper places, are a series of doubtful beds, between the well-marked Jurassic and the Cretaceous. These rocks are quite variable in their character, sometimes composed, for the most part, of a loose material, clays and grits; again of compact concretionary sand or limestones. But few organic remains have as yet been found in these beds, although the most diligent search has been made, and those are quite uncharacteristic, so that their position remains in doubt. I have therefore ventured to call them beds of transition, or passage between the close of the Jurassic period and the dawn of animal life in the Cretaceous. The locality where the following section of these doubtful beds was taken is near the source of the Little Missouri, upon the northeastern side of the Black Hills (pp. 45-46).

A section of the beds follows in harmony with this statement.

Dr. Hayden continued his explorations during the subsequent years, and in 1867 was begun the series of official reports made by him as Geologist in Charge of the United States Geological Survey of the Territories. The first of these annual reports, which related to the Territory then embraced in Nebraska, was for the year 1867. Only a small edition of this report was published at the time, and the same is true of the two subsequent ones for 1868 and 1869; but in 1873 these three reports were republished in a small volume, and it is in this form that they are now usually quoted.[1] In the first of these reports the Black Hills are scarcely treated, but the general section is reproduced unchanged from earlier publications. In the report for 1868 the Black Hills receive special treatment; their geographical position is carefully indicated, and their topographic features described. The geology is also dealt with, and the following passages should be specially noted:

The geological structure of the Black Hills may be mentioned briefly in this connection. The nucleus or central portion is composed of red feldspathic granite, with a series of metamorphic slates and schists superimposed, and thence upon each side of the axis of elevation the various fossiliferous formations of this region follow in their order to the summits of the Cretaceous, the whole inclining against the granitoid rocks at a greater or less angle. There seems to be no unconformability in these fossiliferous rocks from the Potsdam inclusive to the top of the Cretaceous.

From these facts we draw the inference that prior to the elevation of the Black Hills, which must have occurred after the deposition of the Cretaceous rocks, all these formations presented an unbroken continuity over the whole area occupied by these mountains. This is an important conclusion, and we shall hereafter see its application to other ranges, and also to the Rocky Mountain Range taken in the aggregate (pp. 69-70).

In the report for 1869 Dr. Hayden goes more fully into the geological formation, and this report throws great light on the position of the lowest Cretaceous beds:

I believe that a thin remnant of this belt extends far south to New Mexico, but it is often so obscured, or so easily concealed, that I have been continually in doubt in

[1] First, Second, and Third Annual Reports of the United States Geological Survey of the Territories for the Years 1867, 1868, and 1869, under the Department of the Interior; Washington, 1873.

regard to its existence. Coextensive with all the mountain ranges is a large series of beds above the Jurassic belt which belong to the Cretaceous period, the upper and middle portions of which are everywhere indicated by characteristic fossil remains, as seen on the Missouri River, where they were first studied by Mr. F. B. Meek and the writer. The Cretaceous rocks present five well-marked divisions, Nos 1, 2, 3, 4, and 5, or Dakota group, Fort Benton group, Niobrara division, Fort Pierre group, and Fox Hill beds. On the Lower Missouri No. 1, or Dakota group, is characterized by several species of marine shells and a profusion of impressions of deciduous leaves; but along the margins of the mountain elevations I have never been able to discover a single specimen of organic remains that would establish the age of the rocks. I only know that there is a series of beds of remarkable persistency all along the margin of the mountain ranges, holding a position between well-defined Cretaceous No. 2 and Jurassic beds, and in my previous reports I have called them transition beds, or No. 1. They consist of a series of layers of yellow and gray, more or less fine-grained sandstones and pudding stones, with some intercalated layers of arenaceous clays. In almost all cases there is associated with these beds a thin series of carbonaceous clays, which sometimes becomes impure coal, and contains masses of silicified wood, etc. On the west side of the Black Hills they assume a singularly massive appearance, nearly horizontal, 200 to 250 feet thick, and are called Fortification Rocks. Here also occurs a thin bed of carbonaceous clay. On the eastern slope of the Big Horn Mountains I observed this same series of beds in the summer of 1859, holding a position between Cretaceous No. 2 and the Jurassic marls, with a considerable thickness of earthy lignite, large quantities of petrified wood, and numerous large uncharacteristic bones, which Dr. Leidy regarded as belonging to some huge saurian.

There are very few points of resemblance between these beds and those which form the Dakota group, as seen in Kansas and Nebraska.

All the evidence therefore that I have had to guide me in regard to these beds along the margin of the mountain ranges has been their position (pp. 113–114).

Dr. Hayden's reports for the years 1870–1873 relate chiefly to the Great Plains and other parts of the Western country, and we find no additional matter bearing directly upon the Black Hills until the appearance of Captain Ludlow's report of the military expedition of 1874, which again penetrated this region. The geologist of this expedition was Dr. N. H. Winchell, and his report follows immediately that of Captain Ludlow.[1]

Professor Winchell gives numerous sections of the strata of the Black Hills at different points, but is very cautious with regard to their correlation with other beds, and I find no indication that he differs from the views expressed by Dr. Hayden with regard to the position of the Cretaceous strata, but he does not make use of the sections of Meek and Hayden. The legend of the map does not contain any of the general geological terms, such, for example, as Cretaceous, and the beds which were referred to the Dakota group by other authors are here simply called "Dakota sandstone." They are not represented as extending entirely around the hills, but are put down in patches along the eastern and western sides and at the southern extremity, with

[1] Report of a Reconnaissance of the Black Hills of Dakota, made in the summer of 1874, by William Ludlow, Captain of Engineers, Bvt. Lieut. Col., U. S. Army, Chief Engineer, Department of Dakota. Washington, 1875. Geological Report, by N. H. Winchell, State Geologist of Minnesota, pp. 21–66, 1 map.

large intervals of uncolored regions. It is evident that Professor Winchell did not observe any subdivision of these beds.

This brings us, in chronologic sequence, to the most important geological survey that has been made of the Black Hills, even down to this date, viz, that of Newton and Jenney, in 1875, the geological part of which was, unfortunately, not published until 1880.[1]

The manuscript of this report was prepared somewhat promptly, and Professor Jenney's portion, relating to the mineral resources, was published by Congress in 1876, as Senate Executive Document No. 51, of the first session of the Forty-fourth Congress, but the geological report and the rest of the manuscript remained unpublished for four years, when it appeared as above, having been revised and edited by Mr. G. K. Gilbert. In the biographical notice of Dr. J. S. Newberry the origin of the expedition is stated in the following language:

> In 1875 the Secretary of the Interior applied to Professor Henry, the head of the Smithsonian Institution, requesting him to suggest a geologist to take charge of an exploration of the Black Hills, Dakota, for the purpose of ascertaining the extent and value of the gold deposits discovered there. This request was, by Professor Henry, referred to me, and in accordance with my nominations Mr. W. P. Jenney was appointed geologist and Mr. H. Newton his assistant. The purely geological work of the expedition was for the most part performed by Mr. Newton, and the report now committed to you for publication is the result.

Professor Newton's report on the geology had long been completed and appears to have been in nearly perfect form at the time of his death in 1877. It forms the first part of the volume, occupying 220 pages, and the report is accompanied by an atlas containing three maps. The colored geological map is far more complete than any previous map of the Black Hills and shows, as none of the former ones had done, the remarkably symmetrical character of their geological relations. It shows first that there is a narrow ring of Potsdam sandstone, then a wide belt of Carboniferous limestone; next an encircling trough, aptly compared by Professor Newton to a moat, of red sandy gypsiferous clays, in which is included a purple limestone terrace, all of which is supposed to be Triassic, and to be the equivalent of the "Red Beds" of more southern regions. Skirting this is a very narrow border of highly fossiliferous light-colored Jurassic clays or marls. Then come the foothills, which consist of Cretaceous sandstones and shales referred by Professor Newton to the Dakota No. 1 of Meek and Hayden's section. These slope back to the dark shales of the Fort Benton group, which are succeeded by higher Cretaceous beds that extend to the plains and pass under the Bad Lands of the White River formation.

We are of course concerned here only with the Cretaceous, and strictly speaking only with the lowest member recognized by Professor Newton. In his report he takes up the several subdivisions of the Cretaceous in

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[1]Report on the Geology and Resources of the Black Hills of Dakota, with Atlas, by Henry Newton and Walter P. Jenney. Dept. Int., U. S. Geog. and Geol. Surv. Rocky Mountain Region, J. W. Powell in Charge. Washington, 1880.

their descending order, but uses the numbers of Meek and Hayden. He therefore begins with No. 5 (the Fox Hills group), and deals respectively with this, with No. 4 (the Fort Pierre group), No. 3 (the Niobrara group), and No. 2 (the Fort Benton group), concluding with No. 1 (the Dakota group), under which he includes all that series of rocks which lie between the black shales of the Fort Benton and the Jurassic beds.

The description of this formation is taken almost literally from the numerous memoirs and reports previously published by Meek and Hayden, and is as follows:

Yellowish, reddish, and occasionally white sandstone, with at places alternations of various-colored clays and beds and seams of impure lignite; also silicified wood, and great numbers of leaves of the higher types of dicotyledonous trees, with casts of *Pharella? Dakotensis, Trigonarca Siouxensis*, etc. (p. 174).

It will be observed that under localities quoted Professor Newton does not even mention the Black Hills, but proceeds immediately to characterize the formation as observed in the Black Hills in the following language:

Black Hills.—Prominently developed, forming the capping rock to the foothills that surround the Hills on all sides, appears with its characteristic composition—coarse yellow or red sandstones with discontinuous variegated clays. At places a considerable thickness of very soft and fine white sandstone appears at the base. Elsewhere considerable portions are of hard, dense quartzite. No animal fossils were found, but many remnants of plants—in no case more than mere coaly fragments.

Thickness, 250 to 400 feet.

The rim of Cretaceous strata which encircles the Hills dips outward on all sides or away from the axis of upheaval. The strata begin with the foothills that border the outer edge of the valley. The Dakota sandstone, resting conformably upon the Jura, forms the capping rock of the foothill ridge, and dips outward at various angles from 10° to 40°. Just as the Cretaceous encircles the outcrop of the underlying Jura and Trias, so the different overlying groups of the Cretaceous—the Fort Benton, the Niobrara, the Fort Pierre, and the Fox Hills—succeed each other in regular order, forming a series of concentric ridges that decrease in altitude as the distance from the Hills increases (p. 175).

This description is further reinforced by the following more special characterization:

Taking up the groups now in order, the first to describe is the Dakota. Typically it is a coarse sandstone, generally conglomeratic, yellowish in color, and stained red in places by the oxidation of the iron contained in its nodules. Sometimes the sandstone is white in color and uniform and fine in texture, and in several places large portions of the formation consist of intensely hard, glassy, and compact quartzite, white or brownish in color, and having the density, toughness, sharpness, and conchoidal fracture of typical flint. The quartzitic development was especially observed at the southern end of the Hills, where the Dakota expands into a plateau, and in the region north of Warren Peaks, but it is not confined to those localities (p. 176).

The general relation of these beds to those underlying them in the Black Hills is admirably shown in two sections on pages 140 and 141 of that volume, which are reproduced below as figs. 117 and 118.

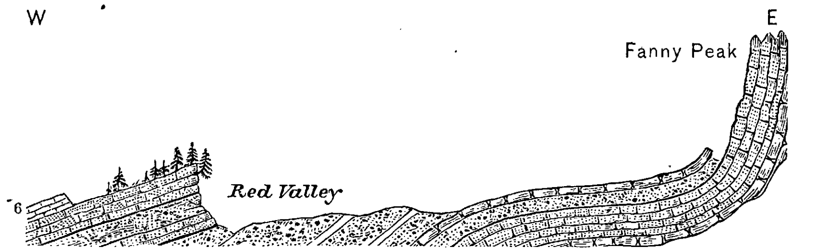


FIG. 117.—Ideal section across the Red Valley at Camp Jenney, showing the foothills at the left and Fanny Peak at the right. (1) Carboniferous limestone; (2) Red sandstone (Carboniferous); (3) Purple limestone (Red Beds); (4) Red clays with gypsum (Red Beds); (5) Jura; (6) Cretaceous.

Upon the geological map accompanying this report have been based all subsequent ones, and very few additions have been made. It is reproduced here with very little change except as regards towns, railroads, etc., resulting from the settlement of the country since that date, and may serve as a general index map of that region (see Pl. LIII).

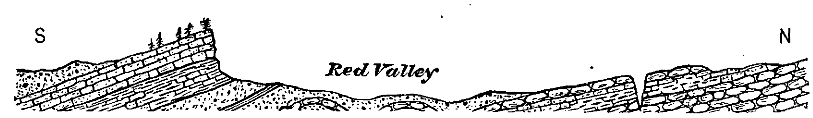


FIG. 118.—Ideal section across Red Valley on Amphibious Creek.[1] (1) Carboniferous; (2) Red sandstones and clay (Red Beds); (3) Purple limestone (Red Beds); (4) Red clay with gypsum (Red Beds); (5) Jura; (6) Cretaceous sandstone capping the foothills.

After the appearance of this report a long interval elapsed before any further special discussion of the geology of the Black Hills took place, during which time the country was being rapidly settled and the more important locations were being seized upon as sites for towns, while an agricultural population was gradually encroaching from without. A State school of mines was established at Rapid City and, in addition to mining interests, some local attention was being paid to geology.

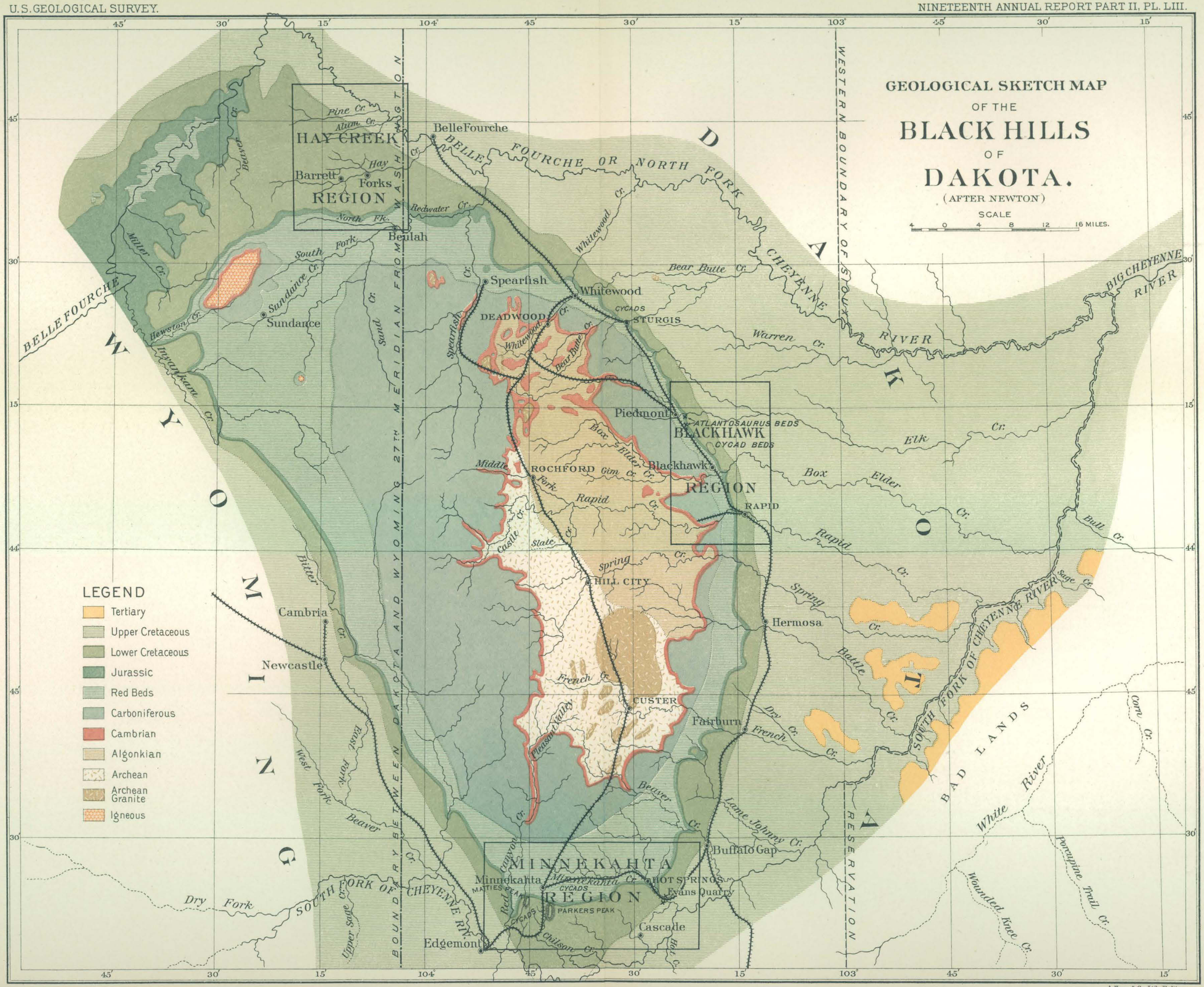
In the year 1888 two papers, by F. R. Carpenter and W. O. Crosby, appeared on the geology of the Black Hills, the priority of which I have not been able to determine.[2]

Each of these papers is an important contribution, and that of Mr. Carpenter contains a map in which the drainage and all the important

[1] Amphibious Creek is the name given in the Geology of the Black Hills to the stream now called Beaver Creek, which in cutting through the rim forms the canyon known as Buffalo Gap. It is unfortunate that the name should have been changed, as there are several other Beaver Creeks in the Black Hills, and the Board on Geographic Names would do well to restore it.

[2] Notes on the Geology of the Black Hills, by Franklin R. Carpenter; Preliminary Report of the Dakota School of Mines upon the Geology, Mineral Resources, and Mills of the Black Hills of Dakota. Rapid City, 1888, pp. 11-52.

Geology of the Black Hills of Dakota, by W. O. Crosby: Proc. Bost. Soc. Nat. Hist., Vol. XXIII, pp. 488-517. Read March 7, 1888.



A. Hoen & Co. Lith. Baltimore.

towns are shown, as well as the general geology. Some considerable advance is made in the knowledge of the geological formations, but it relates principally to the lower beds. The Cretaceous assumes importance only in connection with the discussion of the age of the uplift, which was formerly supposed to be entirely post-Cretaceous; but evidence is adduced in these papers to show that much of the material, even of the lowest Cretaceous, is derived from the older and more central deposits, which must therefore have been elevated at an earlier date. Nothing is here said about subdividing the Dakota group of Newton, and the matter remained in all respects in its original form.

In the summer of 1889 Professor Van Hise, of the U. S. Geological Survey, and Mr. C. W. Hall made a "vacation trip into the Black Hills of South Dakota," and at the meeting of the Minnesota Academy of Natural Sciences on December 3 of that year Mr. Hall read a paper before that academy, an abstract of which appeared in its proceedings of that date.[1] So far as this abstract shows their investigations were confined almost exclusively to pre-Cambrian strata, and the Cretaceous is not mentioned.

In this rapid survey of the history of the discovery of the Cretaceous in the Black Hills and of the Dakota group in general, I have been obliged to leave out of account a series of events connected with the subject in a general way, but without relation to the Black Hills, consisting in the tracing of the Dakota group across the plains from Minnesota to Kansas, the discovery of an immense flora and its elaboration at the hands of Heer,[2] Newberry,[3] and Lesquereux,[4] accompanied by an animated discussion as to the age of the Dakota group.

After numerous mistakes, due to conclusions drawn from insufficient material, to the infancy of the science of fossil plants, and to preconceptions based upon Old World geology, a general consensus was at

[1] Bulletin of the Minnesota Academy of Natural Sciences, Vol. III, No. 2. Proceedings and Accompanying Papers, 1887-1889, Minneapolis, 1891, pp. 185-186.

[2] Les Phyllites Crétacées du Nebraska, par MM. les Prof. J. Capellini et O. Heer: Mem. Soc. Helv. Sci. Nat., Vol. XXII, No. 1, Zurich, 1866, 22 pp., 4 pl. Sur les plantes fossiles du Nebraska, par Osw. Heer: loc. cit., pp. 11-22, Pl. I-IV.

[3] Notes on the Later Extinct Floras of North America, with Descriptions of some New Species of Fossil Plants from the Cretaceous and Tertiary Strata, by J. S. Newberry: Ann. Lyc. Nat. Hist., Vol. IX, New York, April, 1868, pp. 1-76.

Illustrations of Cretaceous and Tertiary Plants of the Western Territories of the United States; Department of the Interior, U. S. Geol. and Geogr. Surv. Terr., Washington, 1878, 4°, 26 pl.

[4] On some Cretaceous Fossil Plants from Nebraska, by Leo Lesquereux: Am. Jour. Sci., 2d ser., Vol. XLVI, July, 1868, pp. 91-105.

Contributions to the Fossil Flora of the Western Territories, Part I; The Cretaceous Flora, by Leo Lesquereux: Rept. U. S. Geol. Surv. Terr., F. V. Hayden, Geologist in Charge, Vol. VI, 4°, Washington, 1874, 136 pp., 30 pl.

A Review of the Cretaceous Flora of North America, by Leo Lesquereux: Eighth Ann. Rept. U. S. Geol. and Geogr. Surv. Terr., for the year 1874, F. V. Hayden, U. S. Geologist, Washington, 1876, pp. 316-365, pls. i-viii.

Contributions to the Fossil Flora of the Western Territories, Part III; The Cretaccous and Tertiary Floras, by Leo Lesquereux: Department of the Interior; Rept. U. S. Geol. Surv. Terr., F. V. Hayden, Geologist in Charge, Vol, VIII, 4°. Washington, 1883. Description and Enumeration of Species of the American Dakota Group Formation, pp. 25-107, pls. i-xvii.

The Flora of the Dakota Group, A Posthumous Work, by Leo Lesquereux, edited by F. H. Knowlton: Mon. U. S. Geol. Survey, Vol. XVII, 4°, Washington, 1892, 400 pp., 66 pl.

last reached which placed the Dakota group into substantial correlation with the Cenomanian of Europe. This view, based almost exclusively on the fossil plants, had become so firmly established that it resulted in a general feeling that Dr. Hayden, Mr. Meek, and others had made a great mistake in referring any of the beds embraced in their Cretaceous No. 1 to the Lower Cretaceous in any sense other than that they were the lowest Cretaceous beds represented in North American geology, and the opinion had come to prevail that there was no Lower Cretaceous in the Rocky Mountain region.

But simultaneously with the latter part of this period investigations in British America, on the Queen Charlotte Islands, in California, in Texas, and in Virginia had led to the certainty of the existence of true Lower Cretaceous beds in each of those regions, and had brought to light the Kootanie, the Queen Charlotte group, the Shasta group, the Comanche series, and the Potomac formation. I had myself been engaged in the study of the Lower Cretaceous flora of the United States, and especially of the Potomac formation, since the year 1885, and had examined a number of the Lower Cretaceous areas in other parts of the country. In 1883 I visited the Great Falls of the Missouri in company with Dr. C. A. White, and I observed that the rocks in that region which Dr. White, in harmony with the tradition of the time, referred to the Dakota group were entirely different in character from the well-known brown sandstone which yields the flora of that group, and I even dared to suspect that such a vast thickness of these beds as is displayed on the Upper Missouri could scarcely all belong to the Dakota group. In 1888, or thereabouts, Mr. R. S. Williams made a collection of fossil plants at the town of Great Falls, which were referred to Dr. Newberry for determination and were described by him in the year 1891.[1] He found them to agree in all essential respects with forms of the Kootanie, as made known by Sir William Dawson, and thus was established the true Lower Cretaceous age of these deposits. Subsequent discoveries have only confirmed this conclusion, and considerable additional evidence has been brought to light. Collections made by Knowlton, Peale, and Weed were elaborated by Professor Fontaine,[2] and in 1895 I visited the region myself and made a much larger collection than any of the previous ones, chiefly from Cascade County, some 25 miles southeast of Great Falls, between the Little Belt and High Wood Mountains, from coal mines in the same formation. This collection has also been studied and reported upon by Professor Fontaine, but his report is not yet published. Suffice it to say that all this material agrees in supporting the conclusion reached by Dr. Newberry as to the substantial identity of this flora with that of the Kootanie beds of British America.

[1] The flora of the Great Falls coal field, Montana, by J. S. Newberry: Am. Jour. Sci., 3d series, Vol. XLI, March, 1891, pp. 191-201, pl. xiv.

[2] Description of some fossil plants from the Great Falls coal field of Montana, by William M. Fontaine: Proc. U. S. Nat. Mus., Vol. XV, Washington, 1892, pp. 487-495, pls. lxxxii-lxxxiv.

A somewhat careful study of the flora of the Amboy clays and of beds of practically the same age on the shores of the Chesapeake Bay and across the State of Maryland to the Potomac had led me to the conclusion that these deposits also lie below the line which should properly separate the Upper from the Lower Cretaceous. Investigations in Alabama and other Southern States had further shown the virtual identity in age of the Tuscaloosa formation and the Amboy clays. The Comanche series had yielded a few fossil plants, which proved to be at least as old as the oldest Potomac beds.[1] All these results, taken together, had led me to believe that the true Lower Cretaceous was really very widespread, and that it would be found in many parts of the West where it had not hitherto been suspected to exist.

In the investigation of the Potomac formation in Maryland the subject of fossil cycads had necessarily become prominent, and I arrived at the conclusion that all the trunks of this character that had been discovered in Maryland are derived from the older beds, which I call the Basal Potomac. Professor Cragin had obtained a fragment from Kansas which certainly belongs to a cycad trunk and which he described as *Cycadeoidea munita* in 1892.[2] He supposed that this fragment came from the Cheyenne sandstone, but after having visited the locality I am satisfied that this could not have been the case, and, taking all the evidence into account, I am inclined to believe that it had weathered out from the base of the true Dakota group, perhaps from the Reeder sandstone.[3]

I mention the cycadean trunks because it was through these that my interest was first attracted to the Black Hills. In February, 1893, the Smithsonian Institution received a letter from Mr. F. H. Cole, at Hot Springs, South Dakota, a dealer in specimens, inclosing photographs of certain petrifactions found in that vicinity, which he said had been called "cycads." The letter and photographs were referred to me on the presumption that these objects were of vegetable origin. I at once perceived that they were fossil cycadean trunks closely resembling those collected by Tyson in 1860 in the iron-ore clays of Maryland and named by Professor Fontaine *Tysonia marylandica*, and, therefore, also similar to the forms found by Mantell and others in the early part of the century in the Purbeck beds on the Isle of Portland and at other points in the south of England. Being greatly interested in the discovery, I recommended that the owner of the fossils be requested to send on a specimen for examination. The request was complied with, and the specimens proved to be all that I had expected. I therefore made the further recommendation that negotiations be entered into

[1] Notes on some fossil plants from the Trinity division of the Comanche series of Texas, by William M. Fontaine: Proc. U. S. Nat. Mus., Vol. XVI, Washington, 1893, pp. 261-282, pl. xxxvi-xliii.

[2] Contributions to the palæontology of the Plains, No. 1, by F. W. Cragin: Bull. Washburn College Lab. Nat. Hist., Topeka, Vol. II, No. 10, 1889, pp. 65-68.

[3] See Mr. C. N. Gould's paper in Am. Jour. Sci., 4th series, Vol. V, March, 1898, pp. 173, 174.

with a view to the purchase of the collection of six specimens, which were offered for sale. This recommendation was also adopted; the collection was purchased, and arrived in May, 1893.[1]

Hot Springs is located on the Red Beds in the valley of the Minnekahta Creek, or Fall River, and it would have been natural to suppose that the cycad trunks had come either from these or from the Jurassic which borders it had it not been stated that they were found "on a high hill." My interest was, of course, strongly aroused to know the stratigraphical position of the beds in which they occurred, and therefore early in September I made an expedition to the region for the purpose of determining it if possible. I had previously corresponded with Mr. F. H. Cole, of Hot Springs, from whom the specimens had been purchased. I had also written to Professor Jenney, who was then at Deadwood, and who kindly consented to join me on my arrival and aid me in the investigation. After considerable search and some difficulty the locality was at length found. The details of this expedition are given below (p. 552).

The general resemblance of these cycad trunks to those that have been discovered in various parts of the world in beds below the Middle Cretaceous raised the suspicion in my mind that these deposits might be older than the plant-bearing Dakota. I learned while there that Professor McBride had been in that region studying the cycads, and that he had collected some and taken them to the State University of Iowa, at Iowa City. In October of that same year he published a description of a species which he called *Bennettites dacotensis*.[2] Professor McBride, and also Professor Calvin, State geologist of Iowa, who had examined the region, presented papers on this subject before the Iowa Academy of Sciences in December, 1893, the latter especially discussing the geological position of the cycads.[3] Professor Calvin shortly after published the results of his investigations in a communication to the American Geologist.[4] Professor Calvin's principal object seems to have been to fix the position of the cycad beds relatively to the well-recognized formations above and below, and it was not, of course, difficult for him to show that they lay between the Fort Benton shales and the marine Jurassic. The idea that this thick formation, amounting in some places to 400 feet, should itself be susceptible to subdivision does not seem to have occurred to him, and after considerable discussion of these more general relations, in which he seems to realize that he is giving a great breadth to the subject, he concludes in the following language:

> Returning finally to the main object for which these observations were undertaken, it is clear that *Bennettites dacotensis* McBride belongs to the Cretaceous period,

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[1] See Science, Vol. XXI, No. 543, June 30, 1893, p. 355.

[2] A new cycad, by T. H. McBride: Am. Geologist, Vol. XII, October, 1893, pp. 248–250, pl. xi. Reprinted in Bull. Lab. Nat. Hist., State Univ. Iowa, Vol. II, No. 4, 1893, pp. 391–393, pl. xii.

[3] See Science, Vol. XXIII, No. 570, January 5, 1894, p. 10.

[4] Am. Geologist, Vol. XIII, No. 2, February, 1894, pp. 79–84; also published in the Proc. Iowa Acad. Sci. for 1893, Vol. I, pt. 4; Des Moines, 1894, pp. 18–22.

and the evidence is practically conclusive that the exact horizon at which the individuals of the species were imbedded is represented by the uppermost layers of the Dakota sandstone.

I was wholly unaware of the work that Professors McBride and Calvin were doing, and had overlooked the article of the former in the American Geologist for October. On my return from the Black Hills I proceeded to elaborate the results that I had reached, but having much else to do I did not complete the paper until after the middle of February, 1894, when I sent it on to the Journal of Geology, in which it soon after appeared.[1] The substance of that paper will be given under the next head.

In all that I said in this paper Professor Jenney concurred, as we were together during the entire investigation, and I sent him the manuscript when completed. The sections were made after mutual consultation, and in the field, and were reproduced in the article without change. The diagrammatic sections are my own, and are based upon the data collected. As stated in that article, we were not satisfied with the evidence furnished by the cycads alone or by the cycads and the fossil wood, but proceeded to discover beds containing fossil plants, both in the lower portion and also in the upper. These two classes of plant-bearing beds differ fundamentally, and the nature of the plants from the lower beds made it practically certain at a glance that they could not belong to the plant-bearing Dakota group. But I was not satisfied to rest the case upon my own judgment as to these plants. I therefore referred them to Professor Fontaine, whose thorough familiarity with the older Potomac flora and Mesozoic plants in general has made him the leading authority on the subject. His report upon the collection is published in this article, pp. 259–260. The concluding paragraph of that report is as follows:

It will be seen from this account that the plants, so far as one can judge from such imperfect material, indicate a Lower Cretaceous and Neocomian age, with rather more resemblance to the Kome than Potomac phase or grouping, but it is by no means certain that the Potomac grouping is not nearest to that here shown.

I also referred the fossil wood to Professor Knowlton, and his report immediately follows that of Professor Fontaine, and is in entire harmony with it as regards the Lower Cretaceous age of the specimens. Indeed it would naturally seem to point to a still earlier period, although it can not be said to prove this.

The specimens from the upper beds were indentified by myself, and are fully described and figured below (p. 702–709, Pls. CLX–CLXXII). There is no reason to suppose that they do not represent the true Dakota group, and the line between the Upper and Lower Cretaceous must fall somewhere between the cycad beds and the upper plant beds

[1] The Cretaceous rim of the Black Hills, Jour. Geol., Vol. II, No. 3; Chicago, April-May, 1894, pp. 250-266.

above the quarry sandstone. Nothing has happened since that paper was published to modify the following statements which it contained:

It thus appears that the flora of the beds above Evans quarry is distinctly that of the Dakota group, while all the plants found below that horizon as distinctly indicate a Lower Cretaceous age. The force of this evidence is to my mind irresistible, and it is safe to predict that if any other paleontological evidence is ever found it will confirm this conclusion. The question still remains as to where the dividing line is to be drawn. Between the cycad and fossil wood horizon and that of the Dakota leaves there are some hundred feet of sandstones and shales. Sixty to seventy-five feet of this consists of the massive or heavy-bedded building stone, which in places becomes flinty and very hard. As the thin shaly layer which separates this from the leaf bed may be safely put with the latter into the Dakota proper, and there seems no reason for separating the similarly constituted layer that intervenes between the cycad horizon and the base of the sandstone from the one upon which it rests, the question is narrowed down to that of the position of the quarry sandstone. That question I will leave to the stratigraphical geologists (p. 263).

Professor Todd, State geologist of South Dakota, in 1894 still continued to place the Dakota group between the Jurassic and the Fort Benton, and to indicate the earlier Cretaceous as "absent."[1] He does not do this in ignorance of the results at which I had arrived, but reproduces my sections (pp. 63–71), speaking of one of them as "particularly valuable both for its completeness, and the careful discrimination and measurement of the strata." Commenting on these sections, Professor Todd says:

A point of special interest should be mentioned here, namely, that numerous specimens of cycad trunks have been found at various points. Those which have been quite carefully studied and described by Mr. L. F. Ward (Journal of Geology, 1894), of the United States Geological Survey, and Professor McBride (American Geologist, 1894), of the Iowa State University, were collected in the southern part of the Hills, southwest of Minnekahta and southeast of Hot Springs. Specimens also have been found several miles north of Rapid City, and in a ravine southwest of that place. They all seem to be traceable to the lower layers of the Dakota sandstone, and Mr. Ward, partly for this reason, strongly suspects that the lower layers of the so-called Dakota formation may be older than that period (pp. 71–72).

This is certainly a very mild statement of my position; and my language was intended to express something much more than a strong suspicion as to the Lower Cretaceous age of these deposits.

But whatever doubts there may have been then, they have all been set completely at rest by subsequent events. During the summer of 1894 Professor Jenney, while operating in the coal-mining district of Hay Creek, Crook County, Wyoming, in the northwest portion of the Black Hills, but within the Cretaceous rim, found fossil plants in great abundance associated with the coal. True to his instincts as the type of a scientific collector, he proceeded to collect these plants, and, as a pure labor of love, he obtained during the summer and sent to Washington by official mail one of the finest collections that has thus far been

[1] A preliminary report on the geology of South Dakota, by J. E. Todd, State Geologist: South Dakota Geological Survey, Bulletin No. 1, Sioux Falls, 1894, p. 22.

made from any part of the West. They were sent direct to me, and my interest in them, as may well be imagined, was intense. I received them for the United States Geological Survey, and when they had all been unpacked and duly recorded I sent them to Professor Fontaine for determination. He gave them his painstaking attention, and prepared the able report which I embody in this memoir (pp. 645–702, Pls. CLX–CLXIX).

It is needless to anticipate this report further than to say that the plants completely demonstrate the Lower Cretaceous age of the Hay Creek coal field. Professor Jenney was good enough to make a careful study of the stratigraphical relations of the numerous beds in which the plants occur, representing a large number of horizons, which were fully shown in careful sections. At my request Professor Jenney has furnished extensive notes upon his work there, which are embodied in this paper, and he has also kindly furnished a map of that region. All these data together will, I trust, render the whole subject clear to the geologist.

In a revision, which I made in 1894, of the genus Cycadeoidea of Buckland, which genus probably embraces all the fossil cycadean trunks thus far found in America, I described from notes and sketches made by Professor Jenney a new species of that genus, which I called *C. Jenneyana*.[1] The description there given was of course very meager, and is completed in this paper (pp. 627–632, Pls. CXXI–CXXXII).

This species was made known to me by Professor Jenney, who had long been aware of the existence of the two large trunks at the State School of Mines at Rapid City. He had been to the pains to inquire into the source of these and had learned that they were collected many years before, about 10 miles northwest of Rapid City, by a gentleman named Leedy. Being exceedingly anxious to ascertain whether this locality also lies in the Cretaceous rim of the Hills, I went to Rapid City early in August, 1895, where I joined Professor Jenney, and we proceeded to the locality and made a thorough examination of the general region. A more complete account will be found under the description of the Blackhawk region (infra, pp. 560–563), and I need only say here that, as we expected, the beds yielding this specimen lie above the Jurassic, and the cycads were associated with the heavy sandstones which constitute the lowest Cretaceous deposits. These beds are therefore substantially the same, in their stratigraphical relations, as those yielding the other cycads and fossil plants already referred to. Numerous other specimens had been collected and carried away by persons who desired to profit by them, and not one could be found by our party. Some of these, as will be shown, were subsequently obtained by purchase. A great amount of fossil wood occurs in that locality, a good collection of which was made.

[1] Fossil cycadean trunks of North America, with a revision of the genus Cycadeoidea Buckland: Proc. Biol. Soc. Washington, Vol. IX, April 9, 1894, pp. 75–88. (*C. Jenneyana* is described on p. 87.)

From Rapid City I proceeded to Hot Springs, where I obtained considerable additional material, some of it from localities already described, but the remarkable trunk which I call *Cycadeoidea excelsa*, and which is described below (p. 637), was collected in an entirely different locality, which is fully indicated in connection with the description of the species, and its location on the map is given as exactly as the data will permit.

In both my visits to the Black Hills, in 1893 and 1895, I saw large numbers of fossil cycads at various places, mostly in the hands of dealers in specimens, who held them for sale, often at moderate prices, but others were seen in heaps of stones along with specimens of ore, coal, building stone, and other products of the country, often symmetrically arranged in pyramidal forms, at railroad stations and elsewhere. As the funds at my disposal were limited, I was able to purchase only such as appeared to me to represent distinct species, although I was aware that, not having as yet described the species, I might easily be mistaken in the matter, and that doubtless many new species existed which could have been easily obtained by anyone who had the means.

Well knowing the fate of most of such material, which usually gets into the hands of private individuals making no pretensions to science and who wish such specimens merely as curiosities, but who hold them in high esteem and are unwilling to part with them, or in most cases are so situated that no scientific man ever sees the specimens again, I was glad to learn that Professor McBride had himself secured a large number of specimens for the State University of Iowa, where I hoped they would soon be taken up and submitted to thorough scientific study.

But even after he had secured all he desired great numbers remained, and when, the following year, Prof. O. C. Marsh approached me on the subject and manifested a special interest in these objects, I gladly imparted to him all the information in my possession relative to the best means of securing them, including the names and addresses of dealers who had them for sale, the prices at which they were held, and the localities from which they had been collected, so far as these were known to me. I greatly hoped that with the resources at his command, Professor Marsh would rescue from oblivion and insure to science many of these interesting paleontological treasures.

I heard nothing further from Professor Marsh until on March 18, 1898, I received a letter from him stating that he had obtained a large collection of cycads from the Black Hills and requesting me to come to New Haven and describe them. As the present paper was then already in an advanced stage of preparation and the descriptions of those in my hands were already written and would be included in it, it seemed to me that the opportunity should not be lost of embracing under the same head all the new material that might be accessible. I therefore immediately consulted with the Director on the subject and received orders to proceed at once to New Haven and take all necessary notes on Professor Marsh's collection.

This work was performed from the 22d to the 31st of March. This collection consisted of 87 specimens, and notes were taken upon each of these and the more important of them were fully described. Having with me the descriptions of all the other cycads, I paid special attention to characters which could not be observed in the specimens already described, either because these were too perfect to show any internal structure or from defectiveness of any kind. All variations that the new material indicated from the specimens previously taken as types of species already identified were also carefully noted, with a view to the correction and expansion of the characters. All the new species were of course very carefully dealt with.

In addition to these notes Professor Marsh placed a photographer at my disposal and all the more important specimens were photographed, often from various points of view, for purposes of illustration. All these notes and illustrations appear in their proper places, embodied in the descriptions of the species.

While at New Haven, engaged on this collection, Professor Marsh informed me that two additional invoices were soon expected from the Black Hills, and that he wished me to include these also, if possible, when they arrived. But I could not then wait for them and returned to Washington. On May 20 he telegraphed me that the first invoice had arrived, and on May 31 he similarly notified me of the arrival of the second invoice. The two invoices contained 39 specimens, which, added to the 87 specimens previously received, constitutes a collection of 126 cycadean trunks and fragments.

As nearly all of the first large collection had been obtained from the Minnekahta region, very close to where the original types were discovered, and as these two new invoices were from the Blackhawk region, from which so few cycads had been thus far made known, it was especially important that these should be included in this report, and therefore, at a risk of considerable delay, I undertook their elaboration, which was accomplished in a little over a week, viz, from June 6 to June 13, and this included the work of photographing the important specimens. All the data thus secured are embodied in the descriptions below and constitute a very material increase in our knowledge of the cycadean vegetation of the Black Hills Cretaceous.

Nearly all the specimens in the Yale collection were reported either from the Minnekahta region or from the Blackhawk region, and but very little additional information accompanied the collections. The last invoice from the Blackhawk region was accompanied by data specifying the location of the specimens somewhat in detail, giving distances and direction from Black's ranch, but this embraced comparatively few specimens. The first invoice contained one specimen which was said to have been found between 2 and 3 miles west of Sturgis, South Dakota, a wholly new locality.

With the exception of a small collection obtained by Professor Marsh from Mr. Stillwell, in Deadwood, and reported by him from the Minnekahta region, all of these large collections which Professor Marsh secured were made by Mr. Henry F. Wells, of Sturgis, one of Professor Marsh's trusted collectors of fossil vertebrates, who had been induced to turn his attention to a search for cycads, and whose skill as a collector readily enabled him to locate the cycad beds and obtain quantities of specimens which had been overlooked by more superficial observers. I was certain that Mr. Wells must have covered a considerable area in his explorations beyond that which I had myself seen or that other collectors had visited, and as the work of determining the species proceeded I was more and more impressed with the importance of a fresh survey of the cycad regions, with a view to more exact correlation of the different beds with each other, and a more satisfactory determination of the stratigraphical position of the cycad beds in general. I felt that if I could secure the guidance of Mr. Wells to all these localities this result could be accomplished, and I corresponded with him upon this subject. He expressed a willingness to accompany me to all the localities at any time that I might designate.

I was unable to bring this about until the early part of October, 1898, when, by previous arrangement, I met Mr. Wells at Sturgis, and we devoted eight days to this work, with very satisfactory results. We first visited the new locality between two and three miles west of Sturgis, where specimen No. 1 of the Yale collection was obtained by Mr. Wells. He had found it on a low spur of the foothills, which had dropped or slipped down from the high cliffs to the westward, and was entirely out of position. A second imperfect specimen had been found by him near the same spot, and still lay on the surface. Mr. Wells stated that he had explored the cliffs from which these materials had fallen, but had thus far been unable to find any cycads in position. We then proceeded to the Blackhawk region and went over all the ground covered by his explorations, and later to the Minnekahta region, which was examined in the same way.

The more special results of this expedition, including geological sections, will be given under the Minnekahta and Blackhawk regions, respectively, but some of the general conclusions arrived at from this examination, which was much more thorough than any that I had previously given to the question, may properly be stated here. It is well known that these Cretaceous sandstones form the foothills surrounding the Black Hills, and that they present more or less of an escarpment facing the central core of the hills and separated from the higher and more interior uplift by a broad valley occupied by the Red Beds, which surround the Hills. As a matter of fact, however, the lower part of the escarpment is almost always occupied by beds that are lower than the Cretaceous, the base itself consisting of a greater or less thickness of the Red Beds themselves, succeeded by the whole thickness of the Jurassic, which may amount to 150 feet. Upon this lie the Cretaceous sandstones, which, should they be all represented, would form a cliff more than 300 feet higher, sometimes making a total of nearly 600 feet above the lowest part of the broad encirling valley.

At one time, of course, all these materials extended over the area now occupied by this valley and they have been carried away by the general process of denudation. This process, however, was somewhat peculiar in consequence of the large amount of gypsum contained in the Red Beds, which, as soon as exposed, rapidly disappeared, resulting in a systematic undermining, as it were, of the cliffs, which gave way along an irregular border and either sank or slipped down so as to occupy at different periods positions much lower than that from which they came. The further influence of lateral denudation, forming deep canyons in the sides of the external wall, resulted in the final formation of a large number of narrow spurs or low sloping ridges, often containing the remains of the original cliffs, practically unchanged, after having sunk down to lower positions and still remaining easily identifiable with the cliffs from which they had fallen. The present position of these cliffs, therefore, is no indication of their true position, and although this can usually be determined where large masses have held together, this can not be done in case of loose materials that cover the slopes. Here rocks from all positions in the Cretaceous series lie mingled together and cover the ground to considerable depth, occupying horizons topographically much lower than the base of the Cretaceous. Sometimes these spurs are reduced to small mounds, isolated in the red valley, and cycadean trunks have been found far out in the middle of the valley on such mounds and ridges. Being of a character much more durable than even the hardest of the sandstones, they remain intact wherever they may happen to be, and some have been found lying on top of the Red Beds themselves, all traces of their original matrix having disappeared.

This accounts for a fact that had long puzzled me, viz, the occurrence on many of the cycad trunks of a coating of lime or calcareous matter, often turning one side of them pure white and being very firmly cemented to the rock and difficult to remove. This had led some to suppose that the cycads came out of the calcareous limestone of the Jurassic. As a matter of fact it proves nothing, since the greater part of the cycads that have thus far been found have lain in a position many feet below the base of the Cretaceous, often upon the Jurassic limestone, but usually associated with vast quantities of sand rock, which had accompanied them in the general settling down of the strata to which they belonged.

It is easy to see from all this how very difficult it is to determine the true position of the cycad beds, especially as they are never found adhering in a natural way to the rock in which they were originally embedded, but are always washed out and found lying in all positions, indicative of more or less transportation, or at least local displacement. This is not affected by the fact that nearly all the specimens that Mr. Wells has found that were overlooked by other collectors were more or less buried in the ground, only small parts projecting sufficiently for him to recognize their character. The materials in which they were buried were as heterogeneous as those on the surface, and it would often require many feet of excavation to reach the original bed upon which these loose materials rested.

There are, however, a few facts which may be taken as constituting evidence as to the position of the cycads.

First, a few specimens have been found, if not actually in place or precisely where they grew, at least high up on the original cliff, and it is clear that their position must have been at least as high as that in which they lay.

Second, the cycads and the fossil wood are almost always closely associated, although the latter is much more abundant. Both being silicified, the conditions which would preserve the one would also preserve the other, and therefore it seems probable that both occur at pretty much the same horizon. There are a few cases in which the fossil wood has actually been found in place; that is, as erect trunks in position and prostrate logs projecting from the original cliffs. The fossil wood is not found at all horizons, but only within a certain limit of elevation, and it is not believed that the cycads have a wider vertical range than the wood.

Third, both the fossil wood and the cycads, even on the lowest slopes at which they occur, and however far below their original position, are usually associated with a certain general class of rocks whose character is sufficiently distinct to make it possible to ascertain their original position, and this is the same class of rocks in which the fossil wood is found when seen in place.

All three of these classes of evidence combine and harmonize in fixing the position of the cycad bed, which is always the next important series of rocks that underlie the hard quartzitic sandstones that occupy the uppermost strata, with a thickness of from 75 to 100 feet. The cycad and fossil wood bed consists of softer sandstones separated by thin beds of shale and is not usually over 50 feet in thickness, but may possibly be 75 or 100 feet at some localities.

It may be as well to mention here that on this expedition I took considerable pains to examine the relation of the Cretaceous to the Jurassic, and especially to the uppermost member of the latter, which contains the "Atlantosaurus beds." I visited the original bed from which bones were first taken, at the foot of Piedmont Butte, and was fortunate in finding Mr. George R. Wieland engaged in taking up the bones of a large animal. This spot is 1 mile due east of the town of Piedmont. I measured the bed and found it 54 feet in thickness, and the particular horizon at which the bones were then being excavated, and which had itself a thickness of about 6 feet, was about 40 feet below the top of the Jurassic or base of the Cretaceous. It is a dark clay shale and at this point rests upon heavy beds of white sandstone. It was impossible to decide, either here or at any other point I examined, whether there is unconformity between the Cretaceous and the Jurassic. The particular bed in question is about 100 feet above the bed of Elk Creek and has an elevation above sea level of about 3,400 feet.

As will be seen later, this bed is therefore about 300 feet below the cycad horizon, and cycads actually occur 4 miles southeast of that place.

The Atlantosaurus beds, as thus described, are exceedingly characteristic of the Jurassic of the Black Hills. In my first paper in the Journal of Geology[1] they were accurately described as occupying the uppermost 50 feet of the Jurassic, although at that time I had no idea that these constituted the Atlantosaurus beds. During the present expedition I examined them at every point where the cycad beds were studied and never failed to find them, with almost exactly the same character and nearly the same thickness. In many places fossil wood occurs in a very fine state of preservation near the summit of these beds and in contact with the Cretaceous, while lignite is the form taken by the wood when it is preserved in the clay shales immediately below. They are the same as No. 5 of Professor Jenney's section of the Hay Creek region, the Beulah clays, of which he gives a full account in his notes published in this paper (infra, pp. 568–593), and many of the features which I have here mentioned were observed and recorded by him.

When all the facts above stated are taken into consideration the difficulties in the way of measuring sections in this region become apparent. It is obviously impossible to reach any reliable conclusions by attempting to make sections of the fallen and disturbed materials that occupy the slopes on the sides toward the broad valleys. In most cases it is impossible to say where the Red Beds end and the Jurassic begins or to find the line between the latter and the Cretaceous. In order to measure a section in such a region it is therefore necessary to find a slope which is not adjacent to a broad valley; that is to say, to find some deep canyon a cross section of which will have the form of the letter V and upon the sides of which there has been no opportunity for the slow undermining of the cliffs and the resultant covering up of the slopes by the materials that have come down from above, but in which there has been a rapid and natural denudation, at all stages of which the materials liberated have been carried away, leaving the surfaces exposed. Such exposures are not easy to find, and often are not deep enough to embrace the entire thickness of the beds which it is desirable to measure. The section measured by Professor Jenney and myself in 1893, on the slope of Red Canyon, was an unusually favorable one, and as will be seen, I was able on this occasion, in a few cases, to find other suitable places and to make sections illustrating each of the general regions.

II. THE MINNEKAHTA REGION.

As it was this region which yielded the first cycads, through which my attention was drawn to the general subject, it seems natural to treat it first. I include in it all the southern portion of the Black Hills which has thus far yielded any fossil plants, and this is embraced in a rectan-

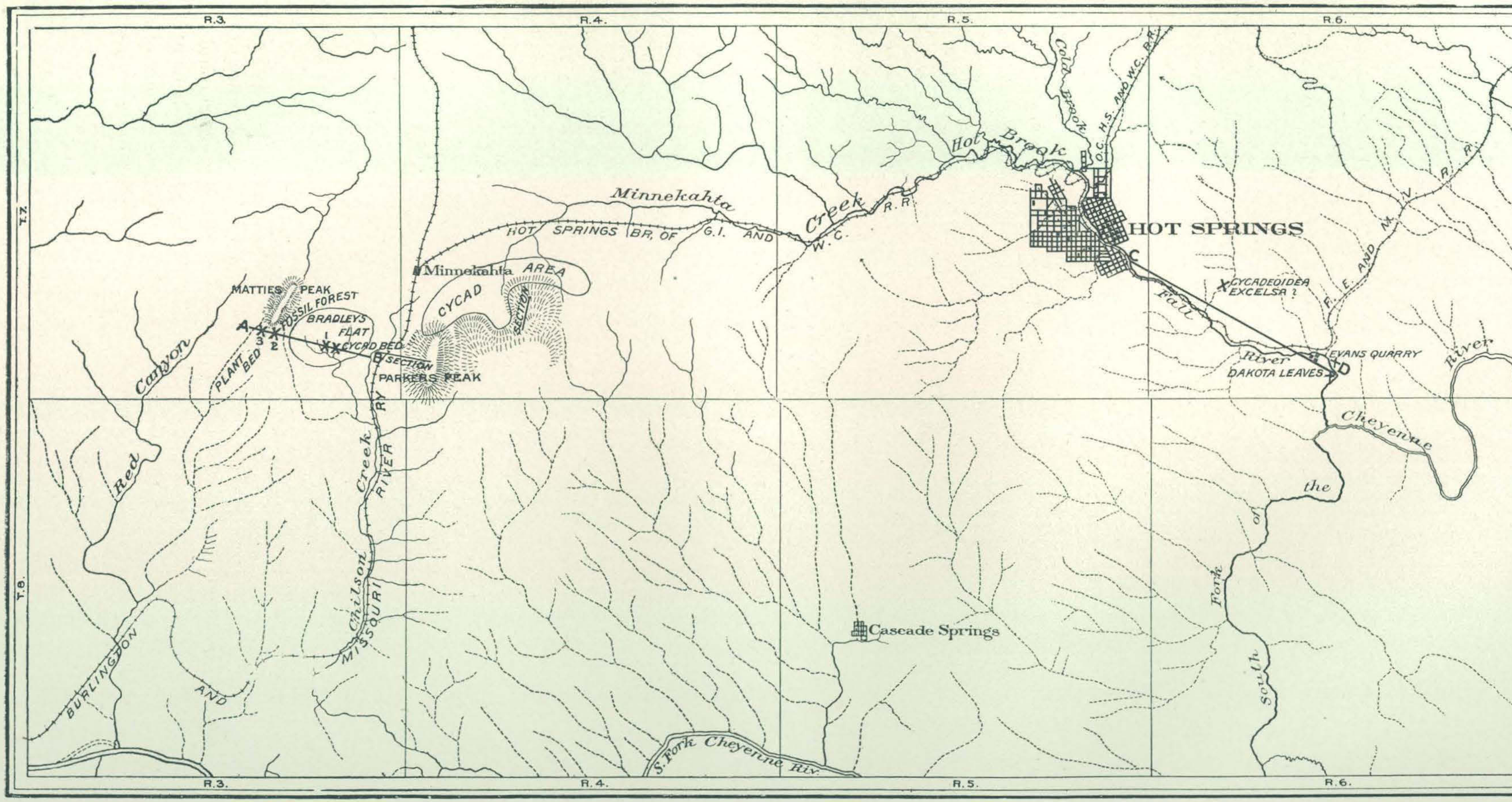
[1] Jour. of Geol., Vol. II, No. 3, April-May, 1894, p. 255 (cf. No. 7 of section No. I.)

gular area having Edgemont for its southwestern corner and extending eastward to the Evans quarry, which lies near the middle of the area north and south. The accompanying map of this region (Pl. LIV), which I have had expressly prepared, embraces townships 7 and 8 S., range 3–6 E., lying wholly in Fall River County.

It nearly all lies within the valley of the Minnekahta River, or, as it is now more commonly called, Fall River. The immediate area within which the first cycads were found is very near the divide between this stream and Red Canyon, while the actual slope on which the most of them occurred is that of a small tributary of Chilson Creek which falls into the Cheyenne between Edgemont and Cascade Springs.

When I visited this region in 1893 for the purpose of determining the exact location of the cycads purchased of Mr. Cole, as above described (p. 542), I proceeded directly to Hot Springs and arrived there on the 5th of September. Professor Jenney met me there from Deadwood, by arrangement. I also found Mr. Cole and arranged with him to accompany us to the locality. An outfit was secured and the 6th and 7th were occupied in making this investigation. The locality itself was on or near the horse ranch of Messrs. Payne and Arnold, and we secured the services of Mr. Payne, who was perfectly conversant with all that region, and he took us immediately to the spot. It is about 3 miles southwest of Minnekahta Station on the Burlington and Missouri Railroad, about 1½ miles west of the bed of the small stream above mentioned, on the foothills formed by the Cretaceous sandstones. We made a somewhat extended examination of the country round about. A mile or more to the northwest of the cycad locality we found the divide between that stream and Red Canyon. Another branch of the first-mentioned stream comes into it from the west, and lies to the south of our area, which is therefore on a southeast slope and near an abrupt descent into a canyon. From this point northwest to near the crest of the divide, the highest point of which is called Matties Peak on the township plat of the General Land Office, the slope is moderate and nearly uniform. At the foot of this crest and about 1½ miles northwest of the cycad locality occurs an extensive fossil forest. The wood is all completely silicified, and consists of prostrate trunks of various sizes and lengths and an abundance of smaller fragments, many of which are scattered about on the sloping plain a long distance below the actual horizon at which they were petrified. At that horizon many still remain, apparently undisturbed, and in one place a trunk over 20 centimeters in diameter was seen projecting several feet from beneath the massive sandstone ledge.

To the south of Matties Peak is a saddle, beyond which the crest of the divide is lower, and here the forest is seen to the best advantage. The most prominent object is a silicified log over 75 centimeters in diameter and 25 meters long, lying where it fell, which may not have been at a very remote date. It had broken away from its roots at the surface of the ground, leaving portions of the stump still exposed, and the entire



MAP OF THE MINNEKAHTA REGION OF THE BLACK HILLS, SOUTH DAKOTA.

root could probably be exhumed. Over the area of ground beyond the present trunk, where the upper limbs and branches would naturally have been, great numbers of fragments and splinters were scattered, clearly indicating that many of these branches must have remained attached when the tree fell.

It will be noted that all this is within the drainage of the Cheyenne River, and therefore it corresponds perfectly with the location of the petrified forest described by Edgar Allen Poe, as quoted above (p. 529), viz, "Near the head waters of the Chayenne, or Chienne River, which has its source in the Black Hills of the Rocky chain." Of course it is possible that there are other fossil forests that would answer this description, but I know of none, and the chances of its being this identical spot are increased by the necessity that it should occur in a geological formation in which petrified forests are to be looked for. It could not, therefore, have been in the Red Beds below nor in the Fort Benton above, and the area is restricted to the Lower Cretaceous. It is therefore scarcely possible that he could have referred to any other than the forest under consideration. A large amount of silicified wood also occurs at the cycad locality itself, and there is reason to suppose that the horizon is practically the same. The whole of this region, including the entire crest of the divide and the area extending to the bottom of the canyon of the cycad bed and far to the southeast, consists of the series of hard sandstone that were treated in the Black Hills report as constituting the Dakota group.

The great improbability that the cycads could have lived in Dakota time, or contemporaneously with the flora of the Dakota group, led me to suspect that these beds were below that horizon, and I resolved not to leave the field until all the evidence on this point that was attainable had been examined. In the immediate vicinity of the fossil forest and cycad bed there were no evidences of plant remains of any other class. The crest above the fossil forest consists of hard, chiefly massive sandstones, which may be traced far around the Hills, and form the upper part of the abrupt escarpment above the soft Jurassic and the Red Beds. On the inner face of this escarpment it was therefore possible to observe a great thickness of the Cretaceous in a limited area; and passing over this crest a little to the southwest of the fossil forest we entered the first lateral canyon which leads into Red Canyon on the west, so named because in it the Red Beds are well exposed. The escarpment here is more or less overgrown with timber, and although the slope is very steep it was possible to work on any part of it. From the summit of Matties Peak to the bottom of the valley was, by careful measurement, over 500 feet, but considerably over 200 feet of this was occupied by the Jurassic, distinctly marked off from the Cretaceous, while at the very bottom the Red Beds were reached. Above the Jurassic there were about 275 feet of Cretaceous deposits, and on different parts of this slope good exposures occurred, showing considerable variety. It was in these exposures that the search for fossil plants was made, and in one of them it was successful. This occurred 60 to 75 feet above the Jurassic, and in a number of places imperfect plant remains were found, chiefly in a soft pink and gray sandstone.

Matties Peak rises some 75 feet above the fossil-forest horizon, and the plant bed now under consideration is about 125 feet below that of the fossil forest. The plants occurred partly in shales and partly in hard sandstone. They consist chiefly of ferns, and have a facies totally different from that of the well-known flora of the Dakota group. They are all carefully described and figured below, and their affinities would of themselves be sufficient to make the Lower Cretaceous age of the bed that yielded them altogether certain, and it was upon these more than upon the cycads or fossil wood that I rested the case in the article above quoted.

The following is the section measured at this place, with a brief description of each bed, giving its thickness in feet. The diagram which follows will serve to make the matter still clearer.

SECTION OF MATTIES PEAK.

	Feet.
Dakota of Newton, 275 feet.	
13. Massive pinkish sandstone approaching a quartzite locally	75
12. Grayish white sandstone with silicified wood and cycads	30
11. Pinkish and yellowish soft sandstone	75
10. Clays with indications of coal	20
9. Soft pink and gray sandstone with ferns and other plants	25
8. Reddish, pinkish, and yellowish brown massive cross-bedded sandstone	50
Jurassic, 220 feet.	
7. Olive gray clay and sandstone shales, including the Atlantosaurus beds	50
6. Light red soft sandstone	60
5. Olive gray clays and gray sandstone shales	40
4. Olive drab clay	20
3. Yellow sandstone shales	20
2. Olive drab clay	30
Red Beds (Trias).	
1. Red marls, conformably exposed at bottom of canyon	20

This section may be represented diagrammatically as follows:

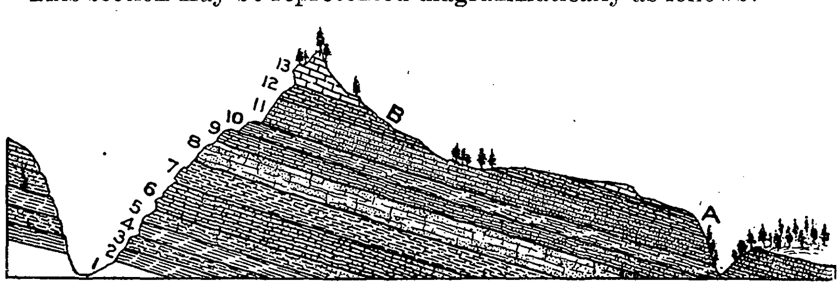


FIG. 119.—Section across the divide between Red Canyon and Chilson Creek. 1, Red Beds; 2-7, Jurassic; 9, Plant bed; 12, A, Cycad bed; B, Fossil forest; 13, Equivalent of Quarry sandstone in section at Evans quarry (see infra, p. 560).

As already stated, this region lies very near the divide between the Minnekahta Valley and the Red Canyon, but is really on the slope of Chilson Creek, which makes down into the Cheyenne River a long way to the east. At the time I visited this place in 1893 I was under the impression that the valley to the east of the cycad beds drained northward into the Minnekahta Valley, and so stated in my article. But this is a mistake, for it is not until we reach the Minnekahta station, at the junction of the two railroads, that we find the beginning of the Minnekahta drainage. A number of small streams from the west, north, and south unite a little way to the eastward and form the Minnekahta or Fall River, whose course is nearly eastward to near Hot Springs, a distance of about 15 miles. It flows chiefly over the Red Beds, and the Cretaceous escarpment lies to the south, forming a conspicuous east-and-west ridge, with a high point at its western end known as Parkers Peak.

On my visit to this region in October, 1898, in company with Mr. Wells, I went carefully over all the ground on which he had obtained his specimens. They all came from a region surrounding the original spot which I examined in 1893, and from which so many of the earlier specimens had been obtained, but Mr. Wells found that there was an area, irregular in outline and more than a half mile square, over which cycads were strewn, though by no means evenly, as they occurred in groups at different points, more or less separated from one another. This area is all within what is called Bradleys Flat and occupies most of the eastern portion of it. There are three spur ridges running out in a southeasterly direction from the main axis, parallel to the line of my section. The central one is that on which the original cycad bed is situated, and cycads were found over nearly the whole surface of this ridge, but chiefly on its southwestern slope, a larger number having been obtained from above the original locality than anywhere else. The most southwesterly ridge yielded cycads only on its northeastern slope, i. e., facing the principal localities of the central ridge. On the most northeasterly ridge cycads were more rare, but were sparingly distributed over the whole of its lower portion, and it was on this ridge that they extended farthest up the slope to the northwest, i. e., in the direction of the main axis.

It was evident from a careful examination of these ridges, especially along the slopes of the deep ravines that separate them, that this whole area must be regarded as out of place geologically and as occupying its present low position by reason of having settled down in the general process of denudation. The disturbance, however, was not so great as in most cases of the kind, and many of the rocks seem still to remain adhering together in a broad sheet, with occasional ledges in which relatively they have never been disturbed, and even outcrops of the hard quartzitic masses belonging at the top of the highest ridges were found normally overlying the softer sandstones in the same relative position in which they may be seen on the crest of the divide 1½ miles farther to the northwest. In the diagrammatic section, Fig. 119, the dip is purposely exaggerated to represent this late tilting of the strata.

I had long been aware that fossil cycads had been found on the south side of the broad valley to the southeast of Minnekahta station. A specimen which I saw in a pile of stones at the station was said to have come from this region, and I was told that others had been found there. Mr. Wells, learning these facts, had explored the country in that direction and had obtained a considerable number of specimens, one of which is No. 5 of the Yale collection, which differs from all others in being completely turned to white flint (see infra, p. 603). The various localities at which Mr. Wells secured the specimens were visited by me, in company with him, and proved to be of exceptional interest from a geological point of view. The south side of the general Red Bed valley, extending a distance of 6 or 8 miles from Parkers Peak eastward, consists of a series of high hills, separated by deep ravines, opening into the valley from the south. Toward the western end of this series these canyons have a more and more northwesterly course, the last one opening out at the north end of Parkers Peak, which is nearly 100 feet higher than the rest and is crowned by the quartzitic rocks that overlie the softer sandstones. No cycads have been found, to my knowledge, on or around Parkers Peak, but at the foot of several of the high ridges to the east of it they occur and the localities were carefully examined by me. The greater number of the cycads of this region, however, were not found near the base of these high ridges but at a considerable distance to the north of them, either on very low ridges extending out into the plain, or on isolated knolls that occur at intervals over a considerable part of the broad valley itself. These knolls consist of the same soft sandstones that belong at the top of the highest hills on the south, and are merely remnants of the materials that were carried away by the process of denudation when the valley was excavated. They are all, therefore, entirely out of place and their position can only be judged by the nature of the rocks with which they are associated. In fact, it was here that a considerable number of specimens were found embedded in the red soil at the bottom of the valley, in the general vicinity of which there were scarcely any remains of the sand rock. Others were deeply entombed in the pure white sand of the Jurassic, and still others lay upon the white calcareous shell rock of that formation and were incrusted with a coating of lime.

It seems probable that these heavy cycad trunks may not have been transported any great distance, and the theory that they have rolled down the slopes of the adjacent hills, at least within any recent period, is completely disproved by the great distances at which they occur from the foot of the hills, often with lateral ridges between. In all probability their original position was not far from vertically over their present one. It is certain that they belonged to the southern range of hills, because they occur much nearer to the south than to the north side of the valley. It must therefore be supposed that the hills and cliffs along the south side formerly extended over the spot where the cycads now occur, and as some of them were found quite close to the foot of these hills this whole region may be regarded as a cycad-bearing area. This area occupies a position to the east and southeast of Minnekahta, distant from 1 to 3 miles from the station, and covers a space of nearly two miles square.

The second of the high spurs to the east of Parkers Peak seems to have furnished the larger number of specimens, and they were found on three sides of this hill around its base. I was therefore specially desirous of making a section of this hill, but owing to the difficulties which I have already explained (supra, p. 549), it was impossible to find any point on the north or northwest sides at which this could be done. It was clear that the Red Beds occupied the lower part and that the whole of the Jurassic was to be found on the slope, but the sandstones from above so deeply covered the flanks of the ridges that the relative thickness of these beds could not be determined. Fortunately, however, a deep gorge had been cut into the side of this projecting ridge, having a southwesterly course and opening out into the canyon between this and the next one on the west. This gorge furnished much better conditions for the measurement of a section, and this was accomplished with considerable success. The hard quartzitic sandstone which forms the highest bed is not present on these ridges and the softer sandstones extend entirely to the summit. The following is the section:

SECTION OF SPUR EAST OF PARKERS PEAK.

	Feet.
Cretaceous, 208 feet.	
7. Rounded summit and slopes at top of ridge, consisting chiefly of soft yellowish or reddish sandstones and thinner sandstone and clay shales, with abundance of fossil wood. This is probably the source of the cycads also	88
6. Nearly vertical ledge of light-colored sandstones	48
5. Slope, mostly covered, consisting of coarse sandstones and clay beds	72
Jurassic, 130 feet.	
4. Olive-gray clay and sandstone shales, including the Atlantosaurus beds	60
3. White sandstone ledge	10
2. Yellow sandstone	20
1. Light-colored rocks, much obscured, probably limestones	40
Red Beds to bottom of canyon	50
Total	388

Parkers Peak is the only one of this range of hills which retains the cap of quartzitic sandstones, and it accordingly rises about 100 feet above the summits of the several more eastern ridges. Its top forms a sort of mesa or elongated table with a north and south trend, and its western face rises directly above the sources of Chilson Creek and is nearly in line between the very similar ridge called Matties Peak 4 miles to the westward, which forms the divide between this valley and Red Canyon, and which was the subject of my first section. The great cycad beds of the Minnekahta region lie between these two high points, and I therefore thought it very desirable to obtain a section of Parkers Peak. This was attended with many difficulties and the section is not as satisfactory as could be desired, but is as nearly accurate as it was possible to make it.

SECTION OF PARKERS PEAK.

	Feet.
Cretaceous, 310 feet.	
8. Hard sandstone ledge, partially quartzitic	100
7. Steep slope, mostly covered, but consisting of soft sandstones corresponding to and probably constituting the fossil wood and cycad bed	75
6. Vertical cliff of soft pinkish and white sandstones	60
5. Slope, mostly covered, of alternating sandstones and clay shales	75
Jurassic, 135 feet.	
4. Olive-gray clay and sandstone shales, including the Atlantosaurus beds	60
3. Other Jurassic beds, mostly obscured	75
Red beds exposed, 100 feet.	
2. Grass-grown slope with occasional red patches indicating Red Beds	50
1. Red beds in the valley to bottom of Chilson Creek	50
Total height of Parkers Peak to bed of Chilson Creek	545

Some 10 miles east of Minnekahta station the broad Red Bed valley gradually closes in to form a canyon narrowing eastward, through which the small stream known as Hot Brook, having its source in numerous thermal springs, passes. This at length unites with several other branches and forms what is there known as Fall River, on which the town of Hot Springs is located. Here the course of the drainage bends southward and breaks through the high ridge on the south, forming a "gap" through the foothills nearly parallel to Buffalo Gap, 15 miles northeast of that point. Its course is here southeast, and where it enters the hills and forms a deep canyon it affords an excellent section through the Cretaceous sandstones, with a length of some 4 miles, to where it enters the Fort Benton clays and ultimately emerges upon the plain and joins the Cheyenne River.

The electric-light plant for the town of Hot Springs, some 5 miles distant from it, marks the termination of the Dakota strata, and Evans quarry, which is just above this point on the left bank of the stream, yields very fine building stone from a massive stratum nearly 60 feet thick, containing no organic remains. But immediately over this building-stone stratum occur shales and sandstones in which dicotyledonous leaves had previously been found by Professor Jenney. It was in consequence of this that he had assumed that the cycads were from the true Dakota group yielding dicotyledonous leaves. But it soon became apparent, on visiting the region, that this was not the case and that the equivalent of the cycad bed was some distance below the quarry sandstone, which is virtually the equivalent of the massive sandstone forming the crest above the fossil forests.

We made a careful measurement of this section and it was published in my article. In my second visit, in 1895, I could find no reason for any essential modifications in that section, and I therefore reproduce it here without change. The quarry sandstone dips very rapidly to the southeast, so as to come down to the bed of the stream at the electric-light plant and to constitute the rock over which a fine cataract flows at this point and through which the water has worn deep longitudinal grooves. Immediately over these rocks there is a bed, some 6 or 8 feet in thickness, of dark clay and argillaceous sandstone shales, with carbonaceous matter and some impure coal. In this bed was found a great abundance of more or less comminuted vegetable matter, with short fragments of culms of reed-like plants, which it has not been possible to determine. There also occur, in certain of the shales, a few tolerably well-preserved dicotyledonous leaves, some of which have been determined, and were sufficient to prove beyond a reasonable doubt that this stratum belongs to the true Dakota group. A small collection was made near the cataract over the hard sandstone on the right bank of the stream, above the electric-light plant.

This bed was easily followed to the quarry, where it constitutes the overlying mass which it is necessary to remove in order to uncover the workable sandstone below. At this point the bed also contains layers of soft white sandstone of considerable thickness. Large blocks of this had been thrown down and lay strewn at the foot of the quarry. On the surfaces of these, and more or less scattered through their mass, were impressions of dicotyledonous leaves of Dakota types. The shales were also found in place above the quarry, and some of these yielded very good specimens. No fossil plants were found in any bed below this layer. For a long distance on both sides of the canyon the quarry sandstone forms the crest of the ridge, constituting a more or less abrupt escarpment of from 25 to 75 feet.

Higher up the stream the beds below the quarry sandstone come into view, consisting of softer sandstones, argillaceous shales, and carbonaceous layers, with impure coal seams, all highly charged with gypsum. These finally come down to the bed of the stream and are ultimately seen resting upon the Jurassic clays, which in turn overlie the Red Beds. Some distance below Hot Springs the Cretaceous can be seen at the summit of the cliffs with the whole thickness of the Jurassic below them and the Red Beds at the base. These latter, at and about Hot Springs, are overlain by heavy beds of conglomerate, probably of Pleistocene age.

The following is the section as measured below Hot Springs:

SECTION AT EVANS QUARRY.

Fort Benton.

11. Grayish black clays with layers of ferruginous concretions, extending to the south fork of the Cheyenne River—contact conformable.

Dakota of Newton, 339 feet.

	Feet.
10. Pink sandstone, mostly thin-bedded, with ripple marks and fucoid-like impressions	30
9. Soft black shales, with traces of carbonized plant remains and some fragments of fossil wood	15
8. Pink and gray sandstone	30
7. Clay shales and sandstones, the latter sometimes white, all plant bearing, much comminuted vegetable matter, matted beds of swamp plants, and well-preserved dicotyledonous leaves of Dakota types, determinable	10
6. Black clay full of carbonaceous matter, with locally 6 inches of impure coal	4
5. Quarry sandstone, massive, light pink, soft, weathering iron-brown	60
4. Soft yellowish and reddish sandstones	100
3. Drab-colored clays with carbonized vegetable matter and gypsum crystals, interbedded with yellow sandstones	30
2. Soft yellow and reddish sandstones with some clay layers	60

Jurassic.

1. Olive-gray, drab, or bluish clays with reddish and yellowish sandstones, to base.

This section may be represented diagrammatically as follows:

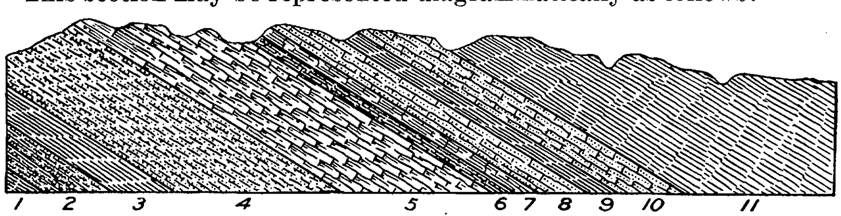


FIG. 120.—Section through Minnekahta Canyon. 1, Jurassic; 3, Equivalent of plant bed in section No. 1; 4, (Upper portion) Equivalent of cycad bed in section of Matties Peak; 5, Quarry sandstone; 7, Dakota leaf bed; 11, Fort Benton.

It will be seen by a comparison of these sections that they are in substantial agreement, although no effort was made to make them so. The upper member, No. 13, in the section of Matties Peak (supra, p. 554) probably represents the quarry sandstone of this section, which was considerably thicker at that point, 15 feet more being found, exclusive of erosion; but these rocks were often much harder, and no quartzitic rocks were seen in the quarry. On account of the débris thrown down from the quarry and other obstructions, it was not possible to examine the next member below with as much care as was desirable in view of the fact that it seems to be the equivalent of the cycad and fossil-forest horizon; i. e., No. 12 of that section corresponds to the upper 30 feet of No. 4 of the present one.

III. THE BLACKHAWK REGION.

In a letter which I received from Professor Jenney, dated August 28, 1893, he gave me the first intimation that cycadean trunks had been found in other parts of the Black Hills than the Minnekahta region. In that letter he says:

I learned from Professor Carpenter, formerly of the School of Mines at Rapid City, that there is a fine cycad in the collection of that institution. The specimen was found lying on the surface near Piedmont, South Dakota, a small station on the Fremont and Elkhorn Railroad, some 18 miles north of Rapid City and nearly 50 miles northeast of Hot Springs. Professor Carpenter tells me that this cycad may have been derived from either the Jurassic or Dakota. Near by are the "Atlantosaurus" beds in the Jurassic, from which Prof. O. C. Marsh obtained many bones of a new species of "Atlantosaurus." Fossil bones, Professor Carpenter (who first discovered these fossils) tells me, are very abundant in the Piedmont locality. It would appear that the cycad-bearing beds, whatever age they may be, encircle the Black Hills, so it is probable that other specimens may be found.

Being much interested in this statement, I wrote him at once with regard to it, and his next letter, dated September 22, 1893, contained the following additional information:

I find that the two specimens of cycads at the School of Mines are in all probability of a different species from those found at Hot Springs. The specimens may belong to one individual. One is the dome-shaped termination of a trunk about 15 inches in diameter; the other appears to be a fragment of the trunk. Compared with the Hot Springs variety, the trunk of this is taller, more cylindrical, and the markings of the leafstalks rudely pentagonal, seven-eighths to 1 inch in diameter, sometimes irregularly four-sided, not rhombic like those we found. I can not learn the exact horizon at which these cycads were found. Some person brought them to Rapid City, where for months they remained in a vacant lot until noticed by the dean, who removed them to the School of Mines. So it is not at all certain that they were originally derived from the same or equivalent beds as those yielding cycads at Hot Springs.

In a third communication, dated October 8, 1893, on the same subject, after having examined the specimens at the School of Mines and made outline sketches of their general form and also of the form and size of the leaf scars, which he kindly inclosed to me, Professor Jenney further states :

Now about the cycad specimens at the School of Mines. After some detective work I have learned that the man who found them is now living in Florida. I have written him to ascertain the exact locality. I hope in a few weeks to have a camera and will then photograph the specimens. I inclose a rude outline sketch with measurements of these specimens at the School that will show you the shape; also a sketch showing the variations in shape in the leafstalk cells. These specimens differ from the Hot Springs species in having a more cylindrical and much taller trunk, free fron excrescences or branches, and in the shape and arrangement of the leafstalks, which are in the School specimens imperfectly trigonal, quadrilateral, or pentagonal, and frequently strongly winged on two opposite angles. The arrangement of the leafstalk pits on the trunk is not so symmetrical in the concentric spiral lines as exhibited in the Hot Springs species. The leafstalks in the School specimens can be seen passing entirely through the outer bark of the cycad, a distance of 5 to 6 inches, terminating at the pith-like core. It would be possible to break them out in prismatic pieces of flint, the exact cast (?) of the original leafstalk.

Still later, October 21, he adds:

I have continued my detective work on the cycad specimens at the School of Mines and have at last traced them back to the man that found them, now at Keuka, Florida. In 1877 Mr. J. M. Leedy, of Rapid City, found the cycads in the foothills some 6 or 8 miles north of Rapid City. They remained at his ranch for a long time and were taken to Rapid City for exhibition at a fair held in Liberty Hall; were not returned, but at the conclusion of the fair were thrown out in a vacant lot near the hall, remaining there several years until removed to the School of Mines. Mr.

Leedy states that he found the specimens north of Box Elder Creek, on the divide between that stream and Elk Creek, and east of the railway (Fremont and Elkhorn), so they would be much nearer Rapid City than Piedmont. I will visit the locality soon and try to find more specimens at the same horizon.

Some negotiations were entered into for the loan of the specimens to the United States National Museum, but Professor Jenney's connection with the State School of Mines terminated about that time, and as I intended to visit the Hills again I did not press the matter further then.

As already stated (supra, p. 545), I stopped at Rapid City in the summer of 1895, when on my way to Oregon, Montana, and California, arrriving there August 19. I proceeded on the same day to the State School of Mines in company with Professor Jenney, and through the kindness of Dr. V. T. M'Gillycuddy, president of the State School of Mines, I was permitted to examine the specimens about which so much had been said. In the meantime I had described the species[1] and named it *Cycadeoidea Jenneyana* for Professor Jenney, my description being based on his notes. President M'Gillycuddy very generously consented to the loan of the specimens to the United States National Museum, and arrangements were made for their shipment to Washington, where they arrived in due course of events and were here on my return from California in the fall. They are thoroughly described and illustrated below (pp. 627, 628, Pls. CXXI–CXXV).

The problem was to ascertain the exact locality from which these specimens had been taken, and we spent the rest of the day in making careful inquiries of the citizens of Rapid City and of all persons in that vicinity who were in possession of any information on the subject. We succeeded at length in finding Mr. Gilbert Getchell, a citizen of Rapid City, who, although he does not seem to have first found the specimens, stated that he accompanied Mr. Leedy at the time that the specimens were brought in, visited the spot with him, and assisted him in loading them into the wagon. He offered to accompany us as our guide and felt sure that he could show us the exact spot. On the next day a party consisting of Professor and Mrs. Jenney, Mr. Getchell, and myself proceeded to Blackhawk, a station on the Fremont and Elkhorn Railroad, 7 miles northwest of Rapid City, and there obtained a conveyance in which our party visited Black's ranch, about 2 miles nearly due north of the station. It was less than half a mile north of the house on Black's ranch where the cycads lay when Mr. Getchell first saw them. Not only this spot but the whole region to the north and northeast was thoroughly explored. No cycads were found, every fragment having been carefully gleaned by other parties, as explained above, but an abundance of silicified wood occurred at nearly all points and even at the place where the cycads were.

The locality is on the left bank of a ravine which has a southward course and runs past the ranch house. It is a little level opening

[1] Proc. Biol. Soc. Washington, Vol. IX, April 9, 1894, p. 87.

below a wooded hill. On the hillside, immediately above, fossil wood was more abundant than at any other point. The rocks consist of brown sandstones similar in all essential respects to those of the cycad locality in the Minnekahta region. The level area on which the cycads lay is far below the top of the Jurassic, and the sandstones have all settled down through erosion of the looser materials from a considerably higher position.

The above is all that was known of the occurrence of cycads in the Blackhawk region prior to Mr. Wells's discoveries. His last two invoices to Professor Marsh contained 39 specimens from that region, viz, Nos. 88–126 of the Yale collection, and these were described by me in June, 1898. In the National Museum there are 4 specimens from there. If to these we add the two large trunks that belong to the State School of Mines, South Dakota, we have a total of 45 specimens from the Blackhawk region, which are treated in this paper.

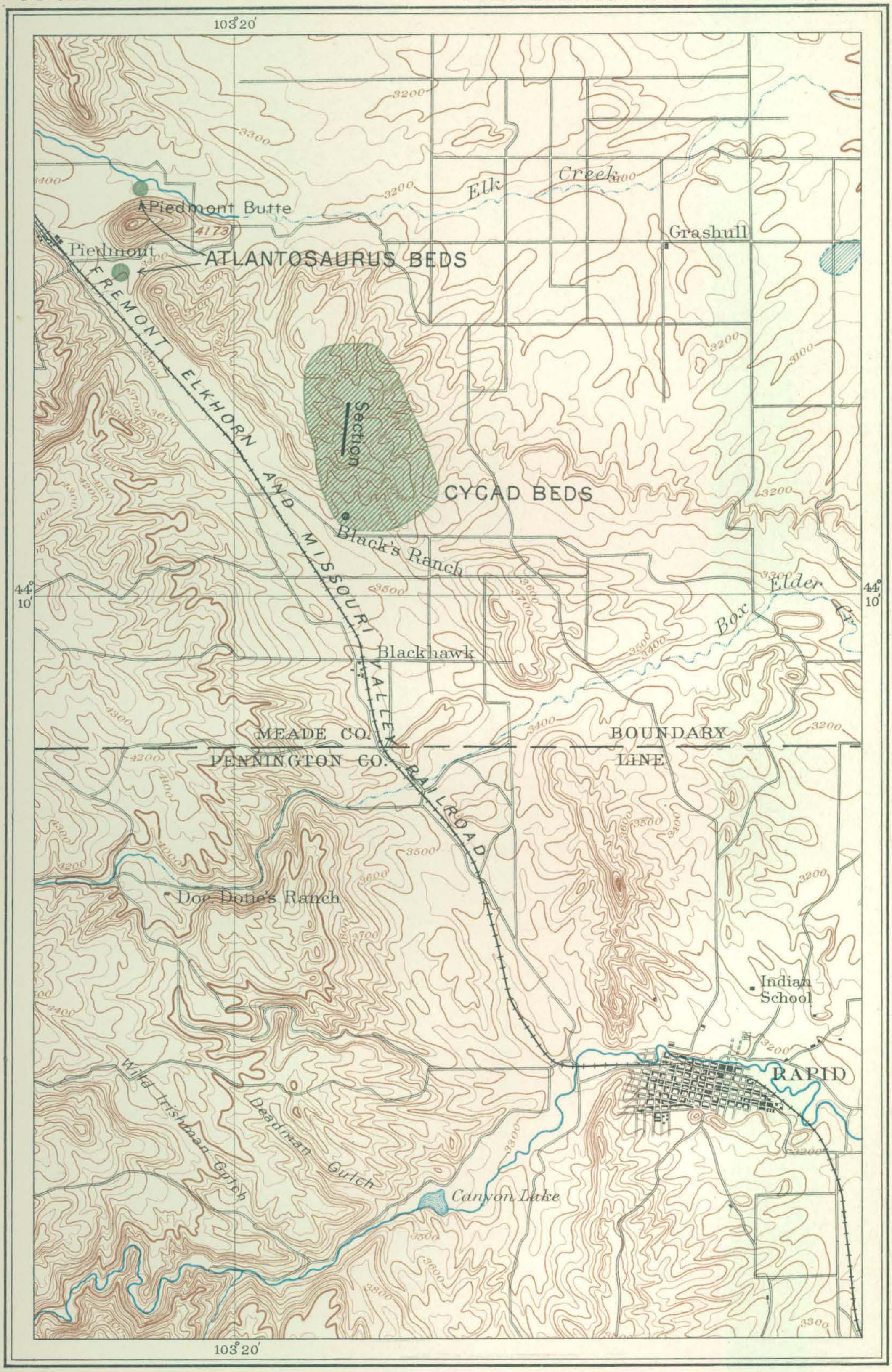
As, on the occasion of my visit to Black's ranch in 1895, none of my party had been able to discover any additional specimens, I was exceedingly curious to know where Mr. Wells had obtained so large a number. The labels on the specimens showed nothing beyond the fact that they had been found in the Blackhawk region. Professor Marsh had, however, at my suggestion, impressed Mr. Wells with the importance of giving more specific localities for the cycads, but so late in the day that it was only in case of the last and smallest invoice, containing 14 specimens, Nos. 113–126, that Mr. Wells had undertaken to be more exact in this matter. All this emphasized the importance of my visiting the region again, and under his guidance, minutely examining each of the localities. This is what was done in October, 1898. A few of the specimens found by him were not far from the locality pointed out by Mr. Getchell as that of the original specimens, but were somewhat farther up a small ravine, which has a due south course and opens into the larger ravine having a southeasterly course that passes by the ranch house. By following up this ravine still farther, we passed over a large number of additional localities and these extended entirely over the divide to the north and northeast. All of these specimens occurred out of their natural position, among loose rocks that had slipped down from the higher cliffs, and the same is true for most of the specimens from the localities farther to the northeast on comparatively low ground. They had, therefore, no geological significance and there was no possibility of measuring a section to indicate their geological position. It was of the utmost importance, however, that a section should be made, and in order to do this I was obliged to explore the high hills to the north, which are in their original position.

About 3 miles due north of Blackhawk and 4 miles southeast of Piedmont there is a peculiar conformation of the surface, consisting of what seems to be, from whatever side it is viewed, a high plateau, rising 300 feet above the valley through which the railroad passes and having a length nearly north and south of about 3 miles and a width of nearly 2 miles. But when one reaches the summit of this high hill, one finds that it consists in reality of a sort of gulf or amphitheater, not shown on the topographic map, with a depth of between 200 and 300 feet, but having an outlet on the eastern side, and also a depression in its rim on the south side; otherwise it is entirely surrounded by the high ground covered with the Cretaceous sandstones, has every appearance of a true basin, and reaches at the highest points the 3,900-foot contour line. The uppermost rocks are somewhat quartzitic and barren, usually forming precipitous ledges, but the next terrace below consists of the typical soft sandstones with which the fossil wood and cycads are usually associated and are found mingled with them on the spurs and slopes below. In this particular case, however, it has fortunately happened that a number of cycads, and among them some of the largest and most interesting, were found virtually in place at this high level on the inner slope of the rim of this basin at its southern end. Mr. Wieland had also found a specimen on the west side at the same level and another half a mile north of the basin at a little lower level. The discovery of these specimens is very important in confirming the view at which I had previously arrived, that this highest terrace below the quartzitic cap constituted the cycad horizon. In fact it demonstrates this, at least for the Blackhawk region.

I therefore determined to make a section at the precise point at which these cycads occurred. It was impossible to obtain this from the south side on account of the gradual slope and the number of slips which obscured the strata, and I was obliged to go over on the inside of the basin at its extreme southern end and measure the section from that side. Owing to the size of this inclosed valley, however, some of the same difficulties presented themselves that occur in cases where broad valleys are adjacent to the slopes, and it was impossible to measure the thickness of the Jurassic or even to find its contact with the Red Beds, if the latter occur at all. The following is the section as thus measured:

SECTION 3 MILES NORTH OF BLACKHAWK.

	Feet.
Cretaceous, 200 feet.	
5. Whitish or yellowish sandstone, greatly varying in hardness, occasionally somewhat quartzitic	46
4. Soft, yellowish sandstone and sandstone shales with occasional reddish clay seams, especially near the base; cycads found in place within 6 feet of base	50
3. Ledge of soft light sandstone	10
2. Slope mostly covered with débris of sand rock, grass, and herbage	94
Jurassic exposed, 100 feet.	
1. Jurassic, much obscured, to bottom of canyon	100
Total exposure	300



THE BLACKHAWK REGION OF BLACK HILLS SOUTH DAKOTA

SHOWING THE CYCAD AND THE ATLANTOSAURUS BEDS

BY LESTER F. WARD

1898

A. Hoen & Co. Lith. Baltimore.

The largest cycad from that region, No. 100 of the Yale collection, and the largest but one in the world, was found at a height of 110 feet above the Jurassic contact or 80 feet below the top of the highest crest on the south end of this basin on its inner slope, and several other of the most interesting specimens were found either near this or in relatively the same position somewhat farther east.

A less successful attempt was made to measure a section at the north end of the basin, where the rim was found to rise 86 feet above the top of the Jurassic, exposed below. But it is probable that the highest part of the rim here is considerably below the cycad horizon and the plain slopes away to the northward, so that no full section can be obtained. On the west side, where Mr. Wieland found a cycad at about the same horizon as those at the south end, the rim is very thin and the rocks have the appearance of dipping rapidly to the westward. This is, however, undoubtedly due to the effect of undermining and tilting them at the time that the broad valley on the west was being eroded. On the slope toward the basin the dip is in the opposite direction, doubtless from a similar cause.

The entire cycad area therefore of the Blackhawk region, as we now understand it, forms a sort of rectangle about a mile and a half wide east and west and 3 miles long north and south, with Black's ranch at its southwestern corner, and it extends in altitude from the 3,600- to the 3,750-foot contour line (see map, Pl. LV). All the specimens, however, found below the 3,750-foot contour line are of course out of place.

IV. THE HAY CREEK REGION.

After Professor Jenney and I had discovered, in 1893, that there was a large series of beds underlying the true Dakota group in the Black Hills, the idea of developing an extensive fossil flora assumed a definite shape in the minds of both of us. His prolonged investigations in all parts of the Black Hills in the capacity of a mining expert rendered it highly probable that if such a flora existed he would sometime find it when studying such outcrops as promised to yield coal. An occasion of this kind presented itself much earlier than I had expected, when, the following year, he was employed by the railroad companies to investigate the coal fields on Hay Creek, a tributary of the Belle Fourche, which rises in Crook County, Wyoming, and flows slightly north of east, joining the Belle Fourche opposite the town of that name. Valuable beds of coal were discovered on the upper tributaries of Hay Creek, and this general region is now known as the Hay Creek coal field, with Barrett post-office near its center. The map (Pl. LVI) shows in detail the nature of the Hay Creek coal field, and indicates the stratigraphy, as worked out by Professor Jenney, and all the localities from which fossil plants were obtained by him and sections made.

The history of Professor Jenney's investigations will now be given.

In June, 1894, I received a letter from him dated June 10, from which I give the following extract:

I have just returned from a three weeks' camping expedition in the foothills of the eastern part of the Bear Lodge Range. I had occasion to study carefully the Hay Creek coal field, situated 40 miles northwest of Deadwood, and have measured many sections covering the Dakota group of Newton. I found much that would interest you. It is true I could not find any cycad trunks, but think we will yet find impressions of the leaves. Fossil wood is quite abundant in this formation. In one place a huge tree is sticking in the face of a cliff; the trunk is 3 feet in diameter and extends along the face of the cliff for 40 or 50 feet, forming across the rifts in the rock a kind of natural bridge. I could only take specimens of the sapwood and heartwood of this silicified trunk. It is too large to send to Washington.

I find in the Hay Creek district four distinct plant-bearing horizons that will prove very useful in separating the Dakota group into the different epochs. I could only collect a few plants from each, but have carefully recorded the localities. Several will, if worked, yield, I am satisfied, finely preserved plants. It is true I have not found in the Lower Cretaceous a great variety of plants, and that good specimens are not common.

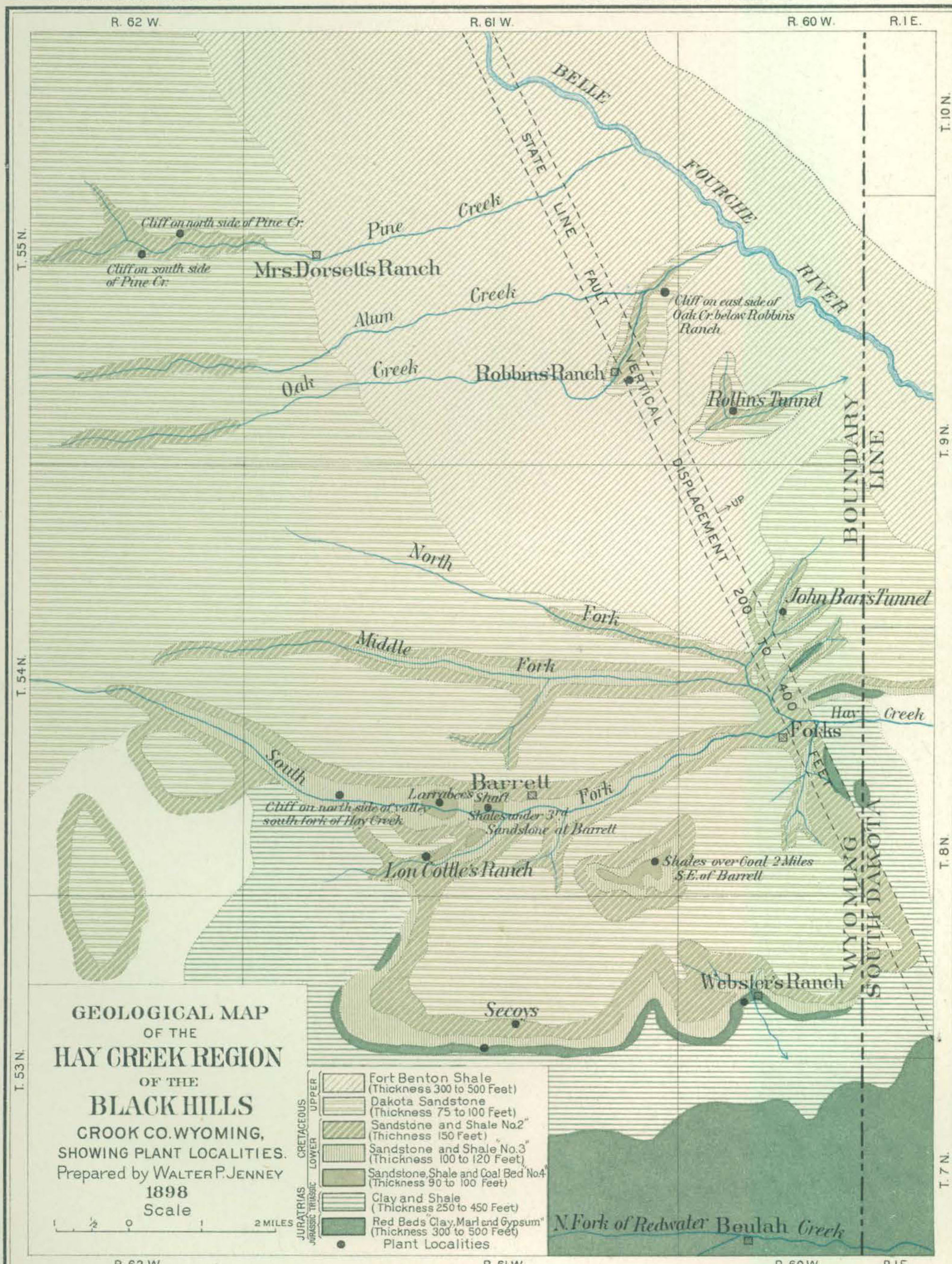
I discovered between the Jurassic and the Dakota group of Newton evidences of unconformity, i. e., that the Jurassic formation had suffered considerable erosion prior to the deposition of the Cretaceous. Further, between the top of the Jurassic beds with characteristic marine fossils and the base of Newton's Dakota group there are about 50 feet of beds as to which I am as yet unable to determine whether they should be classed as Jurassic or as Lower Cretaceous. These beds are ash-gray clays with calcareous clay nodules, apparently without fossils. At the top of this undetermined series of beds and just beneath the sandstone shales with plant remains, the supposed base of the Cretaceous, occurs a bone-bearing bed, from which I obtained fragments of fossil rib bones 2½ inches wide, ½ to 1 inch thick. The "Atlantosaurus" beds of Professor Marsh, that Professor Carpenter states were identified by him near Piedmont, South Dakota, at once came to mind.

I hope to have time to search the locality and its vicinity and determine the horizon of these animal remains.

To return to the Dakota of Newton, I find it naturally separates into the following (this is of course subject to future discovery and to the determination of the plants of the several horizons):

GENERAL SECTION OF THE DAKOTA GROUP OF NEWTON.

	Feet.
Upper surface, probably somewhat eroded, overlain by Fort Benton Shales.	
1. The Dakota sandstone with characteristic plant remains. The base a massive sandstone of variable character with respect to hardness, percentage of iron, etc	100
2. Clay shales, sandstone shales, and soft sandstones with, locally, beds of carbonaceous shale and plant remains, plants, ferns of modern type, and ribbon-like fucoids; at base of this member a massive cross-bedded sandstone 50 feet in thickness; contact stratum, a breccia of clay and sandstone marking unconformity	150
3. Massive sandstone 40 feet, underlain by drab clay shales and carbonaceous shales with plant remains. Plants, ferns, cycad-like in type, pine needles, plant impressions like modern Equisetum, leaves of willows, rushes, etc	100
4. Soft sandstones, clay shales and clays with one workable (3 to 5 feet thick) and several smaller local seams of coal, plant remains, peculiar ferns, cycad-like, and long flattened pine needles	100



A. Hoen & Co. Lith. Baltimore.

Page.

5. Ash-colored clays with calcareous nodules. No fossils observed; near top at contact with No. 4 occur, locally, fossil bones........................ 50

This member may be Jurassic.

6. Jurassic clays and shell limestone with marine fossils—Belemnites, Ostrea, Exogyra, etc.

Professor Jenney commenced almost immediately to send on packages of fossil plants. Three packages were sent on June 16, two on June 28, five on July 8, and one on July 12. In addition to this, he sent a box containing specimens collected in August and September. Altogether the collection is one of the finest that has ever been made from any part of the West. It came in admirable condition, with every specimen carefully and accurately labeled, indicating its locality and the particular stratum from which it was obtained. This collection was forwarded to Professor Fontaine for determination, and his report upon it is embodied in this paper (pp. 645–702, Pls. CLXII–CLXIX).

In one of Professor Jenney's letters, dated August 20, 1894, he gives the following additional facts, which are well worth recording:

I hope the collections I have sent in will insure the determination of the age of the coal and the separation of Newton's Dakota group into its several horizons. Since my last letter I have done a great deal of detailed stratigraphic work in the interval between the Red Beds and the Fort Benton shale.

I find overlying the marine beds of the Jurassic about 50 feet of light-colored clays with nodular layers of clay limestones. These beds I first supposed to be possibly Lower Cretaceous, and marked them No. 5 in the section I sent you in my letter. I have found evidences that these beds are probably Jurassic shallow-water deposits; they carry often large trunks and limbs of fossil wood, and in the layers of impure limestone a few small Ammonites near the top of these beds; just below the contact with the base of No. 4, Cretaceous, occurs a bone-bearing bed—large elongated vertebræ and fragments of leg and thigh bones, all in a poor state of preservation. These beds recall the Atlantosaurus beds of Marsh to my memory, but as I have not the original papers by Professor Marsh on those saurian remains I can not say more as to their probable place in the section.

There are evidences that the land was rising at the close of the Jurassic, for some of the No. 5 beds may be brackish or fresh water, and that before the deposition of the lowest beds of the coal series (division No. 4, Newton's Dakota) the land was above water and had suffered a quite extensive denudation, and that the workable and lowest beds of coal were deposited in basins, channels, and valleys in the eroded Jurassic. This I believe has not been noted before. I find the dynamic geology of the region far more complicated as I study it than was at first apparent. There are faults, elevations of strata, both anterior and subsequent to the formation of the coal. I have been able to send you quite a representative collection of the plants of No. 2 division of Newton's Dakota; a less extensive one of the plants of No. 3 division, and but few plants from No. 4 division, the horizon of the coal. I did not try to collect from No. 1, the Dakota sandstone proper, as the plants from that horizon are well known. I have hired three or four miners, and will open the coal in No. 4, in a new field I have discovered in an unexplored section of this region. If there are any plants I will send you collections made.

As I think I wrote you, I find evidences of unconformity between No. 3 and No. 2 and between No. 2 and No. 1. I have been unable to detect any unconformity between No. 4 and No. 3. The great unconformity of the Jurassic and No. 4 has been noted. On the higher ridges of Jurassic surface, No. 3 rests on the Jura and No. 4 is absent.

I think I can get you plants that will show No. 4 to be older and distinct from No. 3, though the stratigraphy shows apparent uninterrupted deposition.

Not content with performing these important services, Professor Jenney has taken time to prepare for me, with permission to use in this report, an extended series of notes upon the Hay Creek region and a large number of sections from the most important plant-bearing beds. It is with great pleasure that I avail myself of the data thus furnished, which I insert bodily into this memoir. The map of the Hay Creek coal field was also prepared by him; and taking this in connection with his descriptions and sections, we have a very full statement of the geology and paleontology of that region.

Professor Jenney continued to furnish these notes down almost to the time of going to press. It is my duty to add that he has performed all these services for the pure love of science, and the spirit by which he has been actuated may be gathered from the following remark in his letter of April 17, 1898, inclosing the last of his manuscript, where he says:

Use these notes when you can in writing, and all other notes, maps, and data sent. Do not worry about giving me credit. The object to be attained is the best monograph on the coal field. So use all data as your own and publish over your own signature, unless there is good reason for not doing so. You have full authority to omit, change, or publish any or all of the material sent in such manner as you shall deem best.

A copy of Professor Fontaine's manuscript describing the fossil plants of the Hay Creek coal field was sent to Professor Jenney, and his notes include a discussion of the stratigraphy from the paleontological standpoint.

FIELD OBSERVATIONS IN THE HAY CREEK COAL FIELD.

By Walter P. Jenney.

THE DAKOTA GROUP OF NEWTON.

In the report on the geology of the Black Hills based on the field work of the survey of that region made in 1875, Mr. Henry Newton, the geologist of the survey, wrote:

It has already been remarked that the concentration of attention on the main body of the Hills prevented a thorough study of the Jura. In a still greater degree it reduced our opportunities for the examination of the Cretaceous. Very few of our excursions penetrated more than the basal member, and the only examinations of the entire series were in our rapid approach to the Hills via Beaver Creek and on our return march. So far, however, as our observations extended, it was evident that the Upper Missouri section of Meek and Hayden was applicable without essential modification.[1]

Mr. Newton quotes from the Invertebrate Paleontology of Professor Meek as follows:

No. 1.—Dakota group.

Yellowish, reddish, and occasionally white sandstone, with at places alternations of various-colored clays and beds and seams of impure lignite; also silicified wood,

[1] Geology of the Black Hills, p. 175.

and great numbers of leaves of the higher types of dicotyledonous trees, with casts of *Pharella? Dakotensis, Trigonarca Siouxensis, Cyrena arenarea, Margaritana Nebrascensis,* etc.

Localities.—Hills back of the town of Dakota; also extensively developed in the surrounding country in Dakota County [Nebraska] below the mouth of the Big Sioux River, and thence extending southward into northeastern Kansas and beyond. Thickness, 400 feet.[1]

Mr. Newton, writing from his own observations on the Dakota group in the Black Hills, describes it as follows:

Prominently developed, forming the capping rock to the foothills that surround the Hills on all sides; appears with its characteristic composition—coarse yellow or red sandstones with discontinuous variegated clays. At places a considerable thickness of very soft and fine white sandstone appears at the base. Elsewhere considerable portions are of hard, dense quartzite. No animal fossils were found, but many remnants of plants—in no case more than mere coaly fragments. Thickness, 250 to 400 feet.[2]

Mr. Newton placed in the Dakota group all the sandstones and clays included between the Jurassic and the Fort Benton, following Dr. F. V. Hayden, who had studied this formation along the Missouri River, and who first identified the Dakota sandstone in the Black Hills, Dr. Hayden having accompanied as naturalist and geologist the expeditions under command of Gen. G. K. Warren in 1855 and of Capt. W. F. Raynolds in 1859, who made brief visits to the Black Hills.

Mr. Newton has in the text quoted briefly explained the imperfect and hurried character of the investigation of the later geological formations in the foothills, which was unavoidable from the necessity of concentrating the work upon the metamorphic region of the interior of the Hills, with its placer gravels and gold-bearing veins.

In the summer of 1877 Mr. Newton returned to the Black Hills for the purpose of making a more complete investigation of the geological structure and to supply many omissions in the field observations made in 1875. While there engaged he died at Deadwood from typhoid fever. The manuscript of his report on the geology of the Black Hills was left incomplete at his death and was not published until 1880.

From the early work of Dr. Hayden in this region the unity of the Dakota group was not questioned until the visit of Prof. Lester F. Ward in September, 1893, who came to the Hills with the object of determining, if possible, the horizon of the remarkable fossil trunks of cycads found near Hot Springs, South Dakota. In the search for the cycad locality and in the approximate determination of the horizon from which these fossil trunks had been derived I accompanied Professor Ward, as related elsewhere.

The following summer I was engaged in an investigation of the economic value of the coal of the Hay Creek region in the extreme northern Hills, distant 90 miles north-northwest from Hot Springs. In the progress of the field work it was found that workable beds of coal occurred in the lower part of the Dakota group. Later, as the relation

[1] Geology of the Black Hills, p. 174. [2] Geology of the Black Hills, p. 175.

of the different beds was worked out, and as collections were made of the fossil plants, it became apparent that the Dakota group was made up of a number of distinct formations, separable stratigraphically, and that each division was characterized by a fossil flora peculiar to itself, by which it could be readily recognized. The collections of fossil plants were forwarded for determination to Professor Ward at Washington. There was also sent a general section of the strata exposed in the Hay Creek region, a description of the several divisions determined stratigraphically of the Dakota group, and a statement of the approximate position of each plant-bearing bed or horizon, referred to its proper division and measured from the Jurassic below and also from the Dakota sandstone above.

These plant collections, with the accompanying notes, were referred by Professor Ward to Prof. Wm. M. Fontaine for examination.

The divisions of the Dakota group, determined stratigraphically, were confirmed by the study of the plants by Professor Fontaine, who further determined that the divisions (Nos. 3 and 4) lying at the base of the Dakota group, and including the coal beds of economic importance corresponded most nearly in flora to the Lower Potomac. The division above (No. 2), lying immediately beneath the Dakota sandstone (No. 1), was correlated by its flora substantially with the upper portion of the Older Potomac (Aquia Creek series), and all of the Dakota group included between the Jurassic at its base and the true Dakota sandstone at the top was thus placed in the Lower Cretaceous.

In the determination of the horizon of the fossil cycads in the Hot Springs region Professor Ward had previously identified the upper 100 feet of strata of the Dakota group as constituting the Dakota sandstone proper, characterized in the southern hills by an abundance of well-preserved dicotyledonous leaves. The underlying beds included between the Jurassic and the Dakota sandstone were shown to be in all probability Lower Cretaceous, from position, from the abundance of fossil cycad trunks, and from the confirmatory evidence of a small collection of fossil plants obtained.

The field work in the Hay Creek region and the plant collections made have furnished data for the division of the Dakota group into distinct epochs, corresponding to the prominent divisions of the Cretaceous of the Atlantic coast. Further, it has made certain the determination by Professor Ward of the Lower Cretaceous age of the larger part of the strata in the Black Hills heretofore included in the Dakota group.

THE HAY CREEK COAL FIELD COMPARED WITH THE POTOMAC FORMATION.

1. *Character of the sediments.*—The beds forming the Dakota group of Newton are either pure sands, clays, or mixtures of clay and sand. Granitic sands (arkose) are absent. These sediments are consolidated into rock strata of varying hardness. The sands form sandstone in

many localities, particularly in the lower part of the Dakota sandstone, of a quality suitable for building purposes. The clays occur as clay shales, save the under and over clays of the coal beds, which are commonly soft fire clays, though with a shaly structure.

The beds show little or no disturbance after deposition. Erosion has taken place in certain beds prior to the deposition of the later strata resting upon them. The clay balls and lenses—irregular masses and sheets of clay described as occurring in the Potomac formation, the result of the destruction of preexisting clay beds—do not seem to have their counterpart in the Black Hills. So far as the writer has had the opportunity to examine the Dakota formation in other localities in the belt encircling the Black Hills, it everywhere has the above-described character.

2. *Persistence of plant horizons.*—Certain horizons carry plants throughout the Hay Creek region; notably the plant horizon of division No. 3 at the base of the cliff-forming sandstone (No. 3); also the bed of carbonaceous shales about 100 feet below the base of the Dakota sandstone in division No. 2.

3. *The Lower Cretaceous a coal-forming period in the Black Hills.*—At the opening of the Lower Cretaceous the beds of workable coal were deposited in hollows eroded in the Jurassic surface. A period of quiet must then have occurred, long enough to form coal with a thickness of from 3 to 6 feet. The coal appears to have been formed where the vegetation grew and to have been deposited in basins, channels, and small irregular swampy tracts between the Jurassic hills.

Like the coal beds of the Carboniferous, the Hay Creek coals have an under clay, filled with fragments of plant remains, and an overclay, in which occur, in favorable localities, well-preserved plants. Overlying and capping the clays with the included coal are thick beds of sandstone.

In division No. 3 thin coals occur, but are seldom found of workable thickness. In division No. 2 a bed of black carbonaceous shale occurs continuously over a considerable area. In the Dakota sandstone thin impure coal seams without economic value are found in the upper shaly strata.

4. *The Newcastle coal.*—At Newcastle, Wyoming, at the Cambria coal mines, on the southwestern border of the Black Hills, coal also occurs in the lowest beds of the Lower Cretaceous. The horizon of the Newcastle coal is about 50 feet above the top of the Jurassic. The coal is peculiar in character, having been apparently deposited in the bottom of a lake, and formed mainly from the leaves of some species of conifer. The coal is underlain by hard, massive sandstone and is directly covered by thick sandstone strata, without a trace of the underclay or overclay commonly occurring with coal beds the world over.

At the Cambria mines this coal is 7 to 9 feet in thickness. Seams of splint, or impure coal, 4 to 8 inches thick, occur in the upper part of the bed. On weathering on the slack dump the fragments of these splint layers disintegrate into bunches of long, flat, pine needles, brown colored on the surface; on breaking, of a brilliant jet-black coal within. These conifer leaves are 3 to 4 inches long, and as a result of one or two seasons' exposure to weather a fragment of splint comes to resemble a bunch of coarse brown-colored hay. These needles will burn when lighted with a match.

The Newcastle coal is heavy, dense, breaking into shaly fragments, thin at the edges, like rock spalls from a quarry. The ash is nearly pure silica, apparently made up mostly of fine sand deposited with the vegetable matter forming the coal. The percentage of ash varies widely in different parts of the coal bed, but averages about 13 to 18 per cent of the weight of the coal shipped. In coking, this coal gives off a large amount of condensable products—tar, ammonia, etc.

The Newcastle coal is used on the locomotives of the Burlington Railroad, as a fuel for steam boilers at the Homestake mines, and in the form of coke in the smelting furnaces (D. & D. Smelter) at Deadwood, South Dakota. It is not favored as domestic fuel. Microscopic examination of specimens of this peculiar coal from different parts of the bed might throw light on its origin and formation.

5. *Stratigraphical position of the Lower Cretaceous in the Black Hills.*—Most valuable of all is the precisely defined position of the Lower Cretaceous. The Dakota group of Newton embraced all the strata included between the marine Jurassic and the Fort Benton of the Upper Cretaceous. The marine Jurassic is characterized in the Black Hills by a great abundance of fossil mollusks, so that the age of the formation is well established. Resting uncomformably on the marine Jurassic, and formed from the products of its erosion, is the brackish or fresh-water formation which I have designated as later Jurassic, division No. 5 of Newton's Dakota group, the supposed equivalent of the Atlantosaurus beds of Marsh. Whether these beds should be regarded as Jurassic or as transition beds between the Jurassic and Cretaceous, or should be made the lowest division of the Lower Cretaceous is open to discussion. The marked uncomformity between the Lower Cretaceous and these later Jurassic beds, the great change in the character of the sediments in passing from the Jurassic (No. 5) to the Cretaceous (No. 4), and the resemblance of the few fossil shells found in No. 5 to Jurassic forms, have led the writer to place this formation in the Jurassic. There is little doubt that division No. 5 of the Hay Creek section is the same as the beds included between the Jurassic and the Dakota group at Piedmont, South Dakota, on the eastern border of the Black Hills, which were identified by Marsh as the representative of the Atlantosaurus beds of Wyoming and Colorado. The Piedmont locality was visited by J. B. Hatcher, who there found numerous large elongated vertebræ described by Marsh as a species of Barosaurus.[1] Similar vertebræ were found by my assistants in the upper beds of division No. 5, in the Hay

[1] Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, p. 175.

Creek region. Professor Marsh gives the following general section of the geological horizon of vertebrate fossils in North America:[1]

Cretaceous	Dakota group.	
Jurassic	Atlantosaurus beds; Baptanodon beds; Hallopus beds	Dinosaurs: Brontosaurus, etc. Mammals: Dryolestes, etc.
Triassic.		

Referring to the "remains of an enormous dinosaurian"[2] found near Morrison, Colorado, in 1877, and described as *Atlantosaurus montanus*, Professor Marsh writes:

When first found these fossils were supposed to be from the Dakota group, but their Upper Jurassic age was soon after determined by the writer from evidence that placed the horizon beyond dispute.

Professor Marsh continues:

Another locality of Sauropoda, more recently explored by the writer, is in South Dakota, on the eastern slope of the Black Hills. This is the most northern limit now known of the Atlantosaurus beds, which form a distinct horizon along the eastern flanks of the Rocky Mountains, marked at many points by the bones of gigantic dinosaurs, for nearly 500 miles. The strata are mainly shales or sandstones of fresh water or estuary origin. They usually rest uncomformably upon the red Triassic series, and have above them the characteristic Dakota sandstones. On the western slope of the Rocky Mountains the Atlantosaurus beds are also well developed, especially in Wyoming, but here they have immediately below them a series of marine strata, which the writer has named the Baptanodon beds, from the largest reptile found in them. This horizon, also of Jurassic age, is shown in the section.[3]

From the above it is evident that Professor Marsh regarded the Atlantosaurus beds as later Jurassic.

The marine beds of the Fort Benton form a marked boundary to the Dakota group readily identified by the eye as far as the colors of the different formations and the peculiar topography which each impresses upon the field of view can be distinguished.

Upon examining the Dakota group of Newton in detail the Dakota sandstone is readily differentiated stratigraphically from the lower divisions by the abrupt change in the character of the sediments, the Dakota sandstone forming a prominent cliff, while the clays of the Lower Cretaceous immediately underlying it yield to erosion and are covered beneath a long grassy slope. Even more marked is the great change in the flora between the Lower Cretaceous and the Dakota sandstone, but this I need not go into further.

In the Black Hills the strata of the Lower Cretaceous are thus intercalated in a series of well-determined formations, so that the exact relative position is accurately known, both stratigraphically and paleontologically.

Fossil wood occurs in the later Jurassic of Hay Creek, and it is not improbable that fossil plants will be found in the brackish and fresh

[1] Sixteenth Ann. Rep. U. S. Geol. Surv., Part I, p. 145. [2] Ibid., p. 164. [3] Ibid., p. 165.

water deposited beds of the Jurassic when the great extent of territory covered by rocks of this age, stretching along the eastern slope of the Rocky Mountains, is carefully explored and particular search made.

6. *Resemblance of the flora of the Hay Creek coal field to that of the Lower Potomac.*—Professor Fontaine remarks:

> The fact that the Hay Creek flora shows a much greater resemblance to that of the Lower Potomac than to the Kootanie floras of British America and of Great Falls, Montana, which occur much nearer to the Hay Creek region than does the Potomac, of Virginia, is another surprising feature (see infra, p. 702).

In my letter of May 26, 1896, I commented on the insular position of the Black Hills, and stated that from my own observations the modern flora is more nearly related to that of the Eastern States than it is to the flora of the Rocky Mountains.

The Black Hills may have been covered by the ocean as late as the close of the deposition of the marine Jurassic. No positive evidence has been obtained that any portion of the Hills was above water prior to that date, although the water continued shoaling from the Carboniferous to the later Jurassic. Neither has fossil wood been found in the Triassic or the marine Jurassic, and it is not until the later Jurassic is reached that it occurs.

Jurassic formations occur west of the Black Hills and along the foothills of the Big Horn Mountains, and extend north into Montana and south through Wyoming and Colorado to New Mexico. The eastern shore of the sea depositing the marine Jurassic is not known; neither is it known how far to the east the fresh and brackish waters extended in the later Jurassic. The Upper Cretaceous stretches eastward into Kansas and Iowa. Strata of Jurassic age have not been discovered east of the Black Hills. I found the marine Cretaceous in Arkansas, abutting on the Paleozoic, and searched the contact for the missing formations.

In Cretaceous time a great promontory of land, formed by the union of the Ozark and Ouachita uplifts, stretched from Missouri and Arkansas southwesterly across Indian Territory to the Pan Handle of Texas. This promontory had its origin in the elevation of the Allegheny continent at the close of the Carboniferous. The land nearest to the Black Hills on the east during the Upper Cretaceous was the northwestern shore of this upheaval, which crossed central Kansas in a line running northeastward into Iowa. In Jurassic and Lower Cretaceous time the western border of the continent may have been much nearer to the Black Hills than in the Upper Cretaceous. Is it not probable that the flora of the Hay Creek region may have been derived from the east? Further, occasional strong winds in the Black Hills come from the east and the heavy rain storms often occur with a southeast wind. With all this, with the origin of these winds in the Gulf of Mexico, with the great extension of the Gulf of Mexico to southern Illinois in the Mesozoic, may not easterly winds have been more prevalent and assisted in the migration of the plants westward?

The Cretaceous shore line lies 400 to 450 miles southeasterly from the Black Hills. The Kootanie country is situated on the head waters of the Columbia, distant 750 miles northwest from the Hay Creek coal field. Great Falls, Montana, is somewhat nearer, on the head waters of the Missouri.

Since writing the above I have found that this subject has been gone into extensively by C. A. White, J. S. Diller, and T. W. Stanton, and that Dana embodied[1] their views in a map of North America in the Cretaceous period. According to this map, the Kootanie region would lie on the northeastern shore of the "Pacific border" and naturally would belong to a different floral province. The tiny dot on the map representing the Black Hills, in the middle of the Cretaceous area, seems possibly to have derived its flora from the Alleghany continent. At the present day not only the plants, but many of the animals and birds, are of eastern species.

7. *Absence of certain forms of life in the Cretaceous formation of the Hay Creek coal field.*—Many forms of life which naturally would be expected to occur preserved in the sedimentary strata, appear to be absent. This is the more remarkable because the conditions of climate and of deposition and the known occurrence of a most varied fauna and flora in other parts of the country during Cretaceous time would seem to have been favorable not only to abundant life, but also to its preservation in the fossil state. It is true that such evidence is of a negative character, and that the collections made even in the richest plant localities are scanty, yet it is not without value in throwing some light on the conditions which subsisted in this region during the deposition of the Hay Creek beds.

a. Absence of cycads.—Careful search was made, without success, for silicified trunks or cycads, such as are found abundantly near Minnekahta station in the southern part of the Black Hills. Photographs of these cycads were shown to a number of cattlemen and settlers, but no one could recall ever having seen anything resembling them. The abundance of silicified wood shows that the conditions were favorable for their preservation.

b. Scarcity of dicotyledons in the collections made.—The collections were forwarded to Washington by mail, for which reason selected material only was preserved, but in making the selection all the material left on the ground was carefully examined for impressions of leaves of anything resembling dicotyledons. Only two or three were found, all in the beds of division No. 2. In division No. 1, Dakota sandstone, dicotyledons occur in favorable localities, but are mostly poorly preserved and difficult to identify.

c. Absence of marine beds in the Dakota group of Newton.—The calcareous clays of division No. 5, later Jurassic, appear to have been deposited in brackish waters. A small ammonite, a fragment of a shell resembling Unio, and a few other small and poorly preserved

[1] Manual of Geology, 4th ed., p. 813.

shells were found in layers of impure argillaceous limestone. These fossils bear resemblance to Jurassic forms. All the beds of the Lower Cretaceous and of the Dakota sandstones have been formed in fresh water.

d. Prevailing absence in the strata of the Lower Cretaceous and in the Dakota sandstone of all forms of life commonly occurring in bodies of fresh water.—Fossil bones of many species of the Atlantosaurus, as well as turtles, tortoises, birds, and small mammals are described by Marsh from the Atlantosaurus beds of Colorado, Wyoming, and the eastern slope of the Black Hills. Elongated vertebræ, similar to the forms figured by Marsh, were found in the beds of division No. 5 in the Hay Creek region, the supposed equivalent of the Atlantosaurus beds of Marsh.

From the base of division No. 4 to the top of No. 1, the Dakota sandstone, although many exposures were carefully examined and an area of nearly 120 square miles gone over, yet not even a fragment of a fossil bone was anywhere found, not a single specimen of a fresh water or land shell; neither are there in the beds any visible comminuted fragments of shells. Insects also seem to be wanting. What can be the reason that while the beds in divisions No. 1, No. 2, and No. 3 were formed in a body of fresh water, supposed to have stretched for hundreds of miles, fishes, turtles, reptiles, and aquatic birds have left no trace of their presence? Neither can I recall finding any fossil plants of species which would be aquatic in growth.

Fossil wood, which is very abundant in the upper beds of division No. 2, and occurs more sparingly in divisions No. 3 and No. 4, is nowhere found to have been attacked by boring mollusks. This is merely an evidence of the absence of the sea or of brackish water, all mollusks which attack wood being marine; but I have thought it best to record the fact.

Whatever may have been the character of the vast body of fresh water in which these beds were deposited, it is reasonably certain that it must have had an outlet, and during the time that the beds of divisions No. 4, No. 3, No. 2, and No. 1 were forming, it could never have been saline to such a degree that chemical precipitates would occur, such as are characteristic of salt lakes—lakes without outlet. All the beds of these divisions are either clays or sands. Chemically precipitated beds, as limestones, calcareous sediments, gypsum, and marls carrying peroxide of iron, are absent. With the exception of concretions of limonite, which occur quite abundantly in the Dakota sandstone, much of which is probably of recent formation from atmospheric waters, all the iron in these beds is in the form of peroxide.

Briefly reviewing the evidence, it may be remarked that the coal of division No. 4 and its accompanying shales were deposited in local marshes, occupying depressions eroded in the Jurassic surface. The coal was evidently formed where the vegetation grew. The beds resemble the coal formations of the Carboniferous in having underclay and overclay, the latter carrying impressions of fossil plants, and also in the character of the coal itself—dry, black, noncoking, with little ash or sulphur.

The third division opened with alternating conditions, forming thin coals interbedded with shales and soft sandstones, but closed with a considerable sinking of the region and the deposition of a persistent sandstone covering the whole Hay Creek region and dipping northerly and easterly until concealed beneath the marine beds of the Upper Cretaceous.

Division No. 2 opens with the formation of a heavy sandstone, continuous over a great area. The lower stratum of this sandstone is in many localities a conglomerate or breccia, and there are evidences that the underlying No. 3 sandstone suffered some denudation before the deposition of the No. 2 sandstone.

These sandstones show evidences, in ripple marks, in cross-bedded structure, in layers of coarse sand, and in a few beds of conglomerate, that they were deposited in shallow water by currents having frequent changes of direction. Division No. 2 closes with beds of clay and sandy shale, and locally thin, irregular seams of impure coal, deposited in quieter waters and during alternating changes of level. The evidence is seldom seen of denudation having taken place on the surface of division No. 2 before or accompanying the deposition of the Dakota sandstone, because the contact of the two divisions is in most places concealed.

The Dakota sandstone shows more than any other sandstone the effect of currents of water in its formation. The sediment varies widely in character in short distances and in different beds. Broad sheets of heavy ripple marks occur, cross-bedded structure is strongly marked, and iron in the form of limonite is abundant in certain layers. In short, from an examination of the beds there is no evidence that the conditions which existed in the Hay Creek region during the Lower Cretaceous were either unfavorable to the existence of life or to the preservation of the life record in the rocks. The land was entirely above water at certain epochs, with marshes, swamps, and shallow isolated lakes in the depressions between the hills. These conditions were permanent long enough, during the deposition of the beds of division No. 4, to form in the deeper basins solid coal 3 to 5 feet in thickness, free from partings of shale.

Later, in early Cretaceous time, there were intervals of quiet waters depositing fine sediments—clays, sandy shales, and fine sandstones. To these mud flats succeeded widespread deposits of sand, laid by swift currents, and ripple-marked by the waves. High winds occurred, which tore branches from trees and leaves from ferns and bore them to shallow sand flats, where they were buried and preserved. It was the age of reptiles and reptilian birds, yet not a bone or tooth marks their presence.

What was the nature of the body of this fresh water stretching for hundreds of miles, without land or fresh-water shells, with no trace preserved of fishes? Contrast the paucity of all life, save plants, in these Lower Cretaceous beds with the wonderful preservation of fossil forms, particularly dinosaurs, in the Laramie formation of Converse County, Wyoming, southwest of the Black Hills.

In conclusion, it is not improbable that the absence of cycads may have been due to unfavorable climatic conditions on the northern slope of the Black Hills. The cycad locality near Minnekahta station is on the southern slope of the Hills, 90 miles south of the Hay Creek coal field, and may in early Cretaceous time have had a milder climate than the more northern region.

Until all the different coal basins lying on the southern and western border of the Black Hills have been investigated and particular search has been made for dicotyledons but little can be argued from their apparent absence in the Hay Creek region. The Lower Cretaceous completely encircles the Black Hills, and the outcrop of the beds of this age forms a narrow belt along the eastern foothills at the edge of the plains. On the southern, western, and northern sides the area covered by this formation is much greater, and isolated basins occur near Minnekahta, at the Cambria coal mines near Newcastle, Wyoming, at Inyankara, and west of Sundance, Wyoming, where more or less valuable and extensive deposits of coal have been opened. It is a great field, and the collections made are but an indication of what may be reasonably looked for as the result of a thorough investigation of the Lower Cretaceous belt. The Dakota sandstone at Evans quarry, near Hot Springs, South Dakota, carries finely preserved dicotyledons. A limited collection was made from this locality by Professor Ward in September, 1893, described below (pp. 702–709, Pls. CLXX–CLXXII). In the Hay Creek region the Dakota sandstone carries fossil plants in the upper beds, but in all the localities examined the plant remains were so decomposed and carbonized that none were collected.

It might be argued that the prevailing absence of land and fresh-water shells in the Lower Cretaceous of Hay Creek was due to the dissolving action of carbonic acid produced by the oxidation of the carbon and organic matter in the beds. But this cause would not account for the nonpreservation of the bones of reptiles, which are largely composed of lime phosphate.

The different beds vary in composition from nearly pure clays, with very little organic matter, to carbonaceous shales which will burn like impure cannel coal; from sandstones filled with carbonized plant remains, in every gradation, to almost pure sand. Further, it has been shown that these beds have been deposited under most varied conditions, so that it is not reasonable to invoke the destructive action of carbonic acid to account for the nonpreservation of fossil forms, largely composed of lime carbonate, throughout several hundred feet of strata covering so great an area. Had this been the cause there would have occurred exceptional localities with the preservation of calcareous fossils.[1]

SECTIONS OF THE HAY CREEK COAL FIELD.

The following is a section of Cretaceous strata on the cliff on the east side of the canyon of Oak Creek, about 2 miles north of Robbins Ranch, Crook County, Wyoming:

Section in Oak Creek Canyon.

	Feet.
Top of plateau.	
11. Red sandstone, much denuded	2
10. Carbonaceous shale, with thin coal	1
9. Red sandstone	10
8. Shales and sandstones on partly exposed slope	60
7. Carbonaceous black shale, coaly	1
6. Drab sandstone shales, with finely preserved plant remains	4
5. Yellow sandstone	3
4. Drab clay and sandy shales	2
3. Gray sandstone	7
2. Gray sandy shales	5
1. Black carbonaceous shale, base of cliff, creek bottom	4
Total exposure	99

The Dakota sandstone, beds 9, 10, and 11, is here but a remnant left by erosion. A mile to the southeast this formation outcrops 60 to 80 feet in thickness along the cliffs at the edge of the plateau.

Beds 1 to 8, inclusive, are placed in No. 2 division. Only a part of the strata of this division is exposed, the lower beds lying beneath the water in Oak Creek.

Bed 6 is a remarkably productive plant-bearing stratum, and deserves more extended exploitation. This plant horizon is the highest in division No. 2 from which collections were made, being 61 feet below the base of the Dakota sandstone. The locality is only reached from the plateau above, on the southeast side of Oak Creek. The bed yielding plants outcrops at the top of the cliff, which, like a wall, incloses the contracted bottom of Oak Creek.

Bed No. 1 is here barren of plants, but is traced by openings made in search of coal along the base of the cliff to the bluff near Robbins Ranch, where, in the overlying shales, many plants were found.

It is also the stratigraphical equivalent of the plant-bearing shales on Pine Creek, 2 to 2½ miles west of Mrs. Dorset's ranch, distant 7 to 8 miles west from the Oak Creek localities.

Below is given a section of Lower Cretaceous, exposed on the north bank of Pine Creek, 2 miles west of Mrs. Dorset's ranch:

Section on the north side of Pine Creek.

	Feet.
Top of low ridge.	
12. Massive gray sandstone, weathering in large blocks, stained on surface Indian red to iron black	30
11. Light-gray sandy shales, base not exposed	5

[1] Professor Meek, in Invertebrate Paleontology, notes casts of fossil shells in Dakota along the Missouri River.

		Feet.
10.	Unexposed slope	30
9.	Yellow sandstone, weathering brown	4
8.	Gray clay shales, base covered	4
7.	Unexposed slope	28
6.	Yellow sandstone, thin bedded	8
5.	Gray sandy shales	2
4.	Clay shales with imperfectly preserved plants	2
3.	Unexposed slope	6
2.	Yellow sandstone, thin bedded	3
1.	Gray sandy shales with well-preserved plants, forming low bluff	14
	Total exposure	136
	Unexposed slope to water of Pine Creek	5

Bed 12 forms the base of the Dakota sandstone. All the rest of the section is included in division No. 2.

The section is important from the large collection of plants obtained from bed No. 1 near the roadside along the bank of Pine Creek. This horizon is 106 feet below the base of the Dakota sandstone.

About one-half mile southwest, on the opposite side of the ravine traversed by Pine Creek, the same beds appear at the top of a sandstone cliff, where the following section was measured:

Section on the south side of Pine Creek.

		Feet.
	Unexposed slope with Dakota sandstone at top not measured.	
9.	Yellow sandstone	7
8.	Gray sandy shales, partly exposed	6
7.	Light-gray sandstone	5
6.	Gray sandy shales	3
5.	Gray, drab, and black sandy shales, locally a black coal with abundant fossil plants	5
4.	Gray sandy shales	5
3.	Massive soft yellow sandstone, the upper layers somewhat shaly, with occasional plant remains	35
2.	Drab clay shale	1
1.	Conglomerate of small pebbles, base not seen	2
	Unexposed talus to creek	30
	Total exposure	99

All beds here numbered are embraced in division No. 2.

The conglomerate bed 1 resembles the stratum marking the unconformity of divisions Nos. 2 and 3 in the sections measured at the Barrett and the Larrabee and Young coal mines. Uniting these sections, the thickness of division No. 2 is 149 feet. Bed 5 of this section is the same as the plant-bearing bed 1 of the section half a mile below the north side of the creek. From this bed 5 and from the underlying sandstone a number of fossil plants were collected.

These localities on Pine Creek are rich in well-preserved plants, are accessible, and can easily be found from the data here given.

The following is a section of Cretaceous strata at Rollins tunnel, about 1½ miles southeast of Robbins Ranch, Crook County, Wyoming.

Section at Rollins tunnel.

	Feet.
Top of plateau.	
9. Soft massive reddish sandstone, forming low bluff	10
8. Unexposed slope	25
7. Massive sandstone, ocher yellow, thin bedded at base	20
6. Unexposed slope	35
5. Sandstone, ocher brown, thin bedded	6
4. Unexposed slope	20
3. Gray sandy shales	8
2. Black carbonaceous shales with finely preserved plants	3
1. Drab clay shales	5
Total exposure	132

Bed 9 forms the basal stratum of the Dakota sandstone covering the top of the plateau. All the other beds are in division No. 2. The plant horizon, bed 2, is 107 feet below the base of the Dakota sandstone and is stratigraphically the same as the bed of black shales at Robbins Ranch, Oak Creek, and at the localities 2 to 2½ miles west of Mrs. Dorset's ranch on Pine Creek. This plant locality is in a short tunnel opened at the bottom of a narrow dry ravine in the plateau extending easterly from Oak Creek to the State line.

Below is given a section of the Cretaceous strata exposed on the top of the plateau and in the bluffs along Oak Creek, near Robbins Ranch, Crook County, Wyoming.

Section on Oak Creek.

	Feet.
Top of plateau.	
17. Drab-colored clay shales, weathering in thin lamellar sandstone and sandy shales	2 to 30
16. Sandstone and sandy shales	25
15. Black carbonaceous shales with charcoal and carbonized plant remains imperfectly preserved	3
14. Sandstone, thin bedded	10
13. Massive sandstone, yellow to gray, weathering reddish and ocher brown, forming cliff	40
12. Unexposed slope with outcrops of sandstone	60
11. Soft massive sandstone, weathering thin bedded, forming top of bluff on Oak Creek	15
10. Black carbonaceous shale and clay	3
9. Light purplish sandstone	10
8. Gray clay shales	2
7. Reddish-purple sandstone and sandy shale with concretions of iron	4
6. Soft yellow sandstone	6
5. Clay shales and sandy shales with well-preserved plants	2
4. Gray shales	3
3. Carbonaceous black shale	3
2. Drab clay	3
1. Sandstone, base not exposed	5
Total exposure	224
Talus	20
Water in Oak Creek.	

Bed 17, the Fort Benton shale, rests unconformably on the denuded surface of the Dakota sandstone.

The whole formation dips northeasterly toward the Belle Fourche River, where the Fort Benton has a thickness of at least 300 feet.

The Dakota sandstone, here 78 feet in thickness, includes beds 13, 14, 15, and 16.

Bed 15 is locally a loosely coherent mass of vegetable remains, mostly leaves, too much decomposed to be determinable.

The remainder of the section lies in division No. 2.

Bed 5 yielded the collection of plants described by Professor Fontaine from the locality "Cliff on Oak Creek, near Robbins Ranch," 6 miles northeast of Barrett post-office.

Below is a section of Cretaceous strata exposed on the north side of the valley of the South Fork of Hay Creek, at the Barrett Coal Mines 1 mile west of Barrett post-office.

Section on South Fork of Hay Creek.

		Feet.
	Top of hill.	
	Soil, sand, and gravel resulting from weathering of the Dakota sandstone	10
19.	Massive soft yellow sandstone	20
18.	Unexposed slope of hill	15
17.	Outcrop of stratum of yellow-brown sandstone	5
16.	Unexposed slope of hill	12
15.	Yellow-brown sandstone	6
14.	Purple clays partly exposed	20
13.	Yellow sandstone, thin bedded	15
12.	Massive yellow sandstone, cross-bedded, forming cliff	45
11.	Conglomerate of small pebbles of flint and quartz	3
10.	Breccia of angular fragments of sandstone and shale in white clay, thickness varying	10 to 3
9.	Yellow sandstone with layer near base of brown iron sand	10
8.	Massive gray sandstone, weathering in thin layers, forming cliff	40
7.	Drab clay shales, with plant remains	2 to 5
6.	Soft sandy shales with carbonized plants	2
5.	Coal	1
4.	Soft yellow sandstone	4
3.	Drab clay shales	12
2.	Coal	3
1.	Drab clay shales	15
	Total exposure	246

The base of the above section is probably 30 feet above the top of the later Jurassic, which outcrops on the opposite side of the valley. Beds 1, 2, 3, and 4, a thickness of 34 feet, lie in division No. 4.

The bed of thin coal, 5, the plant-bearing shales, 6 and 7, and the cliff-forming sandstone, 8 and 9, form division No. 3, 58 feet in thickness.

Sandstones 12 and 13 unite to form the persistent sandstone stratum of division No. 2, which outcrops as a cliff along the hillsides in many localities in the area drained by the branches of Hay Creek.

In division No. 2 are the beds 10 to 18, both inclusive, aggregating 124 feet.

Bed 19, a low cliff near the crest of the hill, is the basal stratum of the Dakota sandstone. It forms a prominent landmark on the hilltops along the north and south sides of the valley of the South Fork.

In this section, estimating the thickness of the beds intervening between the lowest coal and the later Jurassic, the total exposure of Lower Cretaceous (No. 2, No. 3, and No. 4 divisions) is 246 feet.

As the section is followed westward beds 6 and 7 vary greatly in thickness, increasing locally to 30 feet, and finally thinning out to a stratum only 2 or 3 feet thick, resting unconformably on the Jurassic. These beds form a persistent plant horizon throughout the Hay Creek region. From this locality a small collection was made of fossil plants.

In the shales over the lower coal fossil wood occurs quite abundantly.

The following is a section of Cretaceous strata exposed on the north side of the valley of the South Fork of Hay Creek at the coal mines of Larrabee and Young, 1½ miles west of Barrett post-office:

Section at coal mines on South Fork of Hay Creek, near Barrett.

		Feet.
	Top of hill.	
	Soil and sand resulting from the weathering of the Dakota sandstone forming the plateau	10 to 30
20.	Soft massive yellow sandstone	8
19.	Soft yellow sandstone, thin bedded, weathering in a long, grass-covered slope	15
18.	Massive soft gray sandstone	20
17.	Soft yellow sandstone, thin bedded	15
16.	Unexposed, probably clays and shales, forming a grass-covered slope	30
15.	Soft massive shaly sandstone	15
14.	Gray sandstone shales, partly exposed	10
13.	Massive yellow-brown sandstone	7
12.	Unexposed slope	40
11.	Yellow sandstone with concretions of iron oxide	12
10.	Shaly sandstone	10
9.	Yellowish-brown sandstone	3
8.	Shaly sandstone	4
7.	Soft yellow sandstone	9
6.	Breccia of fragments of decomposed clay shale in white clay	3
5.	Soft yellow sandstone	6
4.	Massive yellow sandstone, forming cliff	30
3.	Clay shales and sandy shales	3
2.	Conglomerate of pebbles and sand, with bowlders 1 inch to 2 inches diameter of hard sandstone and siliceous limestone and a few quartz pebbles	8
1.	Soft sandstone and sandy shales	20
	Top of the Larrabee shaft, which is stated to be sunk to a depth of 75 feet, passing through the following strata:	
	Shales, clays, and soft sandstone	55
	Coal	5
	Clay and shales	13
	Coal	2
	Total exposure	373

In the above section the Dakota sandstone, division No. 1, is represented by 17, 18, 19, and 20, aggregating 58 feet in thickness.

In division No. 2 lie beds 6 to 16, inclusive, with a total thickness of 143 feet.

The breccia (bed 6 of section) marks the unconformity with the underlying strata. In this locality beds 7, 8, 9, 10, and 11 of division No. 2 can be seen to unite in outcrop and form a continuous cliff along the hillsides to the east and also to the west of the section measured.

In the same manner beds 4 and 5 of division No. 3 unite to form a cliff. One mile west all these sandstones unite from the cutting out of the intervening shale beds and form a single cliff 60 to 70 feet in height, which continues westerly for 2 miles along the hills bordering the north side of the valley of the South Fork.

Beds 1 to 5, inclusive, and part of the shales in the shaft should be included in division No. 3, but the line of demarcation from the underlying coal and shales of division No. 4 is covered, so that these two horizons can not be here separated.

On the south side of the valley, at a distance of half a mile, the later Jurassic clays outcrop in a range of low hills at such relative elevation with the coal that it is not probable that more than 25 feet of beds intervene between the bottom of the Larrabee shaft and the top of the Jurassic. This gives the total thickness of the Lower Cretaceous at this exposure 302 feet.

Plant remains occur very perfectly preserved in the shales over the lowest coal in the Larrabee shaft. Only a few specimens could be obtained at the time of the examination, owing to the bad air filling the shaft.

The following is a section of Lower Cretaceous strata at John Barr's tunnel, about 4½ miles east-northeast from Barrett post-office, Crook County, Wyoming:

Section at John Barr's tunnel, near Barrett.

	Feet.
Top of low ridge.	
9. Gray coarse sandstone	5
8. Massive yellow sandstone, cross bedded	30
7. Massive soft yellow sandstone, thin bedded	40
6. Coal, impure and shaly	¼ to ½
5. Black carbonaceous shale with plants	2
4. Coal	1
3. Clay	2
2. Yellow sandstone	4
1. Gray clay shale	5
Total exposure	89½

In the above section beds 8 and 9 belong to division No. 2, and the underlying beds are in division No. 3.

The plant horizon, bed 5, lies approximately 150 to 175 feet below the base of the Dakota sandstone, and is the equivalent of the beds carrying plants at the Webster ranch and in shales under third sandstone at Barrett coal mines and other localities given in the third division.

This tunnel, about 60 feet long, is run on the north side of a narrow ravine, $1\frac{1}{2}$ miles north-northeast from Forks post-office. Half a mile above this tunnel there are two shafts sunk in the bed of the ravine by Williams Brothers. The following section is given by Mr. Williams of the beds passed through in sinking the lower shaft:

Section of Williams shaft, near Forks.

Top of shaft at base of Sandstone Cliff, bed 7 of last section.	Feet.
15. Drab clay shales	20
14. Shaly coal	1
13. Sandstone	1
12. Alternating beds of shale and sandstone	12
11. Coal	$\frac{1}{2}$
10. Black shale	2
9. Sandstone	3
8. Coal and shale	1
7. Clay	3
6. Sandstone	2
5. Black clay shale changing to gray shale at base	12
4. Sandrock	2
3. Shale with plants	$2\frac{1}{2}$
2. Sandrock	6
1. White calcareous clay and blue clay	22
Total exposure	90

Bed 1 is later Jurassic, verified by inspection of the last material excavated in the bottom of the shaft and left on the dump.

Bed No. 3 and some of the associated beds may belong to division No. 4, though that formation appears to be wanting in this eastern section of the Hay Creek coal field. Nearly all, if not all, the beds in the shaft above the Jurassic clays are in division No. 3.

Below is given a section of Lower Cretaceous and Jurassic strata exposed near Webster's ranch, 4 miles southeast of Barrett post-office:

Section near Webster's ranch, southeast of Barrett.

Top of low hill.	Feet.
9. Yellow sandstone	14
8. Gray clay shales	12
7. Black carbonaceous shale with fossil plants	4
6. Gray shale	3
5. Unexposed	10
4. Soft sandstone, ocher yellow	10
3. Whitish gray clays	20
2. Unexposed	7
1. Calcareous sandstone with fossil shells, characteristic Jurassic species	2
Total exposure	82

In the above section beds 4 to 9, inclusive, are placed in division No. 3. The prominent sandstones of divisions Nos. 2 and 3 form cliffs one-fourth and one-half mile north of this point.

The horizon of this plant bed 7 can not be accurately determined, but is not more than 200 feet below the base of the Dakota sandstone.

Division No. 4 is wanting in this part of the Hay Creek area, and the beds of division No. 3 rest unconformably on the later Jurassic.

Beds 2 and 3 of this section are later Jurassic (division No. 5) and rest unconformably on the denuded surface of the marine Jurassic bed 1.

The plants collected at this locality were obtained from shales at the entrance to a tunnel run on the black coaly shales in search of a workable seam of coal. This tunnel is caved, so that it can not be entered. It is reported to have been 50 or 60 feet long, and that specimens of well-preserved plants were obtained by the miners working there.

This plant horizon is stratigraphically equivalent to that of the localities at the cliff on the north side of the valley of the south fork of Hay Creek, the shales under third sandstone of section near Barrett, and the beds at John Barr's tunnel, from all of which small collections of plants were made.

The following is a section of Cretaceous and Jurassic strata exposed on the hill near Lon Cottle's ranch, 1 mile southwest of Barrett post-office, Crook County, Wyoming:

Section near Lon Cottle's ranch, southwest of Barrett.

		Feet.
	Top of hill.	
	Soil and gravel	5
32.	Thin bedded ferruginous sandstone	15
31.	Massive sandstone, yellow, and irregularly impregnated with iron oxide, weathering ocher brown	35
30.	Unexposed slope of hill	20
29.	Yellowish-brown sandstone	5
28.	Unexposed slope	20
27.	Yellowish-brown sandstone	5
26.	Unexposed slope	20
25.	Massive yellow sandstone, cross bedded	35
24.	Yellow sandstone, weathering in thin layers	35
23.	Clay shales and sandy shales	4
22.	Soft yellow sandstone	2
21.	Drab clay shales with plant remains	8
20.	Coal	2
19.	Gray clay	1
18.	Soft sandstone, ocher-brown colored, thick bedded	18
17.	Soft yellow sandstone	8
16.	Gray sandy shales	4
15.	Soft yellow sandstone	3
14.	Gray clay shales	4
13.	Coal, impure and shaly	2
12.	Yellow sandy shales	6
11.	Drab clay	3
10.	Coal	1
9.	Gray clay	2
8.	Gray clay shales	7
7.	Carbonaceous shale with thin seam of coal	1

	Feet.
6. Gray sandy shales	15
5. Carbonaceous shales with fossil plants	3
4. Soft yellow sandstone, iron stained	1
3. Light gray and white clay with calcareous concretions and some crystallized gypsum	35
2. Yellow soft sandstone and sandy shales	6
1. Drab clay shales and sandy shales	13
Unexposed	3
Total exposure	347

Water in creek, the south branch of the South Fork of Hay Creek.

In this section beds 31 and 32 represent division No. 1, the Dakota sandstone.

Beds 25 to 30, inclusive, aggregating 105 feet, form division No. 2, which is at this locality, from the union of the two massive sandstones, beds 24 and 25, into a single cliff, not separable from division No. 3.

Division No. 3 embraces beds 19, 20, 21, 22, and 23, and the cliff sandstone 24; in all, 52 feet of strata. Bed 21 is the persistent plant horizon of this division.

In division No. 4 are beds 4 to 18, inclusive, a total thickness of 78 feet; bed 4 resting on the eroded surface of the later Jurassic.

Beds 1, 2, and 3, aggregating 57 feet, are later Jurassic, and cover nearly the whole thickness of that formation; the marine Jurassic outcropping near the bed of the creek a short distance west of this section.

Adding 40 feet for the upper beds of the Dakota sandstone, removed by erosion, the thickness of the Dakota group of Newton, which included division No. 5 of the later Jurassic, is 387 feet.

At this locality the strata exposed of divisions Nos. 2, 3, and 4, representing the Lower Cretaceous, aggregate 230 feet.

From bed 5 a small collection of fossil plants was obtained.

THE GEOLOGICAL HISTORY OF THE BLACK HILLS.[1]

THE CARBONIFEROUS.

The Black Hills, in common with the whole Rocky Mountain region, were deeply submerged beneath the ocean in the early Carboniferous, the water shoaling near the close of the period. Thick limestones were first deposited, succeeded by alternating beds of brilliantly colored sandstones, with no apparent break in the regular deposition of the sediments until the purple limestone of the Triassic, lying at the base of the Red Beds in the divisions of Newton, is reached.

There are strong evidences that the Carboniferous strata extended in an unbroken sheet over the entire area of the Black Hills uplift. Cliffs of Carboniferous limestone completely encircle and inclose the

[1] The Archean, Cambrian, and Silurian are set forth in Newton's report and briefly in my late "Report on the geology and ore formation of the Black Hills in the Union Hill mine investigation" in the Black Hills Mining Review for March 21, 1898, pp. 6-17.

central metamorphic area, and attain an elevation far above the surface of the slates and schists. The great limestone divide in the northern central hills, though its surface has lost several hundred feet of Carboniferous strata by erosion, has an elevation equal to that of Harneys Peak, the highest point of granite in the Archean area. The conclusion is inevitable that these Carboniferous beds were at one time continuous over the central part of the hills and have been removed by erosion. The beds deposited later, provisionally included in the Carboniferous, are sandstones and marls, more or less colored by peroxide of iron, in every shade of color—yellowish-white, orange, light to dark red.

THE TRIASSIC.

It is as yet undetermined whether any portion of the Black Hills was dry land during the Triassic. The writer found near the head branches of Sundance Creek, in the Bear Lodge Range, evidences of faulting and unconformity between the Purple limestone and the later sedimentary formations, the Lower Cretaceous abutting on upturned Purple limestone.

The characters of the marls, Purple limestone, gypsum, and other sediments of the Red Beds indicate a deposition, mainly from the action of chemical forces, taking place in a shallow sea, probably cut off from direct communication with the ocean and subjected to recurrent periods of desiccation, all the beds apparently barren of life. The marls are colored by peroxide of iron, evidence of the absence of organic matter in the beds. Some evidences of unconformity, much obscured by the soft nature of the beds, were seen in the exposures where marine Jurassic rests on the Red Beds.

THE MARINE JURASSIC.

The Jurassic opened with a shallow mediterranean sea teeming with life. The small size of the mollusks and other forms preserved in the beds of the marine Jurassic is thought to be evidence that the water was brackish. The reddish and purple shades of color in some of the beds of fine sediment indicate that the material of which they were composed may have been derived from the erosion of the Red Beds in adjacent more elevated sections of the Hills. Fossil wood has not been found to this date in the marine Jurassic, though it is abundant in the clays of the later Jurassic, so that positive evidence is wanting of the occurrence of areas of dry land in this epoch. The increase in thickness of the Red Beds and marine Jurassic in the valley of Red Water, separating the Bear Lodge from the main range of the Beach Hills, is an indication of the proximity of land furnishing the material from which the sediments were derived. The Bear Lodge and the Black Hills are distinct upheavals, and may have been in places above water at a much earlier period than has been heretofore thought probable.

THE LATER JURASSIC.

An interval of time occurred between the elevation of the region which raised above water the marine Jurassic beds in the marginal belt of the Black Hills and the deposition of the later Jurassic (No. 5). The elevation was locally irregular; the Jurassic and underlying Red Beds were bent upward into ridges and gentle folds, still traceable in the topography of the region, and the whole surface was later subjected to erosion which wore the soft strata into hills and valleys. In the depressions in this eroded surface the soft clays and marls of the later Jurassic were laid down.

Along the crests of the Jurassic ridges in the Hay Creek coal field the later Jurassic is absent. All the evidence derived from the occurrence of the beds of division No. 5 tends to show that these low elevations were dry land in that subepoch. The old eroded Jurassic surface is in places well exposed to investigation in the Hay Creek field, notwithstanding the great relative modifications in the elevation and topography of the Black Hills due to the continental elevation of the whole Rocky Mountain region at the close of the Cretaceous and to the great volcanic disturbances which occurred in the northern part of the Hills and the Bear Lodge Range during the Tertiary.[1] The sediments of the later Jurassic were evidently formed from the denudation of the marine Jurassic beds in the vicinity. Fossil wood is quite abundant in the clays and sands of the later Jurassic (No. 5). Saurian bones, more or less waterworn and decomposed, occur locally in the upper beds.

THE LOWER CRETACEOUS.

An elevation of the region occurred at the close of the Jurassic or at the opening of the Cretaceous, shutting off the area surrounding the Black Hills from communication with the ocean. It is not improbable that this elevation of the land was continental in its extent and involved the great basin lying between the Rocky Mountains and the western shore of the Allegheny continent, stretching from the Pan Handle of Texas across Indian Territory, Kansas, Nebraska, and Iowa. Some erosion of the Jurassic surface occurred before the coal formation, division No. 4 of the Lower Cretaceous, was laid down in local swamps, basins, and irregular channels lying between the low hills and ridges of the post-Jurassic topography.

This unconformity of the Cretaceous and Jurassic is strongly marked in many places in the marginal belt and was first noted by Dr. Franklin R. Carpenter.[2]

During Lower Cretaceous time many oscillations of level occurred; the relations of dry land, swamps, and open bodies of shallow fresh

[1] Vide published report on the Geology and Ore Formation of the Black Hills, referred to above, p. 587.

[2] Preliminary Report of the Dakota School of Mines upon the Geology, Mineral Resources, and Mills of the Black Hills of Dakota, Rapid City, 1888, p. 46.

water appear never to have been constant. Only in the deposition of the coal in division No. 4 is there evidence of a period of comparative quiet sufficiently long to admit of the formation of workable beds of coal in the Hay Creek field. With respect to relative areas, the beds of division No. 4 cover or underlie the smallest area. Division No. 5 covers nearly all the marine Jurassic on which it rests. The massive sandstones of divisions Nos. 3, 2, and 1 appear to have extended over the whole Hay Creek region and to have reached nearly, if not entirely, over the Bear Lodge Range. In places on Hay Creek evidences were observed of unconformity between division No. 2 and division No. 3, a break in the uniform deposition of the beds corresponding to the marked change in the flora. Less plainly marked, owing to the soft nature of the beds, is the unconformity between the clays of No. 2 and the Dakota sandstone No. 1.

UNCONFORMITIES BETWEEN THE SEVERAL DIVISIONS OF THE DAKOTA GROUP OF NEWTON.

Between all the divisions some change of level occurred, some elevation or depression of the land, some advance or retreat of the water, with more or less denudation of the surface, before the later beds were laid down. Yet no profound disturbance of the strata or upturning of the sedimentary beds occurred. The oscillations of level were quiet and the successive deposits of clays, sands, and intercalated coals appear to be nearly conformable in position. Only by examination of extended exposures of the strata are the evidences of unconformity seen.

The unconformity between the marine Jurassic and division No. 5, or the later Jurassic, is well defined. The greatest unconformity exists between the Jurassic and the Lower Cretaceous. In all the exposures examined in the Hay Creek region division No. 4 always rests on No. 5 or the later Jurassic, but in many places the beds of division No. 4 are absent and division No. 3 rests directly upon No. 5. Along the crests of the ridges of the Post-Jurassic topography the eroded surface of the marine Jurassic is overlain directly by the shales and massive sandstone of division No. 3. No positive evidence was seen of unconformity between divisions No. 4 and No. 3 in exposures where the contact could be examined.

It should be noted that No. 4 was deposited in local basins of limited extent, covering only a relatively small part of the Hay Creek region, while No. 3 stretches broadly across the field, overlying the post-Jurassic ridges and reaching far up into the Bear Lodge Range; that No. 4 was a coal-forming epoch of comparative quiet, but that in the deposition of No. 3 there was evidently a slow sinking of the land or rising of the great body of fresh water filling the Missouri basin, the subepoch opening with quiet waters and the deposition of clays and thin coals and closing with the formation of the massive cliff-forming sandstone (sandstone No. 3), which covers a larger area than the lowest beds of the same division.

The following sketch of the ideal section across the Hay Creek coal field shows this reaching out of No. 3 beds onto the land, the waters rising, and each successive bed advancing farther and farther on to the post-Jurassic surface until all the local elevations were buried under sandstone No. 3.

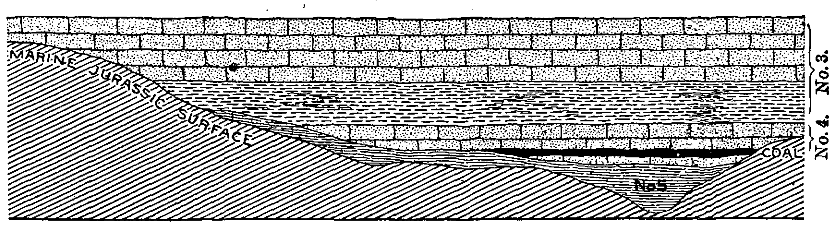


FIG. 121.—Sketch showing the extension of the No. 3 beds onto the land, the land sinking, the waters rising, and each successive bed advancing on the denuded Jura surface until all elevations were buried under sandstone No. 3; a coal-forming period in the early No. 3, a sandstone-depositing in the latter part.

While no marked break was discovered in the uniformity of the deposition of the beds between No. 4 and No. 3, the plant horizon in division No. 3, situated in the shales immediately beneath the No. 3 sandstone, can be distinguished in collecting from the plant-bearing beds of clay overlying the coal at the base of No. 4 by the greater abundance in the Hay Creek region of certain forms of plant life. In No. 3 the leaves of Cycadaceæ (Zamia-like forms), commonly in a fragmentary condition, are abundant, while in No. 4 there are more ferns, usually with delicately cut fronds, together with remains of conifers.

Unfortunately, good exposures of the plant beds in division No. 4 are rare on Hay Creek, and the collections made are very meager. Still, the plant remains found impressed the writer with the thought that there was possibly a somewhat warmer climate in the region during the deposition of No. 3 than had prevailed in the coal-forming epoch of No. 4.

Between division No. 3 and division No. 2 were found irregular beds of conglomerate composed of water-worn pebbles embedded in clay, and other evidences that some erosion of the No. 3 sandstone had taken place prior to the formation of sandstone No. 2, this unconformity marking the break in plant life.

The upper beds of division No. 2 are mostly soft clays, clay shales, and sandy shales, so that evidence of unconformity between No. 2 and the Dakota sandstone No. 1 is very difficult to obtain. Further, the contact at the base of the cliffs of the Dakota sandstone is rarely exposed for observation. There are some evidences of a denudation of the No. 2 beds before the deposition of the Dakota sandstone, and the great break in plant life makes this more probable. The Dakota sandstone covers an immense area in the Missouri basin, and from the nature of its formation should naturally be expected to be unconformable to the Lower Cretaceous, on which it here rests.

The unconformity of the Dakota sandstone and Fort Benton seems to be the result of erosion of the upper beds of No. 1 by the advancing sea depositing the Fort Benton clays, the profound sinking of the region admitting the ocean into the Missouri basin.

DYNAMIC GEOLOGY.

The relation of the coal-bearing areas to the Black Hills uplift and to local subordinate uplifts and their dependence on these will now be considered.

All the coal beds so far discovered occur in the outer border of the Black Hills, in such proximity to influences of the uplift that it is somewhat less probable that workable coal of division No. 4 will be found beneath the later formations far out from the Hills by drilling or shafting. The condition prerequisite for the formation of coal—the elevation of the land above water—seems to have obtained only in close proximity to the uplift.

In the deposition of the beds of division No. 3 the conditions were very different; there were widespread marshes forming coals, mostly of too limited duration to admit of workable beds being deposited; oscillations of level and frequent changes of conditions, both of life and of the deposition of sediments, being the rule. Thin coals have been found in No. 3 beds, in the Belle Fourche well, and in other drill holes put down through the later formations; also in this division in the areas of the Dakota group resting on the high ridges of the Jura surface in the Hay Creek region.

All coals occur in broad expansions of the belt covered by the Dakota group, which completely encircles the Black Hills uplift, and also in places where there are extensive areas of Lower Cretaceous beds nearly horizontal in dip. Where the dip (which is radial from the centers of uplift) is steep, the belt is narrow and no coal is found. For this reason the narrow outcrops of the Dakota group from Bear Buttes to Buffalo Gap, along the eastern border of the Hills, do not carry more than thin coals. This is another instance of the influence of the uplift.

All have been formed in local basins, channels, and depressions, and in some cases in the bottom of lakes, eroded in the Jura surface, so that the governing factor of the localization of the coals of division No. 4 is the post-Jurassic topography. In this localization the depressions in the Jura surface have been influenced by local uplifts and elevations of the land as well as by the folding of the Triassic and Jurassic beds, and also by certain faults, which in occurrence antedated the Cretaceous.

Incident to this deposition of the strata of division No. 4 in local basins, it is noticed that where the Dakota group is thick, particularly with the beds of divisions Nos. 3 and 4, the coal is thick; and where the formation is thin the coal beds are thin or absent. It has also been observed that the sandstone capping the coal (the No. 4 or ocher sandstone) is thick when the underlying coal is thick, and when thin seldom covers workable coal. The thickness of the Dakota sandstone increases in the Bear Lodge Range, and in no way appears to be an indication of the thickness of the coals lying at the base of the Dakota group. Eliminating the Dakota sandstone and division No. 5, the relative thickness of the coals seems to be indicated by the thickness of divisions Nos. 4, 3, and 2; that is, by the development of the Lower Cretaceous—a result of coal sedimentation. The thickness of the Lower Cretaceous increases from the margin to the center of a basin or coal field. Not only do the individual beds increase in thickness, but new beds are intercalated in the series. The coal is thick near the center of the basin and thin at the sides; also, impure or shaly coals become locally purer in quality toward the deeper depressions in the basin. The Lower Cretaceous divisions (Nos. 4, 3, and 2) may thus in the aggregate thickness vary between a minimum of 100 feet and a maximum of 300 feet.

The rules for prospecting for coal may be laid down as follows: That the workable coals all occur in local basins in the broad areas of the Dakota group; that when the Lower Cretaceous beds are thick, coal may be sought for, but when thin the coal is thin or wanting; that coal is wanting over high ridges in the Jurassic and occurs only in depressions in the post-Jurassic surface.

PROPOSED NAMES FOR THE DIVISIONS.

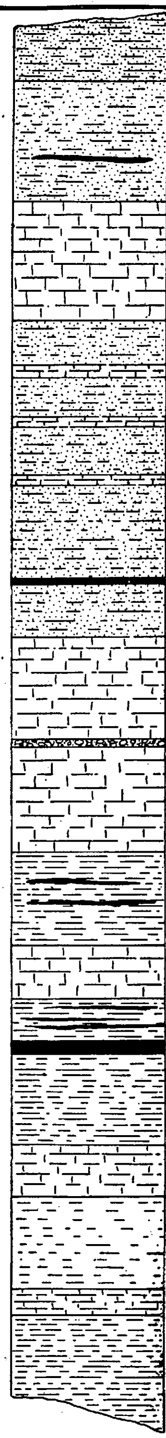
No. 1. The Dakota sandstone.
No. 2. The Oak Creek beds.
No. 3. The Barrett shales.
No. 4. The Hay Creek coal formation.
No. 5. The Beulah clays.[1]

V. CRETACEOUS FLORA OF THE BLACK HILLS.

In discussing the flora of the Black Hills Cretaceous it has seemed best in this paper to divide the subject and treat it under four separate heads. The advantages of a strictly systematic treatment are not ignored, but in the present case such a treatment would in large measure obscure certain prominent considerations which seem to outweigh those of system.

The great predominance of the fossil cycads in the Black Hills renders it desirable that they be brought into somewhat clearer relief than would be secured by simply allowing them to occupy their natural position in the general botanical arrangement, and I have thought best to emphasize this fact by not only assigning to them a separate chapter, but also by making this the first chapter in the part devoted to the flora.

[1] Long outcrops of division No. 5 occur 3 or 4 miles north of the town of Beulah, in Red Water Valley, adjacent to the Hay Creek coal field.



System	Series	Division	Thickness	Description
Cretaceous	Upper	Fort Benton	250 to 300 feet.	Gray and drab-colored clay shales, with some thin-bedded calcareous sandstones, all of marine origin, much eroded in the Hay Creek region.
				Unconformity
		Division No. 1.—Dakota sandstone.	35 to 45 feet.	Soft, thin-bedded yellow sandstones, with sandy shales, commonly ferruginous. Local beds of carbonaceous shales and thin, impure coal with plant remains occur. The strata heavily eroded.
			30 to 45 feet.	Massive sandstone, varying in hardness and color with the amount of iron oxide contained in the beds. Colors yellow to ocher-brown, weathering on surface iron-brown. In some localities a white sandstone. Forms a prominent cliff in the topography of the region. The No. 1 sandstone.
				Unconformity
	Lower	Division No. 2.	60 to 120 feet.	Soft sandstones, clay shales, and clays; light-gray, yellow, and shades of purplish red, with two or three layers of thin ferruginous sandstone. A persistent carbonaceous shale with plant remains occurs 90 to 100 feet below the base of the Dakota sandstone, Division No. 1, as indicated in the column. Carbonaceous shale with plants, 3 feet.
			35 to 40 feet.	Massive yellow sandstone, often cross bedded. The outcrop of this sandstone commonly combines with the massive sandstone forming the top of Division No. 3, making a prominent cliff along the slopes of the valleys. The No. 2 sandstone.
				Conglomerate, 2–3 feet.—Unconformity
		Division No. 3.	35 to 40 feet.	Massive sandstone, light-gray to ocher-yellow in color, showing on weathering a thin-bedded structure. The No. 3 sandstone.
			5 to 10 feet.	Gray clay shales with plants.
			5 to 25 feet.	Clay shales with local thin beds of impure coal. Fragments of fossil wood are abundant in the clays. Locally this bed is absent in the section.
		Division No. 4.	10 to 20 feet.	Massive sandstone, ocher-yellow, weathering yellowish brown on the surface. The No. 4 sandstone. Gray and drab-colored clay shales, with local thin coals. Plant remains.
			2 to 6 feet.	Coal. Mined at the mines of Larrabee and Young and at Barrett.
			20 to 35 feet.	Gray clay shales and sandy shales with plant remains.
			5 to 20 feet.	Soft gray or yellow sandstones with carbonized plant remains.
				Unconformity
Jurassic	Upper	Division No. 5.	25 to 35 feet.	Whitish and light-gray clays with some sandy shales and concretions of white, calcareous clay. The upper layers carry in many localities fossil wood and the bones of saurians. Atlantosaurus beds.
			5 to 10 feet.	Light-gray thin-bedded sandstone.
				Unconformity
	Lower (marine).		200 to 300 feet.	Marls, clays, sandy shales, and soft sandstones, the beds colored yellow, gray, olive, reddish, and dull purple shades. Fossil Ostrea, Gryphæa, etc., abundant.

FIG. 122.—General section of the strata occurring in the Hay Creek coal field, Crook County, Wyoming.

General section of the strata occurring in the Black Hills.

Position in the Black Hills.	Geologic age.	Formation.	Subdivision.	Minor divisions.	Thickness in feet.	Origin and mode of occurrence.	Water-bearing character.	Character of the strata.
Margin of the plains.	Mesozoic.	Cretaceous.	Upper.	Fort Benton.	600 to 800.	Marine formation covering a vast area surrounding the Black Hills.	A few small springs are found in this formation.	Thick beds of clays and soft-clay shales, gray, drab, and black in color, with some thin sandstones. Certain of the beds are superior brick clays.
Foothills.				Dakota.	75 to 100.	The true Dakota sandstone. Fresh-water deposition. Occurs in the outer rampart of hills along the Red Valley.	These sandstone beds form the principal water-bearing strata of the Black Hills.	Massive sandstone, with some beds of clay in the upper part. The whole formation is more or less ferruginous and the colors of the rocks vary widely, from white and yellow to iron-brown in localities but a limited distance apart. Quarried for building stone.
			Lower.	Coal, plant, and cycad beds.	250 to 350.	Formerly included in the Dakota sandstone. A fresh-water deposit.		Clays and massive sandstones, with local beds of coal near the base. The coal fields of Cambria (Newcastle) and Hay Creek are at this horizon.
		Jurassic.	Upper.	Fresh or brackish water.	35 to 50.	A brackish-water deposit occurring on the outer margin of the Red Valley.	Some small springs flow from these beds, commonly with more or less brackish water.	Soft clays, marls, and sandstones of white, olive, and reddish shades. They include local deposits of fire clay.
			Lower.	Marine.	200 to 300.	A marine formation occurring with the overlying beds.		Soft thin-bedded sandstones and shales with clays and some thin shell limestones. The beds are colored yellow, gray, olive, reddish, and purplish shades.
Marginal zone.		Triassic.	Upper.	Red beds.	300 to 350.	By erosion forms the "Red Valley" encircling the Black Hills.	A few small springs of water charged with gypsum.	Soft, disintegrating sands, marls, and clays of a brilliant Indian red from the contained iron, with local irregular deposits of gypsum mined for plaster.
			Middle.	Purple limestone.	25 to 35.	Purple limestone. Marine. Forms the inner boundary of the "Red Valley."	The source of many large springs. Water usually of good quality.	Hard, thin-bedded limestone, dark colored and bituminous, affording when burnt a remarkably pure white lime.
			Lower.	Variegated sandstone.	150 to 200.	Variegated sandstones. Marine. Bound the "Red Valley."	Not known to give rise to springs.	Soft sandstones and marls, colored all shades, from yellow, orange, and pink to light and dark red.
Central plateau and inner border region.	Paleozoic.	Carboniferous.	Upper.		350 to 500	Marine. Occurs in the inner foothills and central divide.	Seldom gives rise to springs save in the central divide of the Black Hills.	Alternating sandstones and limestones in massive strata, with some beds of shales. Prevailing colors gray and white.
			Lower.		300 to 400	Marine. Forms the great central plateau and borders the uplift.	Many streams flowing across this limestone sink in these beds. Springs occur in the central plateau.	Massive limestone, gray and white in color, often cavernous. Certain beds furnish a superior white lime.
		Silurian.	Trenton.		35 to 50	Marine. Occurs with next above.	This formation is not known to give rise to springs.	Drab and reddish colored shales. These shales have nowhere been found to carry fossils, and are provisionally included in the Trenton.
					40 to 50	Marine.		Yellow limestone in thick beds. Quarried for building purposes.
		Cambrian.			350 to 500	Marine. Borders the central metamorphic area.	Strata almost impervious to water where not fractured.	Sandstones, calcareous shales, and clay shales, mostly thin-bedded, gray, drab, and reddish-brown in color.
Outer rim of central area.			Potsdam.		25 to 35	Marine. Occurs outcropping in the zone bordering upon the metamorphic area.	A water-bearing stratum, owing to the wide joints and fissures in the beds.	Hard quartzite in thick beds, gray, brown, and iron stained, with a coarse conglomerate locally at the base in contact with the shales, on the upturned edges of which the quartzite rests unconformably.
Central nucleal area.	Algonkian.				Many thousand feet.	Metamorphic.	Carries but little water relatively.	Chloritic, talcose, and hydromica slates, hornblendic and mica schists, siliceous slates, and hard metamorphic quartzites with quartz veins.

NOTE.—On the Black Hills uplift igneous and volcanic rocks have been, in post-Cretaceous time, intruded through the Archean metamorphic slates and all the overlying sedimentary strata from the Cambrian to the Upper Cretaceous. These igneous rocks are in great variety, including porphyry, trachyte, rhyolite, and phonolite. The rhyolites and trachytes form prominent igneous peaks—Terry, Custer, Crow, and Bear Butte—in this section of the Hills.

The fossil forests, though less important, partly because so imperfectly worked up, nevertheless possess a special historical value, as has been shown, and the one species systematically described will be placed under a special head.

The remaining material, consisting of impressions of leaves, fronds, fruits, and other organs, naturally fall under two separate heads on account of their different geological positions, those from the lower beds belonging to the Lower Cretaceous, while those from the upper ones belong to the true Dakota group. With regard to the former of these classes, in view of the small number found in the Minnekahta region, most of which also occur in the Hay Creek region, it has not been thought best to treat them separately.

Four subdivisions will therefore be made of the general subject, as follows:

1. Fossil cycadean trunks.
2. Fossil forests.
3. Other Lower Cretaceous plants.
4. Plants from the Dakota group.

1. FOSSIL CYCADEAN TRUNKS.

In the historical and geological portions of this paper it has been necessary to discuss the occurrence of cycadean trunks in the Black Hills at considerable length, and it only remains to speak somewhat more specially of the particular localities from which the important specimens were taken. The six specimens originally purchased of Mr. F. H. Cole were all reported to have been found on the spot to which Messrs. Cole and Payne guided my party in 1893, viz, on the southwest side or slope of the middle ridge of Bradleys Flat. These embrace Nos. 1–6 of the collection of the United States National Museum, and constitute the types of *Cycadeoidea dacotensis* (McBride) Ward emend., *C. Colei* n. sp., *C. pulcherrima* n. sp., *C. Paynei* n. sp., and *C. colossalis* n. sp. No. 7, which is the type of *C. minnekahtensis* n. sp., was found by me on the same spot, as were also Nos. 8–19, mostly fragments, and representing *C. McBridei* n. sp. (Nos. 8, 9, 10, 13, 14, and 16), *C. occidentalis* n. sp. (Nos. 11, 12, 17, and 18), *C. Marshiana* n. sp. (No. 15), and possibly *C. minnekahtensis* (No. 19). The small specimen obtained from Mr. Homer Moore in 1895 was thought by him to be from this locality, but as it belongs to *C. Jenneyana*, most of the specimens of which have been found in the Blackhawk region, I regard this as doubtful. The two specimens belonging to the Woman's College of Baltimore (Nos. 1501 and 2128 of the museum of that college), purchased by Mr. Arthur Bibbins at the World's Columbian Exposition at Chicago in 1893, who was informed by the person who sold them to him that they were from the Black Hills and had been cut and polished in Germany, belong also to *C. Jenneyana*, and are probably from the Blackhawk region. The two specimens obtained by Professor Jenney from Mr. McBride were doubtless correctly represented as from the last-named region, and also belong to *C. Jenneyana.* Two other specimens which Professor Jenney obtained for me from Mr. Stillwell are from the same source. One of them represents *C. Jenneyana*, and the other is the type of *C. Stillwelli* n. sp., a species which also occurs in the Minnekahta region. The precise locality from which the two original type specimens of the first of these species were obtained has already been quite fully described (supra, p. 562), and that of the only specimen known of *C. excelsa* n. sp. will be stated as accurately as the data permit under the description of that species (infra, p. 638).

The much larger number of specimens (126) represented in the great Yale collection scarcely extends the range above indicated. With the exception of No. 1 of that collection, representing *C. dacotensis*, and found 2 miles west of Sturgis, as already explained (supra, p. 548), these specimens all came from the Minnekahta and Blackhawk regions. The careful survey, however, which I made of those two fields in October, 1898, having Mr. Wells as my guide, has greatly broadened the earlier conceptions of them, and has not only shown that the area over which the cycads occur in both is quite large, but also that their geological position is everywhere practically the same. It is the geographical and probably only to a limited extent the geological position that gives specific variety to the cycadean flora of the Black Hills. The commoner species, such as *C. dacotensis*, *C. McBridei*, and *C. Stillwelli*, will probably be found at nearly all points where cycads occur, while the rarer ones will be restricted to special regions.

An important extension which these new discoveries has made in the Minnekahta region is the development of the large cycad-bearing area to the southeast of Minnekahta station eastward from Parkers Peak. Mr. Wells pointed out where he had obtained a large number of specimens in this area, but with the exception of the one that was so striking from being completely chalcedonized (No. 5 of the Yale collection), I was unable to identify any of the specimens from his verbal descriptions. This will probably be done in the future, as he can doubtless recognize most of them from the figures in this paper. As all three of the ridges constituting the cycad-bearing area of Bradleys Flat are immediately adjacent to one another, this may be regarded as a unit so far as the geographical distribution is concerned. Mr. Wells was able to show me the exact spot where each of the most striking of the large specimens occurred. Most of them were on the middle ridge, but No. 21 of the Yale collection, the large and fine specimen that constitutes the type of the new species, *C. Wellsii*, was found on the most southwesterly of the three ridges. A number of the other more striking specimens were also found there, including No. 14 of the Yale collection, doubtfully referred to *C. minnekahtensis*.

With regard to the Blackhawk region, it is equally clear that primarily there was one general area such as I have described, and that the specimens have not been laterally transported to any great distances. Those found at lower levels may be regarded as having probably been imbedded in rocks almost vertically over where they occurred. Not only are the slopes to the south and southeast of the amphitheater the result of the gradual undermining and dropping down of the higher sandstone ledges, but the amphitheater itself has its inner walls lined with these rocks, while those on the inner side of its rim dip inward toward its center on all sides, still further emphasizing the manner in which it was excavated. There is therefore no special significance in the particular parts of this general area at which different specimens were found. The two species that specially characterize this region are *C. Jenneyana* and *C. ingens* n. sp., and it may be said that the former of these species predominates at the more southern portions of the area, while the latter occurs chiefly farther north and higher up, near the rim of the basin. It was therefore not until Mr. Wells had explored these latter portions that this species was discovered, but here it was found quite as abundant as *C. Jenneyana* is below.

The general localities for all the cycads of the Yale collection are as follows:

No. 1. Two miles west of Sturgis, 1 specimen.

Nos. 2–87. Minnekahta region (impossible at present to designate their exact location except in the few cases mentioned above), 86 specimens.

Nos. 88–126. Blackhawk region (more precise location of a few specimens given above and others under the description of the species), 39 specimens.

To sum up the subject of the geographical distribution of fossil cycadean trunks in the Black Hills, it may be stated that they have thus far been chiefly found in two areas—the one on the southeast and the other on the east side of the Hills, the latter near the center from north to south. The former of these areas, if we combine, as we properly may, the Bradleys Flat and Parkers Peak localities into one, extends in an east and west direction for at least 5 miles with a width varying from half a mile to 2 miles. The other, as already stated, is from 1 to 2 miles wide east and west, by 3 to 4 miles long north and south.

In addition to these areas, however, cycads have actually been found and collected at four other widely separated points in the Cretaceous rim, one of which I have myself visited. This is 2 miles west of Sturgis, as above stated. Another is the place where the unique specimen representing the new species *C. excelsa* was found, described as fully as the data permit under that species.

A third locality is somewhere between Bellefourche and Spearfish, not yet definitely fixed, but believed to be in the breaks of Hay Creek.

This locality is well vouched for. The specimen was obtained several years ago by Mr. Stillwell from a person residing in that part of the country. Mr. Wells purchased it of Mr. Stillwell and owned it a number of years before disposing of it. He described it minutely to me, and from his description I judge that it represents a new species. He is certain of the above facts as to location and will probably learn further particulars in the future.

The fourth and last of these outlying localities is in the vicinity of Sundance, in Wyoming. Mr. Wells showed me a specimen at his house that he had himself obtained from there, and he intends to make further explorations in that region at an early day. The position of the cycads here is the same as at all other points, viz, in the soft sandstones and shales near the summit of the Cretaceous rim.

Cycads have therefore actually been found on nearly all sides of the Black Hills in the same geological position, and there is no doubt that other localities will be discovered which will close up more and more the intervals separating the areas now known.

All the fossil cycadean trunks that have been found in America thus far probably belong to one genus, the Cycadeoidea of Buckland. In 1894 I published a revision of that genus[1] and in 1897 I described the seven species then known from Maryland.[2] In the latter paper I gave a full description of the genus in the light of modern research. The classification adopted was not that of Engler in Engler and Prantl's Natürlichen Pflanzenfamilien (II. Teil, 2. Abteilung, pp. 24–26), which is modeled after Schimper's treatment in Zittel's Handbuch der Palæontologie (Abth. II, pp. 211–232), and is no longer accepted, having been materially changed by Potonié and Engler in the same work (Nachträge zu II–IV, pp. 14–17; 341, 360). According to this the Bennettitales form a class distinct from the Cycadales, or living cycads, consisting of the exclusively extinct family Bennettitaceæ, coordinate with the family Cycadaceæ, which is restricted to the forms now living. Potonié would refer the greater part of the forms that I have called Cycadeoidea to Carruthers's genus Bennettites, which Count Solms-Laubach restricts to such as have been found to contain seeds in the fruits, i. e., practically to one species, *B. Gibsoni*, and chiefly to one specimen. I have already pointed out[3] that this is simply an accident of preservation and not a good ground for the establishment of a new genus, and therefore I would adhere to Buckland's name, which has priority over all others, and call them all Cycadeoidea. In all other respects I am quite

[1] Fossil cycadean trunks of North America, with a revision of the genus Cycadeoidea Buckland: Proc. Biol. Soc. Washington, Vol. IX, April 9, 1894, pp. 75–88.

[2] Descriptions of the species of Cycadeoidea, or fossil cycadean trunks, thus far discovered in the Iron Ore belt, Potomac formation of Maryland: Proc. Biol. Soc. Washington, Vol. XI, March 13, 1897, pp. 1–17.

[3] Proc. Biol. Soc. Washington, Vol. IX, April 9, 1894, p. 79.

willing to conform to the classification of Engler and Prantl's great work. The arrangement will therefore be as follows:

Subkingdom SPERMATOPHYTA (Phanerogams).

Subdivision GYMNOSPERMAE.

Class BENNETTITALES Engler, 1897.

Famliy BENNETTITACEÆ Potonié, 1897.

Genus CYCADEOIDEA Buckland.

Pls. LVII-LXI.

1827. *Cycadeoidea* Buckland: Proc. Geol. Soc. London, Vol. I, No. 8, pp. 80-81 (session of June 6, 1827).

1828. *Cycadeoidea* Buckland: Trans. Geol. Soc. London, 2d Ser., Vol. II, pp. 375-401, Pls. xlvi-xlix (volume dated 1829, but memoir probably issued separately in 1828).

Trunks chiefly low (30 to 90 cm. in height) and more or less conical or oval in shape, but sometimes tall, reaching over a meter in height, and cylindrical, 15 to 75 cm. in diameter, usually simple, but sometimes branching, with a depression at the summit, in the middle of which, when not decayed, there is a terminal bud of conical shape; terminal bud, however, usually wanting in the fossils, leaving a cavity commonly known as the "crow's nest," by which name, for this reason, the specimens from the Portland quarries are popularly known. The armor consists of appendicular and reproductive organs surrounding and enveloping the axis, the former being the bases of the leaf stalks or petioles, which are surrounded by a dense mat of ramentum or fine hairs.

The leaf stalks are normally four-sided and four-angled, the lateral angles acute and nearly equal, the vertical angles obtuse but unequal, the lower much sharper than the upper, so as to render the cross section subrhombic. This form varies on the one hand to a true rhomb, and on the other hand to a true triangle, the most frequent intermediate type being that in which the upper angle is wanting, and the two upper sides are reduced to a simple curve or arch, so that the cross section assumes the form of a drawn bow and bowstring, the arch formed by the two upper sides representing the bow, and the two lower sides, with the reentrant angle, representing the bowstring. In size the leaf stalks vary from 15 to 35 mm. in width, measured between the lateral angles, and from 5 to 20 mm. in height measured between the vertical angles, or from the lower angle to the summit of the arch formed by the two upper sides. The line joining the former is not generally horizontal or at right angles with the axis of the trunk, but one is usually slightly lower than the other. The line joining the latter is not generally vertical or parallel to the axis of the trunk, but one is usually a little on one side of the other. The only portion of the leaf bases that is always preserved in the fossil state is the mat of ramentaceous hairs that surrounds them. In the great majority of cases the petioles themselves are decayed to a greater or less distance below the summit of these mats, which thus constitute walls surrounding and inclosing the portion that remains of the petioles, if any, and in their absence forming definite cavities having the shape of the cross section of the leaf stalks, which constitute the leaf scars. These leaf scars, with or without the lower portion of the leaf bases, penetrate to the axis of the trunk and form a varying angle with it. Normally this angle is a right angle over all the central portions of the trunk, while below the organs are slightly descending and above more and more ascending to the apex, where they become vertical. At the summit, too, they diminish in size and usually in form, and are reduced in and immediately around the terminal bud to small triangular or polygonal bracts (*perulæ* of Miquel). In some species (*C. Uhleri*) all the organs of the body of the trunk are deflexed, and in some (*C. Goucheriana*, *C. minnekahtensis*) there is a definite zone near the middle of the trunk, below which they are descending and above which they are ascending. The leaf scars are arranged in a more or less exact quincunx order, and usually in two sets of spiral rows around the trunk, in one of which they ascend from the base in the direction from left to right and in the other from right to left, crossing each other at varying angles and both rows making a certain angle with the axis of the trunk, which varies with the species and more or less with different specimens of the same species. One of the two sets of rows is usually more distinct than the other, but the more distinct rows sometimes pass upward from left to right and sometimes from right to left. The bases of the petioles when present and well preserved often show at the surface presented to view a row of pits all around parallel to the walls and at different distances from the margin representing the vascular strands. Other such pits are sometimes present near the center. The petioles are frequently disarticulated at a natural joint, which may fall near or at the summit of the scar or it may fall some distance within the scar. In some species there are two such joints separated by a node. Occasionally these joints consist of a thin membranous diaphragm stretching across the petiole, of firmer texture than the rest of its substance. Even where the petioles are wholly absent the position of the joints or diaphragms can sometimes be determined by a sharp ridge around the inside of the scar. The walls are made up of the ramentum of two adjacent petioles. In some cases these matted masses are so dense as to produce a simple homogeneous plate on all four of the sides, which, where the petioles are wanting, forms a deep, angled cavity of exactly the shape of a cross section of the petiole. Usually the portion of the wall furnished by each of the adjacent petioles can be distinguished by a junction line or commissure, visible along the outer edge of the wall. This commissure sometimes takes the form of an intermediate plate of a less dense consistency than the two outer plates. In other cases this central plate is much thicker than the two outer ones, which latter may be reduced to the appearance of thin linings of the scars. In still other cases the central portion is more or less open and cavitous. The walls vary from 1 mm., or even less, to 5 mm. or, in rare cases, 8 mm. in thickness.

The other class of organs that help to make up the armor are the reproductive organs. These are borne on all parts of the surface of the trunks, except, perhaps, in immediate connection with the terminal bud, which is exclusively an organ of growth. They are scattered about with very little order over the surface among the leaf scars. They are usually of a harder substance than that of the foliar organs, and better adapted to resist the erosive influences to which the fossil trunks are exposed. Where the trunks are worn, therefore, the reproductive axes are liable to protrude somewhat. Viewed from without, they usually present an organ with an elliptical cross section, the longer diameter being nearly horizontal, variable in size, but always larger than the leaf scars. The central portion is often wanting, and a funnel-shaped cavity less deep than the leaf scars takes its place. When the central portions are present they show markings having the form which the outer ends of the essential organs present, which is very variable and usually obscure. Surrounding the central portions are several rows of open scars arranged concentrically. These scars are sometimes triangular, quadrangular, polygonal, or nearly circular; but the most of them, especially the outer ones, are somewhat crescent-shaped, having the concave side toward the center. The inflorescence is a spadix surrounded by an involucre, consisting of the concentrically arranged bracts or scales whose scars were last described. The spadix has a receptacle at base, located near the inner surface of the armor and supplied with fibers from the axis. From the receptacle there rise two kinds of organs: first, peduncles or filaments, known in a few specimens to bear seeds, and conjectured in one specimen to bear anthers at their summits; and, second, elongated chaff-like scales more numerous than the latter and rising above them, the upper portions expanding and forming a dense mat or covering over the essential parts. In most cases all these organs are wholly included in the armor, the only seeds that have thus far been found being deeply embedded in the tissues. The organs of inflorescence are probably axillary, but owing to the proximity of the leaf scars this is not generally apparent. In regions of the surface where they occur they usually crowd the leaf scars and cause variations in their shape. This effect is most marked on the upper sides of the scars, often quite obscuring or obliterating their normal features.

The axis of the trunk inclosed in the armor when complete consists of four parts, which, enumerated from without inward, may be denominated respectively as (1) the libro-cambium, (2) the parenchymatous wood, sometimes called the cortical parenchyma, (3) the wood proper or fibrovascular zone, and (4) the medulla or pith. In many cases the libro-cambium zone can not be definitely distinguished from the cortical parenchyma, and nothing is visible but the large and numerous vascular bundles passing out from the interior into the leaves; but sometimes there occurs a definite line or thin zone of loose tissue immediately below the bases of the leaf stalks. There is usually a zone of apparently homogeneous cellular tissue, often of considerable thickness, filling the interval between the armor and the woody axis. The woody zone consists of one or more rings of exogenous tissue traversed by medullary rays. Where more than one, they are separated by thin interstices of parenchymatous tissue. The medulla is usually large and composed of coarse parenchyma.

The genus Cycadeoidea is illustrated by five plates devoted to characteristic trunks from Europe and America. Pl. LVII represents the two original species of Buckland, *C. megalophylla* and *C. microphylla*, from the Purbeck of the Isle of Portland, and also a third species, *C. portlandica*, from the same beds, described by Carruthers in 1870. All of the specimens here figured were found by Dr. Alfred Russel Wallace and myself on the occasion of our visit to Portland on August 17, 1894, and the specimen represented by fig. 3 is the one collected by us in one of the quarries.[1]

On Pl. LVIII is reproduced the figure of *Cycadeoidea Masseiana* Cap. & Solms., which appeared in the Sixteenth Annual Report of the Survey with a full history of its discovery and significance (cf. Part I, pp. 502–510, pl. ciii). It is a fair representative of the genus from the Italian beds.

On Pl. LIX is given a reproduction from a photograph sent me by Prof. H. B. Geinitz of the great *C. Reichenbachiana* (Göpp.) Cap. & Solms., now in the Dresden Museum. It was found at Lednice, near Wieliczka, in Galicia, a century and a half ago, and treated by Knorr and Walch in their great work of 1755. It was long regarded as the largest fossil cycad in the world (see infra, pp. 604, 605).[2]

Pl. LX represents a group of cycads from the iron ore beds of Maryland, all belonging to the genus Cycadeoidea. Several of these are embraced in the group represented on pl. c of Part I of the Sixteenth Annual Report of the Survey, but at that date they had not been named or described.

This was done in 1897,[3] but no references were then given to published figures. This may therefore be regarded as the first illustration of these species, and the group constitutes an excellent representation of the genus Cycadeoidea. The specimens represented in this group were all collected or obtained by Mr. Arthur Bibbins and belong to the Woman's College of Baltimore.

[1] See Sixteenth Annual Report U. S. Geological Survey, Part I, pp. 484–486.
[2] For synonymy see Proceedings of the Biological Society of Washington, Vol. IX, 1894, p. 85.
[3] Proceedings of the Biological Society, Vol. XI, 1897, pp. 9–17.

Finally, on Pl. LXI is given a group of the leading types of the species from the Black Hills, embracing the six original trunks obtained from Mr. Cole and the large branching trunk, *C. minnekahtensis*, collected in 1893.

CYCADEOIDEA DACOTENSIS (McBride) Ward emend.

Pls. LXII-LXVI.

1893. *Bennettites dacotensis* McBride, in part: American Geologist, Vol. XII, p. 249, pl. xi, fig. 1 (non fig. 2); Bull. Lab. Nat. Hist. State Univ. of Iowa, Vol. II, No. 4, Iowa City, 1893, p. 391, pl. xii, fig. 1 (non fig. 2).

1894. *Cycadeoidea dacotensis* (McBride) Ward, in part: Proc. Biol. Soc. Washington, Vol. IX, p. 86.

Trunks large (30 to 50 cm. high, 30 to 50 cm. in diameter, 100 to 150 cm. in girth), short-cylindrical, contracted below, dome-shaped above, symmetrical, sometimes laterally compressed and elliptical in cross section, probably subsequent to entombment, bearing a number of short secondary axes or undeveloped branches in the form of rounded protuberances, or, in case of decay, of corresponding saucer shaped depressions; apex presenting a flattened surface with a central elevation, studded with polygonal bract scars and bases arranged in rows which sometimes proceed in helicoid form from the center outward; rock substance of a dark brown or reddish color, firmly silicified, hard and heavy, sometimes weighing over 100 kilograms, fine-grained; organs of the armor slightly ascending except near the base, the angle increasing toward the summit, where they become vertical; leaf scars, where not interrupted, forming two series of spiral rows which proceed in different directions and intersect one another, those from right to left nearly horizontal below and curving upward until they form an angle of 45° with the vertical axis, the opposite series less distinct, forming a small angle (5° to 10°) with the axis; scars subrhombic and nearly uniform in shape, larger below, diminishing upward, the distance between the lateral angles varying from 16 to 26 mm., and that between the vertical angles from 10 to 16 mm., empty from decay of the petioles, at least to considerable depth, sometimes to a depth of more than 5 cm.; interspaces between the scars very thick though variable, sometimes 16 mm., presenting an undulate or wrinkled surface with indications of deeper lines of separation of the walls; spadices large and somewhat elliptical in outline, the longer axis nearly horizontal, 8 to 10 cm. long, the shorter nearly vertical and 5 to 7 cm.; involucral bract scars numerous, arranged in concentric ellipses around the central organs in many somewhat distinct rows, increasing in size from the center outward, subrhombic, triangular, or polygonal in shape, 2 to 20 mm. in diameter, apparently passing insensibly into the normal leaf scars, empty like them, forming deep cavities or punctations; essential organs of the buds, flowers, or fruits sometimes wanting, their place occupied by a deep circular cavity, more frequently represented by a dark and firm substance, which in some of the smaller ones projects beyond the general surface; armor 5 to

7 cm. thick, separated from the ligneous axis by a definite line; cortical parenchyma 5 cm. thick; fibrous zone 4 cm. thick with three or more rings of wood, or sometimes presenting a number of thin concentric laminæ of alternating black and brown substance, apparently representing as many rings of wood, and inclosing the homogeneous medulla 5 to 15 cm. in diameter, conforming in cross section to the trunk.

Only one of the specimens belonging to the U. S. National Museum is referable with certainty to this species. This is the fine trunk, No. 1, of the collection of six purchased of Mr. Cole. That this is specifically identical with Professor McBride's specimen represented by fig. 1 of his plate there is no room to doubt. It is, however, difficult to reconcile it with his description in view of the fact that in that description he has included two specimens belonging to entirely different species, his fig. 2 showing none of the external characters of fig. 1, or of the specimen in hand, but clearly belonging to the same specific group as several of the fragments collected by Professor Jenney and myself from the Minnekahta locality in 1893, as will be shown below (pp. 613–614). As Professor McBride in his description includes characters that could scarcely have been exposed in the perfect trunk represented by his fig. 1, it seems clear that he derives such from the specimen fig. 2, which was probably a fragment showing these characters in the fractures. It was therefore a question whether to retain the name or not. I conclude to do so for so much of Professor McBride's description as applies to his fig. 1.

The Museum specimen is somewhat larger than the one at the University of Iowa, standing over 44 cm. high, having a girth of 122 cm., and weighing 90.27 kilograms. It is one of the most perfect and beautiful cycadean trunks that have thus far been brought to light.

Thirteen of the specimens in the Yale collection are referred to this species. These are Nos. 1, 3, 5, 6, 13, 30, 39, 43, 54, 62, 63, 95, and 106. Of these Nos. 3, 5, and 54 are nearly perfect trunks, and one of these, No. 54, is larger than the one at the U. S. National Museum.

In Pls. LXII and LXIII are given side, top, and base views of the original type specimen, No. 1, of the U. S. National Museum; in Pls. LXIV and LXV, side and top views of the equally fine and somewhat larger trunk, No. 54, of the Yale collection, and Pl. LXVI affords a view of the inner parts from one side of the Yale specimen No. 13.

This is the most common species in the Black Hills, and has been found in the Minnekahta and Blackhawk regions, and 2 miles west of Sturgis.

CYCADEOIDEA COLOSSALIS n. sp.[1]

Pls. LXVII-LXXII.

Trunks colossal, subconical, more or less laterally compressed, subcylindrical, dark colored, hard and heavy, weighing from 100 to over

[1]It was not thought necessary to alter the proofs of this memoir by quoting the Proc. U. S. Nat. Mus., Vol. XXI, pp. 197-229, as the original place of publication of the new species of fossil cycadean trunks, because the manuscript was prepared in duplicate and simultaneously submitted for publication in both places. As, however, the paper in the Proc. Nat. Mus. appeared in October, 1898, these species, with the exception of *C. Wielandi*, p. 621, are not new here in the strict sense of earliest publication.

300 kilograms, 38 to 79 cm. high, 40 to 66 cm. in major, 26 to 46 cm. in minor diameter, 100 to 180 cm. in girth, bearing numerous relatively small branches not projecting far beyond the general surface; terminal bud low, set in a circular platform of small polygonal scars filled by the bases of the leaves or bracts; organs of the armor and secondary axes horizontal at the middle portion of the trunk, somewhat descending at the lower portion and ascending at the upper portion; phyllotaxy much obscured by the intrusion of other organs, but spiral rows ascending from left to right at an angle varying from 75° below to 45° above plainly traceable; leaf scars subrhombic to nearly rhombic, very small relatively to size of trunk, 13 to 16 mm. between lateral, and 8 to 12 mm. between vertical angles, empty to a depth of 13 to 50 mm., the bottoms of the cavities apparently occupied by portions of the leaf bases; interstices between the scars very variable, but, except at the summit, generally large, sometimes 25 mm., nearly even on the surface but finally marked with mostly horizontal but variously curved or crooked ridges or wrinkles, with occasional indications of planes of separation into two, three, or even five plates; walls much thinner in the upper portion, often broken down in the specimens, displaying the striate inner surface of the scars diminishing in size below; reproductive organs abundant at all parts of the trunk, large, well developed, and conspicuous, after rising somewhat above the surface, forming gentle swellings or more abrupt protuberances, elliptical in shape, the major axis nearly horizontal, 5 to 10 cm. long, the minor axis 3 to 5 cm., usually with a solid center, sometimes with a small central cavity surrounded by firm substance, the whole inclosed within concentric elliptical rings or rows of involucral bract scars which increase in size from the center outward, are empty and have the form of the leaf scars, into which they occasionally seem to graduate; armor 5 to 10 cm. thick, attached to the woody axis by a uniform layer of bark 6 mm. thick; cortical parenchyma 4 to 6 cm. thick; fibrovascular zone also 4 to 6 cm., separated into two distinct rings of wood, each consisting of a loose, spongy substance inclosed in a firm plate or thin hard layer, the outer ring 35 mm. and the inner 25 mm. in thickness, through all of which the medullary rays pass, forming a sort of columnar structure; medulla more or less elliptical in cross section, 11 to 13 cm. by 15 to 20 cm. in diameter, decayed, leaving a cavity at the base in one specimen, and in another having a concentric structure consisting of four zones or rings of soft porous material, scarcely differing except in coloration.

The large perfect specimen, No. 6 of the Cole collection, is the largest cycadean trunk known in the world. Prior to its discovery the great *C. Reichenbachiana* (Göpp.) Cap. & Solms. (see supra, p. 601 and Pl. LIX) from Galicia, which is at the Mineralog.-Geolog. Museum at Dresden, and which I have not seen, had taken the lead. Professor H. B. Geinitz was so kind as to send me an excellent photograph of that specimen and on this I find the dimensions marked. It is 50 cm. high, 54 cm. in major and 44 cm. in minor diameter, and 157 cm. in girth. It is therefore not so tall as the American specimen by 29 cm., has a major diameter 25 cm. less, and a minor diameter 2 cm. less, showing that it is less flattened, but the circumference is 23 cm. less.[1]

Eight of the specimens in the Yale collection belong to this species, viz, Nos. 2, 7, 9, 10, 17, 37, 40, and 55, of which Nos. 2 and 10 are perfect trunks, but are both much shorter in proportion to their size than the great National Museum type. They are also less laterally compressed. They may have been somewhat vertically compressed. No. 37, though incomplete, is a fine specimen weighing nearly 150 kilograms, and has a height of 71 cm. No. 55, though it has lost considerable at the summit, still weighs 110.68 kilograms. No. 40, which represents less than half of the original trunk, is also a fine fragment. The rest are smaller and more imperfect.

In Pls. LXVII and LXVIII are shown side and base views of the great type trunk No. 6 of the U. S. National Museum. Pls. LXIX–LXXII illustrate the species as represented in the Yale collection by Nos. 2, 10, 17, and 55. They show considerable variation in the form and size of the trunks.

All the specimens of this species are from the Minnekahta region.

CYCADEOIDEA WELLSII n. sp.

Pls. LXXIII–LXXV.

Trunks large, ellipsoidal, subcylindrical, or somewhat barrel-shaped, more or less laterally compressed, rounded at the summit, bearing numerous small secondary axes in the form of protuberances, light reddish-brown or drab colored, fine-grained, hard and rather heavy, sometimes weighing nearly 100 kilograms, 40 to 55 cm. high, 30 to 45 cm. in diameter and more than 1 meter in girth; terminal bud not prominent; organs of the armor about horizontal except near the summit; phyllotaxy much disturbed and not traceable; leaf scars rather small, subrhombic or nearly rhombic, often trapeziform or very irregular in shape, average distance between the lateral angles 20 mm. and between the vertical ones 12 mm., none of the angles rounded, all except the small ones at the apex empty to considerable depth; ramentaceous interspaces exceptionally thick, sometimes 2 cm., presenting a smooth but gently

[1] The photograph sent me by Professor Geinitz was taken from the specimen in position as mounted on a support in the Dresden Museum. Judging from it alone I should say that the trunk is here inverted, but to be certain it would be necessary to examine it. It is clear that in the present position the leaf scars have a decided downward direction, which is rare but not unknown (e. g., *C. Uhleri*). Moreover, the scars, which are subtriangular, have now their sharp angle upward, which, if the specimen is right side up, would indicate that the keel of the petioles was on the upper side, a condition which I have met with in only two other species, *C. aspera* and *C. insolita*, described below. Göppert's figure (Jubiläums-Denkschr. d. Schles. Ges. f. vat. Cult., 1853, pl. viii, fig. 4) shows the specimen in the same position, i. e., probably inverted.

undulating surface, lowest in the middle part, rising to the scar which forms a sharp edge, producing the general effect of being molded in plastic clay; reproductive organs very large, abundant, and conspicuous, greatly distorting the arrangement of the leaf scars as well as their form, often nearly circular in cross section, 4 to 5 cm. in diameter, showing the remains of the central organs surrounded by concentric circles of large, empty, and deep involucral bract scars which are semilunar or somewhat triangular in shape, and may reach 7 mm. in length; armor about 7 cm. thick, cortical parenchyma 4 cm., fibrous zone 4 cm., showing two rings, the inner projecting at the base, concentrically laminated and inclosing the much decayed medulla about 12 cm. in diameter.

There are two specimens of this species in the Yale collection, viz, Nos. 21 and 59, the former of which is a fine, nearly perfect trunk, large and handsome, weighing 92.76 kilograms. I was at first inclined to regard them as belonging to *C. minnekahtensis* on account of the general resemblance of the external surface, but this obviously can not be done, because these trunks are unbranched and symmetrical in form. In this respect they approach *C. dacotensis* and *C. colossalis*, but here the surface differs completely. No forms intermediate in either of these respects occur in either collection, and there is no escape from regarding these two trunks as constituting a new species.

I have named the species for Mr. Henry F. Wells, who obtained these and nearly all the rest of the Yale collection, and from whom Professor Marsh purchased them. He may therefore be regarded as the collector, which, under the approved rules for naming species, requires the use of the genitive form.

Pls. LXXIII and LXXIV give side and base views of No. 21, and Pl. LXXV shows the perfect side of No. 59. Both specimens are from the Minnekahta region.

CYCADEOIDEA MINNEKAHTENSIS n. sp.

Pls. LXXVI to LXXIX.

Trunks gigantic, much branched and irregular in form, the type and only perfect specimen known weighing 219.09 kilograms, 74 cm. high, 50 cm. in diameter exclusive of branches, 79 cm. across at maximum spread of branches, 150 cm. in girth, light brown or chestnut colored, smooth on the outer surface, presenting the appearance of having been molded in plastic clay, moderately heavy; branches very large, forming conical protuberances projecting from the middle portion of the trunk, giving it a winged appearance, other branches proceeding from other parts, especially below, composite, i. e., the main branches or primary axes having lesser or secondary branches, prominent terminal buds, sometimes themselves compound, on all the branches, often very perfect with a sort of neck; organs of the armor declined over most of the surface, phyllotaxy obscure and not traceable; leaf scars subrhombic to nearly rhombic, averaging 22 mm. wide by 10 mm. high, the unusual vertical narrowness perhaps due to compression, very variable, however, in all respects, those on the lesser branches smaller, usually empty and striate within; ramentaceous interstices usually thick, 5 to 15 mm., firm and fine-grained, smooth and polished but somewhat undulating, the edges of the scars sharp, always without signs of subdivision; reproductive organs numerous, simulating the small branches, the central part preserved but heterogeneous, showing scars and markings of the essential organs, varying from 12 to 50 mm. in diameter, surrounded by small involucral bract scars; armor about 6 cm. thick, separated from the underlying tissues by a thin porous layer; cortical parenchyma about 5 cm. thick, fibro-vascular zone 8 cm. thick without visible subdivision into rings; medulla not clearly shown, and internal structure generally more or less conjectural.

The remarkably fine but weird and anomalous specimen upon which the above description is almost wholly based was found by our party lying partly buried in the ground in the same place where the other trunks had been gathered. It was overgrown with lichens in many places, and had been regarded so uncouth as not to be worth transporting to Hot Springs. I arranged with Messrs. Payne and Cole to have it shipped to Washington, and it arrived in due time in safety. It holds the fourth rank as to size and weight, but differs from all others in so many respects that a comparison with any is difficult. Specifically it approaches most closely to *C. pulcherrima*, but lacks all the symmetry and definiteness of that form. It is only in the fact that both are very branching, especially around the middle part of the trunk, that they have an external resemblance.

The specimen shows a fine terminal bud at the apex of the principal trunk, and several others on the other branches. Except near the summits of the several branches, the leaf scars and other organs of the armor are decidedly descending, but on the main branch or trunk, some distance above all the lateral branches, there is a sharp line separating the descending from the ascending scars above. This feature I have seen elsewhere only in *C. Goucheriana* from Maryland.

The only other specimen in the collection that could with any propriety be included under this specific head is the small trunk picked up at the same time and place and numbered 19. This may represent a very young state of this species with all the characters in miniature and devoid of reproductive organs. It is branched much in the same way, longitudinally compressed, lacks a little of the base and part of one side below, but for purposes of description is practically complete. The entire trunk was only 18 or 20 cm. high, 14 or 15 cm. in its longer and 7 or 8 cm. in its shorter diameter, with a maximum girth of 36 cm. Its present weight is 1.81 kilograms. The dimensions are therefore less than one-fourth and the weight is less than one-twelfth of the large trunk. It might even have been wholly subterranean, as in the living *Zamia angustifolia*.

Among the fragments in the Yale collection I found eight that belong to this species, and, as the National Museum type is nearly perfect, these add somewhat to our knowledge of the inner parts of the trunk. These specimens are numbered 14, 22, 24, 32, 41, 71–72, 83, and 86. They consist chiefly of branches torn away from large trunks, and several of them may have belonged to the same trunk. Some of them may be found to fit together, but, as they were lying about in different rooms, and even on different floors, of the Peabody Museum, it was impossible for me to correlate them. Certain ones, as No. 14, consist of a mere gnarl of branches, and most of them are proliferous or composite, the branches often having fine, sometimes compound, terminal buds.

Pl. LXXVI shows the only view that has been taken of the type specimen, No. 7, of the U. S. National Museum, and Pls. LXXVII to LXXIX represent Nos. 14, 24, 83, and 86 of the Yale collection, all of which are more or less fragmentary and aberrant.

It occurs only in the Minnekahta region.

CYCADEOIDEA PULCHERRIMA n. sp.

Pls. LXXX–LXXXII.

Trunks large (38 cm. high, 4 cm. in diameter, 130 cm. in girth in the only complete specimen known), short ellipsoidal or subspherical, of a light ash color and moderately heavy, bearing numerous large, short branches at and below the center all round, forming conical protuberances, some of which are 8 to 10 cm. long and 12 to 18 cm. in diameter at the base, rarely compound, i. e., the branches themselves bearing other smaller ones, or two or more arising side by side; branches and all other organs radiate, i. e., proceeding in the direction from the center of the trunk, those of the equatorial zone horizontal, or making a right angle with the axis, those below descending, and those above ascending; leaf scars arranged in definite rows intersecting one another, somewhat spiral, but so placed as to simulate meridians and parellels of latitude, the former series, however, rising from left to right and making an angle which varies with the curvature from 5° to 10° with the vertical axis, the other series rising from right to left, varying from horizontal to an angle of 45°; scars varying in shape from subrhombic to nearly true rhombs and in size from 10 by 19 cm. or smaller near the summit to 16 by 22 cm. measured between vertical and lateral angles, which are usually quite sharp, the sides straight and the whole very definite and symmetrical, usually empty to considerable depth, but partially filled by the remains of the leaf bases, which occasionally show punctations representing the vascular bundles; ramentum walls 2 to 5 mm. thick, wrinkled on their outer edges, often with a distinct median groove, sometimes reduced to thin lamallæ with sharp edges, striate within the scars in the direction of the petioles; reproductive organs not abundant, the more typical ones mostly in the equatorial zone among the branches, which they sometimes resemble, being large with a solid central axis surrounded by relatively large bract scars, nearly circular, with a diameter of 5 cm., other smaller ones scattered among the leaf scars, only slightly disturbing their arrangement, often abortive and reduced to collections of pits in the angles of the walls; armor 6 to 8 cm. thick, irregularly attached to the ligneous axis, which consists of a parenchymatous zone 3 cm. thick inclosing a fibrous zone 25 to 35 mm. thick and divided into two to four exogenous rings; medulla 10 cm. in diameter at the base, enlarging upward to more than twice that size, porous in structure, its outer surface marked with longitudinal ridges which are interrupted and alternating, forming the bases of the medullary rays.

The trunk upon which the above description is almost exclusively based is the one which was called No. 3 of the collection obtained from Mr. Cole, and is certainly, in my judgment, artistically the most beautiful cycadean trunk known. I say this deliberately, after having seen the greater part of all thus far discovered in all countries, and where I have not actually seen the specimens themselves I have in almost all cases seen artistic models, or at least excellent photographs or drawings. The specific name is therefore fully justified.

The characters of the internal structure and the medulla are derived from the large decayed area at the base on one side, which well exposes them, leaving the other side still perfect. The total weight of this specimen is 85.73 kilograms.

Only one imperfect specimen, viz, No. 78, of the Yale collection could be referred to this species, and this not without some doubt.

Pls. LXXX and LXXXI represent side, top, and interior views of the type specimen, No. 3, of the U. S. National Museum. In the last (Pl. LXXXI) the specimen was purposely inverted in order to let the light penetrate more thoroughly the exposed interior and bring out the structure. Pl. LXXXII is a fair view of No. 78 of the Yale collection, which was doubtfully referred to this species on account of the shape of the leaf scars on certain parts of the trunk, which, however, are not well brought out in the photograph.

Known only from the Minnekahta region.

CYCADEOIDEA CICATRICULA n. sp.

Pls. LXXXIII, LXXXIV.

Trunks small and short, subconical, more or less laterally compressed, smooth and symmetrical, unbranched, light yellowish-brown on the weathered surfaces, fine-grained and flinty within, about 20 cm. high, 18 by 22 cm. in diameter, with a girth of about 60 cm., and weighing 13 or 14 kilograms; organs of the armor nearly horizontal; leaf scars arranged in two definite series of spiral rows, those from left to right forming an angle near the base of about 70° with the axis but curving inward in their upward course so that the angle progressively diminishes to about 30° at the summit, those from right to left only slightly curving and making an angle of about 45°; scars very small, almost exactly rhombic, uniform and definite with all the angles sharp, distance between lateral angles 9 to 12 mm. and between vertical ones 6 to 8 mm.; leaf bases present filling the scars to near the top, presenting a roughened spongy tissue; ramentaceous walls very thin, varying from the thickness of tin foil to 2 mm., presenting a beautiful and regular network of whitened lines over the entire outer surface of the trunk, with a faint commissure or elongated openings between the contiguous plates of the thicker ones; reproductive organs not abundant nor well developed, the most typical 3 cm. in diameter, variable in shape and character, consisting of protuberances with a depression at the top or ridges with bract scars on the sides, others anomalous, consisting of small projections or elevations, probably abortive, none of them greatly disturbing the form or arrangement of the leaf scars; armor 3 cm. thick, separated from the wood by a definite line or crack; cortical parenchyma 2 cm.; secondary wood 3 cm., consisting of an outer ring 2 cm. thick and an inner one 1 cm., with a fissure between; medulla elliptical, 5 by 7 cm. in diameter, consisting of a homogeneous substance resembling fine yellow sandstone, clearly marked off from the inner ring of wood.

This species is one of the best defined of all, notwithstanding that it is based upon a single specimen, viz, No. 118 of the Yale collection. This is an almost perfect trunk, and is only obscured by sand and gravel cemented in the scars, so that very little can be seen of the summits of the leaf bases. It was collected by Mr. H. F. Wells three-fourths of a mile north of Black's ranch, about 3 miles north of Blackhawk, South Dakota. Its only affinities are with *C. pulcherrima*, with which it shares the rhombic scars and their definitely arranged rows.

The most perfect side is represented on Pl. LXXXIII, showing the arrangement of the scars. The base is shown on Pl. LXXXIV, Fig. 1, and the summit by Fig. 2 of the same plate.

CYCADEOIDEA TURRITA n. sp.

Pls. LXXXV–XC.

Trunks moderate sized, profusely and irregularly branched, the primary branches often bearing secondary ones, the branches symmetrical, abruptly contracted at the base into cylindrical turret-shaped projections, dome-shaped at the summit, with a terminal bud at the apex composed of small polygonal organs, usually light reddish, soft, friable, and of low specific gravity, but sometimes darker, harder, and heavier, 20 to 40 cm. high, 25 to 50 cm. in diameter, the branches 10 to 20 cm. long, 10 to 30 cm. in diameter, 30 to 90 cm. in girth; leaf bases slightly ascending; leaf scars very irregularly distributed over the surface except of the branches, here sometimes arranged in two sets of spiral rows which intersect each other at about the same angle (60°) with the axis of the branch, subrhombic, the upper and lower angles reduced to mere curves 23 mm. wide, 12 mm. high; leaf bases almost always present, usually projecting, porous; vascular bundles often distinct, set well apart in a row some distance from the margin, with a few others near the center, appearing either as small pits or black dots; ramentum walls thin, 1 to 2 mm., usually with a groove or commissure, sometimes thickening at the angles and affected with elongated pits and other openings, some of these latter passing into abortive flower buds, which constitute all that is known of the reproductive organs of the species; armor 5 cm. thick; woody axis only known in certain branches, thin, 2 to 3 cm., and not visibly divided; medulla in one specimen 9 cm. in diameter, black and homogeneous.

Twelve of the specimens of the Yale collection have been referred to this species, viz, Nos. 15, 45, 49, 51, 65, 66, 67, 70, 74, 75, 82, and 85, and still much remains uncertain as to the characters. They nearly all agree in the most striking feature—the possession of peculiar turret-like branches—but owing to the fragile nature of the rock and the sprangling habit of the species all the specimens were badly broken to pieces and nothing remains but *disjecta membra*. Some of these plants evidently consisted entirely of branches and possessed no trunk proper which could be regarded as bearing these branches, but usually there was a large shapeless mass at the base from which they proceeded in all directions. Such was the case in Nos. 45, 51, 66, and 67, some of which must be nearly complete. Nos. 45 and 75 belong to the harder and heavier sort, and possibly may not belong to this species. They might be referred to *C. minnekahtensis* or *C. Marshiana* but for differences in the leaf scars and petioles, which agree with this species. No. 74 is very anomalous and is only placed here to avoid making new species out of deficient material. The turret, if such it was, is reduced by erosion to a pointed cone without character. The specimen is worn to and into the medulla on one side, but the opposite side is well preserved. The leaf scars are typical, but there is a number of large projecting axes looking like horns, and the specimen, laid on the worn side, has the shape and semblance of a gigantic "horned toad." All the other specimens are much alike, and No. 82 is taken as the type for most of the characters.

So far as the rock substance, color, and external organs are concerned this species is very close to *C. McBridei*, but that species is always simple and consists of one large, short trunk, constituting a broad distinction which all the numerous specimens of both species do not tend in any way to obliterate. In its branching habit it approaches *C. minnekahtensis* and *C. Marshiana*, but the external characters persistently keep it separate from either. In color it somewhat resembles the former, but this is all that can be said.

Pls. LXXXV and LXXXVI show the characteristic turret-shaped branches as typified in Nos. 82 and 67. Pls. LXXXVII and LXXXVIII give side and base views of the fine specimen No. 49. Pl. LXXXIX represents the anomalous trunk No. 74, and Pl. XC reveals a little of the medulla and axis of No. 15.

All the specimens are from the Minnekahta region.

CYCADEOIDEA McBRIDEI n. sp.

Pls. XCI–C.

1893. Bennettites dacotensis McBride, in part: American Geologist, Vol. XII, p. 249, pl. xi, fig. 2; Bull. Lab. Nat. Hist. State Univ. of Iowa, Vol. II, No. 4, pp. 391–392, pl. xii, fig. 2.

1894. Cycadeoidea dacotensis (McBride) Ward, in part: Proc. Biol. Soc. Washington, Vol. IX, p. 86.

Trunks large and very short (25 to 40 cm. high, 25 to 75 cm. in diameter, with a girth of 80 to 250 cm.), more or less laterally or longitudinally compressed, well silicified but somewhat porous or spongy and therefore only moderately heavy, reddish brown in color, occasionally bearing small secondary axes which only slightly project; organs of the armor variable but usually radial in direction; leaf scars arranged in spiral rows intersecting each other at various angles, usually forming an angle with the axis in either direction of from 40° to 55°; scars subrhombic or lozenge-shaped, the distance between the lateral angles varying from 22 to 35 mm., that between the vertical angles varying from 13 to 16 mm., nearly always filled with the well-preserved bases of the leaves which have disarticulated at natural joints leaving a smooth surface, either convex or concave, or occasionally nearly flat, presenting a spongy appearance; vascular bundles of the leaves usually distinct in the form of pits or of dots of darker color arranged in one row all round the margin a short distance from it and with a few additional ones near the center; ramentaceous interspaces thin for the size of the trunks (1 to 4 mm.), compound, i. e., consisting of two or more plates of firmer material separated by intervals of loose porous tissue, very uniform in character and little distorted, the porous tissue often worn to some distance, leaving fissures divided by thin projecting walls; reproductive organs sometimes abundant and conspicuous, but usually rather scarce and poorly defined, some quite large with a cavitous funnel-shaped or crater-shaped center, others simulating leaf scars except that they are surrounded by a loose porous tissue in which angular pits occasionally occur, still others resembling small branches, making it difficult in some cases to decide to which class to refer them, one which has been cut through the center longitudinally showing a heterogeneous mass of internal organs resting on a conical receptacle 25 mm. below its somewhat projecting summit; armor 4 to 8 cm. thick, separated from the cortical parenchyma by a layer of true bark 6 mm. in thickness, of soft texture, its inner surface (exposed in one specimen) covered with small pits or punctations and definitely marked by elliptical scars about 9 mm. long and 5 mm. wide, which are aligned horizontally around the trunk, the longer axis being in this direction, the upper side of the scars usually so indistinct as to make them appear kidney-shaped, the lower side and ends consisting of a dark raised ring or welt with a groove all round it and exterior to it, the central portion occupied by a number of punctations more or less concentrically arranged; woody axis 9 to 12 cm. thick, of which the parenchyma occupies somewhat more than half and is very porous except where traversed by the medullary rays of firmer consistency; fibrous zone divided into an outer soft and an inner harder ring, the inner wall of the latter conspicuously marked by the scars of the medullary rays; medulla in the larger specimens 15 cm. in diameter, but usually elliptical and about 8 by 11 cm., of a uniform porous consistency.

I name this species for Professor McBride because he was the first to deal with it, although he confounded it with *C. dacotensis*, and parts of his description apply to the one and parts to the other species. Still his figures are clear and leave no doubt that his fig. 2 belongs here. In his description of that figure he says that it belongs to "another individual," which, of course, would have been otherwise evident, and parts of his description show that either this or other material in his hands consisted of fragments showing the interior of the trunks, which could not have been exposed in the "large, perfect individual." Most of his description of the internal parts must have been based on such fragments, and the following words appear to apply entirely to the present species: "Leaves not known; their bases as perceived are fusiform or lozenge-shape in cross section, one-half inch by one inch in dimensions, and show the remains of numerous equally developed fibrovascular bundles."

His specimens seem to have come from exactly the same locality as those purchased from Mr. Cole, which I subsequently visited in company with Professor and Mrs. Jenney, with Messrs. Cole and Payne as our guides. There was found the large branching specimen, *C. minnekahtensis*, and there, too, I picked up 12 fragments of different sizes and shapes. These were numbered in continuation of the Black Hills collection, of which there are 7 nearly perfect trunks, and therefore included Nos. 8 to 19. Of these, 6 certainly belong to the present species, viz, Nos. 8, 9, 10, 13, 14, and 16. Two of these fragments, Nos. 10 and 14, are found on comparison to fit together, and therefore, of course, to belong to the same trunk. When placed in their proper position they constitute the greater part of it, but a large segment is missing from one side. Among these specimens, all differently broken, a much larger number of characters are exposed than could be seen in any number of perfect trunks. Wherever two or more display the same parts they are in substantial agreement, and it is therefore assumed that such features as are only visible in some one specimen would be found in the rest if the proper parts could be exposed. The beautiful markings on the inner surface of the liber zone, as above described, are to be seen only in specimen No. 16 (see Pl. XCIII). That all trunks of the species were of the short, conical shape indicated by Nos. 10 and 14 when placed in their natural position can not, of course, be demonstrated, but the other specimens do not negative this view.

Professor McBride remarks that "the present species is near *Bennettites Gibsonianus* Carr., from which it may be distinguished by greater size and by the fact that in our species the fibrovascular bundles of the leaf stems are of uniform size and distribution, and do not form a horseshoe shape in cross section, as is said to be the case in the English species." In this last one would suppose he was confounding the undivided vascular bundle as it appears in the axis, and especially in its passage through the cortical layer (cf. Carruthers's pl. lvii, fig. 3, in Trans. Linn. Soc., Vol. XXVI) before it divides, with the form assumed by the numerous strands that enter the petiole and appear as small dots on a cross section of the latter (cf. loc. cit., pl. lviii, fig. 2). Neither in the American Geologist nor in the Bulletin of the Laboratory of the State University of Iowa do these strands show clearly in fig. 2, still I think I can detect them; but in nearly all our specimens these bundles are very clearly shown, and they do agree remarkably well with those of Carruthers's figure (loc. cit., pl. lviii, fig. 2). Still I should hesitate to refer the American forms to *C. Gibsoni* on this character alone, and having myself examined the British specimen I do not think it is very close in other respects (cf. Sixteenth Ann. Rept. U. S. Geol. Surv., Pt. I, p. 487).

The absence of perfect trunks of this species in the National Museum collection is not due to its rarity in the Black Hills, as I was satisfied after examining the large number of fragments picked up by myself, but to the frailty of the species. There is in fossil cycads certainly a close connection between the mineral constitution and the original nature of the tissues, and both vary with the species much as different kinds of wood differ in their qualities of hardness, durability, tenacity, etc., in our living forests. Accordingly the substance of the rock in this species is always soft, porous, and light, easily worn by attrition, and therefore frail. Moreover, there is a tendency to early decay of the medulla and woody axis, which caused many of the trunks to become hollow before they were entombed. This made compression and general destruction easy and accounts for the difficulty in securing good specimens.

In view of these facts, I was not surprised to find a large number of specimens of this species in the Yale collection. There are no less than thirteen which I have so referred, although several of these are very abnormal and doubtful. The ones so classed are Nos. 8, 19, 23, 26, 27, 29, 38, 42, 46, 53, 73, 76, and 110. No one of these is absolutely complete, and the greater part of them are mere fragments. In the majority of cases the specific determination is clear at a glance, and this is true even of the smaller fragments. No. 19 is a typical and nearly complete trunk, weighing 51.46 kilograms, and No. 23 is by far the most perfect specimen of the species known to me. It weighs nearly

59 kilograms, but there is a vast cavity at the summit. No. 76 is also nearly complete and a fine example, weighing 23.59 kilograms. There are four dwarf specimens, Nos. 26, 29, 42, and 53, which, though nearly perfect, must be immature trunks if they belong here. They differ too much from each other to constitute a specific group, and I have been obliged to treat them as young, dwarf, or aberrant forms of this species. Nos. 26, 29, and 42 have each a good terminal bud, the only such seen in the species. No. 53 is very small, only 11 cm. high, weighing only 1.57 kilograms, short-conical, and very symmetrical. It represents the species in miniature, and is doubtless undeveloped.

Only one of the specimens of the Yale collection from the Blackhawk region belongs to this species, viz, No. 110, which consists of nearly half of a large trunk showing the much worn outer surface with deep holes, which are often united a short distance within by the decay of the walls so as to produce communicating chambers. The opposite side exposes a large hollow, or trough, consisting of the inner wall of the woody zone. It also shows the attachment of the armor and the underlying axis in an exceptional manner.

Pl. XCI shows the broad side of the trunk resulting from joining Nos. 10 and 14 of the U. S. National Museum collection, which were found to fit together and make considerably more than half of the trunk. This also shows the full height, as we have the true base and all that was left of the summit after the decay of the terminal bud. The scars are clearly shown on the surface, but less so than in fragment No. 9, a portion of the surface of which, enlarged, is shown on Pl. XCII. In Pl. XCIII we have a clear view of the inner wall of the liber zone or true bark, which is marked by scars of a different pattern from any elsewhere observed.

No. 23 of the Yale collection is perhaps the most complete trunk of this species known, and has been illustrated from the broad side, the hollow summit, and the base on Pls. XCIV–XCVI. The inner wall of the armor is exposed in No. 27, and this is shown on Pl. XCVII. Pl. XCVIII, Fig. 1, represents the small trunk, No. 29, of the Yale collection, which may be a dwarf form of this species. It will be noticed that dwarf forms are the only specimens known in which the terminal bud is preserved. This might happen in immature specimens, when in all old trunks this organ would decay too rapidly to become silicified. Fig. 2 shows the smallest specimen of the species, and, indeed, there is much doubt as to whether it belongs here, but it bears too many evidences of being a very young trunk to make it safe to call it a new species, and the characters, so far as they go, point to *C. McBridei*.

Pls. XCIX and C represent the outer (Fig. 1) and inner (Fig. 2) surfaces of the specimen No. 110 from the Blackhawk region, above described.

All the specimens except the one above mentioned have been found in the Minnekahta region.

CYCADEOIDEA MARSHIANA n. sp.

Pls. CI–CV.

Trunks very large, profusely branched, the primary branches often bearing secondary ones, the whole individual frequently consisting of branches, sometimes with a sort of common base, the branches irregular in size, form, and direction, making shapeless or grotesque objects; summits of the branches rounded, bearing small polygonal scars with depressed or cavitous centers separated by deep channels as if from the disappearance of the walls, or filled with the bases of the apical leaves often set in a circular, smooth, flattened area, and having a small conical protuberance or terminal bud at the center; rock substance hard, heavy, and dark colored; general external appearance rough and massive; forms very variable in size and difficult to measure, the largest attaining 91 cm. in its greatest dimension, the lateral generally greater than the vertical dimensions when standing on the base, the former often 50 to 60 cm., the latter 30 to 40 cm.; branches 15 to 30 cm. long, 10 to 40 cm. in diameter, and often over a meter in girth; organs of the armor ascending on all the branches; phyllotaxy usually so disturbed as not to be traceable, but consisting of at least one series of spiral rows of scars passing from right to left at an angle of about 75° with the axis of the branch; leaf scars of medium size or small for the size of the trunks, normally subrhombic, but varying from triangular, or with a mere groove to represent the upper angle, to nearly rhombic, 15 to 30 mm. wide, 7 to 15 mm. high, averaging 12 by 25 mm. for the body of the trunk and 10 by 18 mm. for the branches, usually empty to considerable depth, sometimes filled with the leaf bases, which either present a smooth concave surface or a rough projecting surface formed in part by rows of pointed elevations consisting of the exposed extremities of the vascular bundles lying on the sides of a central conical protuberance the apex of which is formed in part of the more interior strands; ramentaceous interstices usually thick, 5 to 15 mm., hard, roughened, wrinkled, or grooved, often highest next so the scars, sometimes thinner with only a median line; reproductive organs generally abundant on the body of the trunk and larger branches, large, 7 cm. long in a circumferential direction, 5 cm. high, conspicuous, either projecting or cavitous and crater-shaped from the decay of the essential organs, surrounded by concentric rows of large bract scars, sometimes more rare and smaller; armor 4 to 7 cm. thick, but difficult to observe except on the branches where it has little significance; cortical parenchyma 3 to 4 cm.; fibrous zone 2 to 4 cm. with two rings; medulla sometimes seen at the compound base, 12 cm. in diameter, often decayed so as to leave a large cavity, its surface exposed in one specimen showing the scars of the medullary rays in the form of elongated ridges increasing in thickness upward and terminating in a sharp point.

This magnificent species was first clearly made known to me in the Yale collection, where it is represented by five, and probably six, specimens. These are Nos. 4, 11, 33, 44, 47, and 79. The doubtful ones are Nos. 33 and 79. These are single branches of much larger trunks, and their characters are somewhat aberrant. Of the other five there is no doubt, as they agree in all their characters. No. 11 is taken as the type. It is larger than any of the rest, and the next largest specimen in the Yale collection, weighing 221.35 kilograms, and therefore holding the third rank in this respect among the cycads of the world. It has the form of a huge animal, has five primary branches, and when placed in the position in which it probably grew four of these, with the mass to which they are attached, constitute a sort of forepart, with head, thorax, and fore limbs, while the other represents the hinder part and is aligned in the opposite direction. Between these parts is a constriction dividing the two systems. It is very complete, so much so that it has furnished few of the internal characters.

Nos. 4 and 47 are also large trunks, weighing, respectively, 52.62 and 34.93 kilograms, and the other fragments supplement the more perfect specimens so as to make a pretty full description of the species possible.

I have named the species in honor of Professor Marsh, to whose energy and munificence this great collection is wholly due.

When engaged in examining and describing these specimens in the Yale collection I supposed that none existed in the U. S. National Museum, but on revising all my previous descriptions in the light of the new material I discovered that I was mistaken, and that specimen No. 15 belongs to this species. I had referred it with doubt to *C. colossalis*, and under that head had made the following remark: "The only other specimen in the collection of the U. S. National Museum that I can refer to this species is the fragment No. 15, collected by myself in 1893 on the same spot where the others were found. This is a very irregular block or segment broken from near the top of a great trunk. It is similar in mineral character to No. 6, and the leaf scars and other organs agree well with the upper parts of that specimen. The fractures are downward, but follow the plane of the petioles, which are here erect. In No. 15, however, two large and nearly equal branches, whose axes were nearly at right angles to each other, are represented. Viewed from the broken sides, the two axes are clearly seen in contact, having a gnarly appearance, such as is normally produced at the junction or crotch between two branches."

This branching character, as I was well aware, does not belong to the large, perfect specimen, but, having no others, I thought it possible that some of the small secondary axes might in other cases become primary branches; but after seeing so many other specimens of *C. colossalis* all agreeing in this respect, and also a large number of the present species also all agreeing and exhibiting no tendency to vary in the direction of the other species, it became obvious that the branching forms all belonged to one species and the simple ones to another. The specimen No. 15 clearly belongs to the branching species, and now it is easy to see other specific differences.

Pls. CI–CIII furnish a fairly good idea of the great type specimen, No. 11. Pl. CIV represents one of the large limbs torn from a specimen of unknown size, No. 47. Finally, Pl. CV gives us a side view of No. 33, the anomalous character of whose scars has been described. Of course, the peculiarity in the vascular bundles could not be expected to appear in a photograph.

All the specimens are from the Minnekahta region.

CYCADEOIDEA FURCATA n. sp.

Pls. CVI–CIX.

Trunks large, forking above, or sometimes with a third branch, simple below, laterally compressed, eccentric, light colored, soft and of low specific gravity, 35 to 45 cm. high, 25 to 30 by 35 to 40 cm. in diameter, 90 to 110 cm. in girth; organs of the armor mainly horizontal; leaf scars subrhombic, or somewhat triangular, the vertical angles generally rounded, the lateral acute, variable in size, averaging 15 by 25 mm., those on the branches smaller, or sometimes nearly as large, empty; ramentaceous walls variable, usually thin, 1 to 5 mm., much thicker in the angles, firm in texture, grooved or divided into two or three plates; reproductive organs few, large, elliptical, 4 to 7 by 7 to 10 cm. in diameter, either set in depressions or somewhat elevated, surrounded by bract scars, either cavitous in the center or solid, the larger ones simulating small branches; armor 4 to 7 cm. thick; cortical parenchyma 7 cm., clearly distinguishable from the darker zone of wood 6 cm. in thickness; medulla elliptical, 9 to 11 cm. in diameter.

This species is thus far represented by only two specimens, viz, Nos. 18 and 60, of the Yale collection, the latter of which is in such a complete state of preservation that little can be known of its internal structure. It is distinguished from all other trunks known to me by a true dichotomy, consisting of a simple trunk with two nearly equal erect branches and a natural junction or crotch at their point of separation. The axis is far to one side and the trunk is flattened on that side, the entire true base being lateral and the trunk, standing on a false base, belonging to the armor, but naturally flattened in transverse direction. These peculiarities were doubtless the result of the position in which the trunk originally grew among rocks. Besides this striking characteristic, the light color and soft constitution of the rock, as well as the form and arrangement of the scars, ramentum-walls, reproductive organs, etc., distinguished this from all other cycadean trunks. It is a fine specimen, and weighs 49.9 kilograms.

No. 18 consists of two nearly equal branches and one somewhat smaller, arranged in a triangular cluster. Two of them are flat on one side from growing against rocks. The trunk proper can scarcely be said to be represented. The two larger branches are each about 30 cm. in diameter and 23 cm. long, with rounded summits forming something analogous to terminal buds. Fractures about the lower portion yield elements of internal structure, but they relate to the branches only. The external surface is beautifully preserved. This specimen weighs 66.22 kilograms.

Two views of specimen No. 60 were taken, one of the rounded outer surface or back, Pl. CVI, and the other of the opposite flat side, Pl. CVII, within which the true base, set on one side, wholly falls. The indications are that the trunk grew with this side against a vertical rock and was connected with the soil beneath it.

Pl. CVIII is a view of the specimen No. 18, seen from above, and Pl. CIX shows it from the base.

Both specimens are from the Minnekahta region.

CYCADEOIDEA COLEI n. sp.

Pl. CX-CXII.

Trunks rather large, ellipsoidal, 34 to 48 cm. high, elliptical or nearly circular in cross section, 30 to 39 cm. in diameter and 90 to 118 cm. in circumference at the thickest part, simple, the apex studded with small polygonal scars and presenting a smooth disk with a central elevation; rock substance dark brown in color and moderately heavy; organs of the armor except the very lowest manifestly ascending; leaf scars arranged in two series of more or less distinct spiral rows, those passing from left to right forming an angle of 75° and those from right to left of 45° to the vertical axis; scars subrhombic, varying from almost rhombic to nearly triangular with rounded angles, large, averaging 22 mm. wide and 13 mm. high, but ratio of width to height variable, empty to a depth of 2 to 5 cm.; ramentaceous walls usually thick but very variable, doubly grooved or wrinkled, cracked or fissured, often pitted by the scars of small bristles or perulæ; fruiting axes numerous, small, most or sometimes all of their surface occupied by bract scars, central portion correspondingly small, generally cavitous from the disappearance of the essential organs, which appear to have often been immature or abortive; armor about 6 to 7 cm. thick; cortical parenchyma 3 cm. thick; fibrous zone 2 cm., consisting of two rings of wood; medulla about 9 cm. in diameter.

This is a very handsome species of which the type specimen was purchased of Mr. F. H. Cole, for whom the species is named. That specimen weighs 63 kilograms.

The Yale collection contains nine specimens that I was obliged to refer to this species. These are Nos 12, 20, 25, 28, 48, 52, 57, 68, and 80. Of these Nos. 25 and 80 are small and either dwarfed or immature, and Nos. 28 and 52 are small fragments. The rest are fairly typical and furnish good characters. No. 48, though small, weighing only 29.49 kilograms, is perhaps the most typical. No. 57, though not complete, weighs 56.24 kilograms, and was doubtless originally quite the equal of the National Museum type. No. 12 has an unusual number of fruiting axes.

Pl. CX shows a side view of the type specimen, No. 2 of the U. S. National Museum, and Pl. CXI that of the very similar trunk, No. 48 of the Yale collection. The fragment No. 12 of the Yale collection represented on Pl. CXII is somewhat anomalous if not specifically doubtful, but can not be referred to any other known species.

All the specimens are from the Minnekahta region.

CYCADEOIDEA PAYNEI n. sp.

Pl. CXIII-CXV.

Trunks medium sized, laterally compressed, usually enlarging from the base upward to near the summit but sometimes subcylindrical, 30 to 55 cm. high, 65 to 85 cm. in average girth, 20 by 25 cm. to 25 by 35 cm. in diameter, light or darkish brown in color, not specially firm or heavy, bearing few or not any secondary axes; organs of the armor horizontal; phyllotaxy rather obscure, but scars arranged in imperfect spiral rows, chiefly subrhombic, but varying to rhombic or triangular, much distorted in the specimens in hand, but where clearly shown 10 to 16 mm. high and 16 to 31 mm. wide, empty to some depth, their bottoms filled with the partially decayed remains of the petioles; ramentaceous interstices rather thin but variable, usually with a more or less distinct commissure; reproductive organs or their remains numerous and conspicuous, often projecting considerably beyond the general surface in the form of protuberances or terete spongy cylinders, often decayed, leaving large cavities more or less crater-shaped or funnel-shaped, the interior sometimes definitely grooved or marked, surrounded by numerous, sometimes large, triangular involucral bract scars; armor varying in thickness from 2 to 7 cm., attached by an irregular line or thin layer of bark to the cortical parenchyma which is 1 to 2 cm. thick and incloses a fibrous cone of about the same thickness, which is divided into two or three rings; medulla less compressed than the outer parts, 6 to 10 cm. in diameter.

The only specimens that certainly belong to this species are Nos. 4 and 5 of the collection purchased from Mr. Cole. The description of the internal parts is chiefly based on No. 5, which is the smallest of that collection and has been cut longitudinally through the axis, one of the halves cut transversely 12 cm. above the base and the surfaces polished. These sections furnish clear views of the organs of the armor and of the relations of the armor to the underlying parts. The specific identity of the two specimens is based on the external characters, which substantially agree. No. 4 weighs 33.11 kilograms and No. 5, 22.22 kilograms. I name the species for the ranchman, Mr. Payne, who originally discovered the cycads of that region and from whom Mr. Cole obtained them. He it was, moreover, who finally guided us to the locality after Mr. Cole had vainly sought to take us to it the previous day, missing the way notwithstanding that he had been at the spot.

In the Yale collection there are two specimens, Nos. 58 and 69, which I have doubtfully referred to this species, although some of the characters are different from those above described. They are vertically instead of laterally compressed. If this is due entirely to pressure of the superincumbent mass after entombment, it has no systematic value and depends upon the position occupied by the specimen; but eminent authorities have insisted that it is a condition of growth. I am inclined to think that this may be true in some cases, but that the former explanation is the chief one.

The Yale specimens are both smaller than either of the National Museum types, No. 69 weighing 20.86 kilograms, and No. 58, which is dwarf, abnormal, and perhaps immature, 5.33 kilograms.

Pls. CXIII and CXIV give side and base views of the type specimens Nos. 4 and 5 of the U. S. National Museum, and Pl. CXV represents the polished surface of the interior of No. 5, bringing out the relations of the various tissues in a very satisfactory manner.

All the specimens are from the Minnekahta region.

CYCADEOIDEA WIELANDI n. sp.

Pl. CXVI.

1893. *Cycadeoidea Paynei* Ward, in part: Proc. U. S. Nat. Mus., Vol XXI, pp. 212–213 (quoad No. 77 of the Yale collection).

Trunks medium sized or small, cylindrical-conical, somewhat laterally compressed, dark colored, moderately hard with medium specific gravity, rough or jagged on the outer surface, unbranched, about 40 cm. high, 21 by 25 cm. in diameter at the middle portion, 70 to 80 cm. in girth; organs of the armor about horizontal, at least in the middle part; phyllotaxy not traceable; leaf scars normally subrhombic and narrow but much distorted by the fruits, often triangular, sometimes with the upper side downwardly curved, 20 to 25 mm. wide, 12 to 20 mm. high; leaf bases present but not reaching the surface, porous or spongy without visible bundle scars; ramentum walls thin, 1 mm. or less, much broken down in the specimens, with or without an obscure median line; reproductive organs abundant over all parts of the trunk, covering half of the surface and distorting all other organs, large and somewhat elliptical but sometimes nearly circular, 25 to 35 mm. in diameter, often cavitous with a very definite bowl-shaped interior, the bottom smooth and usually raised like that of a blown bottle, or with a boss or button in the center, i. e., the receptacle of the spadices rising up with a depression all round it, sometimes resembling a saucer inside the larger bowl, the central boss or button sometimes with a large, deep slit nearly transverse to the axis of the trunk or in line with the major axis of the cross section, this slit occasionally replaced by a sharp ridge or by a few pits; fruits often partly or wholly preserved, obovate, sometimes rising above the general surface and convex at the summit, either smooth or granular from the exposed extremities of the numerous densely matted seeds; spadices surrounded by involucral bracts, consisting of the receptacle above described as a central boss or button from which rise numerous seminal peduncles of varying lengths, the central ones longest and ascending to the summit, the more lateral ones proceeding outward and terminating at the periphery in such a manner as to form a cylindrical body with a rounded outer extremity, each peduncle terminating in a single seed; seeds 1.5 mm. to nearly 2 mm. in diameter, oblong in shape, 5 mm. long, surrounded by an opalized double seed-coat, their combined mass forming a somewhat irregular layer over the whole upper part of the fruit, extending downward to about the middle, each seed containing a number (6 to 12) of relatively large spherical bodies, sometimes opalized like the seed-coats, possibly representing the archegonia; armor thin, about 4 cm. thick; woody zone not visibly divided, 4 cm. thick; medulla elliptical in cross section, 4 by 6 cm. in diameter.

At the time I described No. 77 of the Yale collection in June, 1898, the specimen was almost wholly covered with an incrustation of lime and very little could be learned of its nature. Sufficient, however, was visible to indicate that it possessed an especial interest. The peculiar granular structure of some of the fruits could be seen, and from such examination as I was able to make I derived the description that I gave on page 213 of the Proceedings of the United States National Museum, Vol. XXI. I included it provisionally and doubtfully in *C. Paynei*, from the general form and appearance, although there were differences even in the external character which were there pointed out, and I was careful not to include the peculiarities observed in the reproductive organs in the description of that species, because I anticipated that these and the other differences might require it to be removed from *C. Paynei* when a fuller study of them should be made.

On my next visit to New Haven in November, 1898, to study a fresh invoice of cycads sent by Mr. Wells, I found another specimen, No. 131, which exhibited most of the external characters of No. 77 and had similar fruits, very few of which, however, contained the whole of the spadix. In a number of cases this had fallen out, leaving the bowl-shaped cavity, but with some of the seminal peduncles adhering to its sides and terminating in the little elongated sockets in which the seeds had lain. This at once revealed to me the true nature of the fruits of No. 77, and I thereupon placed that specimen in a vat of acid and removed the coating of lime. The specific identity of the two specimens was then manifest and it became clear that the small bodies described in the latter and erroneously taken for the silicified cores of the seminal peduncles were the seeds themselves.

I endeavored to impress upon Professor Marsh the great importance of this discovery and the urgent necessity of having sections made of this first case thus far discovered of seeds preserved in the trunk of an American cycad. The extreme rarity of such cases justified this exceptional interest, and I succeeded in arousing in Professor Marsh a part of the interest that I felt in the matter.

It chanced that Mr. George R. Wieland was at the time working in the Peabody Museum. He had himself collected a considerable number of cycads, had spent one day with Mr. Wells and myself in the Blackhawk region, and was greatly interested in the general subject. He had had considerable training in the technique of section cutting, and, with Professor Marsh's approval, he proceeded to make some sections of one of the best spadices of No. 77, which was easily detached from near the fractured margin of the trunk. The longitudinal section first made revealed the whole nature of the fruit and showed its essential identity with the fruits of *C. Gibsoni*, that had been the subject of such prolonged and exhaustive studies on the part of Carruthers and Solms-Laubach, in Europe. It proved also to be at least generically identical with the celebrated fruit called *Bennettites Morierei*, from the Jurassic of Calvados in France, so beautifully monographed by Professor Lignier.

A cross section was also made while I was at New Haven, and from these sections I was able to write the description of the internal structure of these fruits as given above.

I was convinced that other specimens, both in the Yale collection and in that of the United States National Museum, would show perfect fruits if properly treated, and I took that occasion to urge Professor Marsh to inaugurate a systematic study of the Yale collection from this point of view, which he did, and Mr. Wieland has continued the work so auspiciously begun. It is therefore with great pleasure that I dedicate this species to him, the first to bring to light the internal structure of the reproductive organs of the fossil cycads of America.

This species is therefore founded on the two type specimens, Nos. 77 and 131 of the Yale collection. No. 77 is smaller above than below, and is naturally oblique at both base and summit, having lost nothing. It is jagged on all sides with its unequal walls and protruding fruits. It is 32 cm. high. Its major diameter varies from 23 to 25 cm., and its minor from 16 to 21 cm. It has a girth near the base of 74 cm. and at the summit of 66 cm. Its weight is 21.09 kilograms.

No. 131 is larger than No. 77. It is long-conical, very obliquely truncated above so as to want the apex entirely, also irregularly broken across below, but the lowest part probably shows the true base, which was little if at all contracted. It is elliptical in cross section, and a number of pieces broken out of one side of the base have been saved and accompany the specimen. Its present height is 40 cm., which, owing to the obliquity of the fractures, probably represents its full length. The longer diameter near the base is 26 cm. and the shorter one 21 cm. The girth at the base is 70 cm., and at a point just below the upper fracture 66 cm. It weighs 22.22 kilograms.

Pl. CXVI shows a side view of trunk No. 77. A number of fruits are clearly brought out.

CYCADEOIDEA ASPERA n. sp.

Pl. CXVII.

Trunks small, subconical, simple, very rough on the surface, light brown varying to whitish, dark with white streaks within, moderately heavy, about 20 cm. high, nearly the same in diameter, and 70 cm. in circumference; organs of the armor somewhat declined throughout; phyllotaxy not traceable; leaf scars anomalous in having the upper angle much sharper than the lower, the reverse of the usual case and only elsewhere observed in *C. insolita*, lower angle reduced to a groove, a curve, or a straight line, lateral angles always sharp; scars small, 12 to 25 mm. wide, 10 to 15 mm. high, subrhombic; leaf bases present usually projecting 5 to 10 mm. above the walls, presenting a light brown, very spongy and porous surface, without evidence that any of the pores represent the scars of vascular strands; ramentaceous interstices thin, 1 to 5 mm., dark reddish brown, sunk to varying depths among the projecting leaf bases and other organs, scaly and laminated with crooked and twisted plates; reproductive organs as numerous as the leaf scars, projecting much beyond the petioles, sometimes 3 cm. high, solid or variously broken and jagged, occasionally somewhat cavitous, scarcely showing any involucral scales, but in addition to all the other organs described are small angular bracts, mostly broken down, presenting sharp edges and projections over the surface, intermediate in character between scales and leaves, properly to be classed as bristles or perulæ; all the different projecting organs giving the trunk a ragged and bristling appearance; armor, including projections, 6 cm. thick, the vascular strands traceable far into the woody zone and inner limit not definite; parenchymatous layer 15 mm. thick, penetrated by the whitened leaf bundles; secondary wood 2 cm. thick, consisting of two nearly equal rings, the outer white, the inner black or dark blue in the only specimen known; medulla 6 cm. in diameter, dark, fine-grained and homogeneous.

This species is based on the single specimen, No. 104 of the Yale collection, which is somewhat less than half of a trunk that divided along a vertical plane from top to bottom almost as smooth and even as if sawn through by a gang saw, exposing the interior in an admirable manner. Its only affinities are with *C. Paynei*, and the specimen, though smaller, has a remarkable resemblance to No. 5 of the U. S. National Museum (cf. Pls. CXIV and CXV), which was cut through on the same plane as this specimen. The resemblance is, however, more apparent than real, and the descending leaves and especially the inverted scars clearly exclude it from that species. Add to this that no specimens of *C. Paynei* have been found elsewhere than in the original Minnekahta locality, and the improbability of this belonging to that species is very great. It is too perfect a specimen to class as undeterminable, and there seems no course left than to treat it as constituting a new species.

Fig. 1 of Pl. CXVII represents the rough outer surface and Fig. 2 the inner face.

The specimen is from the Blackhawk region.

Cycadeoidea insolita n. sp.

Pls. CXVIII, CXIX.

Trunks medium sized, unbranched, somewhat elliptical in cross section, subcylindrical or subconical; rock substance light colored, moderately hard and heavy; height of trunks 30 to 40 cm., diameter 30 to 35 cm., girth about 1 meter; organs of the armor nearly horizontal; leaf scars irregularly distributed over the surface, very variable in size and shape, rhombic or subrhombic, in the latter case having the more acute angle above and the more obtuse one below, i. e., the opposite of the normal condition, 15 to 25 mm. wide, 8 to 15 mm. high, sometimes empty to some depth, but in some such cases the summits of the leaf bases showing the vascular bundles in the form of little rods or pins projecting upward and forming a row all round the leaf bases close to the margin with others near the center, about 18 to each leaf; leaf bases sometimes projecting in the form of small cones, in which cases the bundles can be seen either as black dots or as little protuberances around the sides of the cones; ramentum walls thin but variable, 1 to 4 mm., firm and sharp on the edges of the scars, grooved along the middle; reproductive organs abundant, disturbing the phyllotaxy, tending to congregate and blend together, presenting a rough surface, usually projecting, rather small and with few bract scars; armor 4 to 6 cm. thick; cortical parenchyma 2 to 3 cm.; fibrous zone 15 to 30 mm., with two or three rings, the outer either preserved and showing fine-grained structure or much decayed, in either case conspicuously partitioned off by the medullary rays, the others also showing woody wedges; medulla 8 by 12 cm. in diameter at the base, enlarging upward, hard and homogeneous in structure.

This species is founded on two specimens in the Yale collection, Nos. 50 and 64, chiefly the latter, No. 50 being only a small fragment. The characters can not be forced into any other species, especially the inverted leaf scars and the peculiar habit of the vascular bundles in the petioles. In No. 33, which is a branch of a trunk of the type of No. 11, and has been referred to *C. Marshiana*, this latter peculiarity is nearly repeated, but this happens in no other specimen of that species.

No. 64 is the lower part of a trunk irregularly broken across the top and down one side to near the middle. The apex is therefore unknown. It is this specimen that has furnished all the external characters, but No. 50 shows precisely the same characters so far as it goes, and adds somewhat to the knowledge of the internal parts. No. 64 weighs 24.95 kilograms and No. 50, 3.29 kilograms.

Pl. CXVIII and Fig. 1 of Pl. CXIX illustrate the trunk, No. 64, but the views can not be said to be very satisfactory. Fig. 2 of Pl. CXIX affords a much better idea of the leaf scars as they are seen on the outer surface of the smaller fragment, No. 50. Their inverted form is here made clear, though some appear as true rhombs.

Both specimens are from the Minnekahta region.

CYCADEOIDEA OCCIDENTALIS n. sp.

Pl. CXX.

Trunks medium sized, conical or ellipsoidal, simple or with a few small secondary axes, well silicified, moderately hard and heavy, reddish brown without, dark or nearly black within; organs of the armor generally ascending; phyllotaxy not traceable in any of the specimens; leaf scars subrhombic, variable in size, 16 to 25 mm. long, 10 to 16 mm. high, usually filled by the leaf bases; bundles not visible; ramentaceous interspaces thin, less than 2 mm., roughened without, white within, contrasting strongly with the black petiolar substance in longitudinal section; reproductive organs rare, slightly protruding, usually having remains of the organs preserved, occasionally decayed so as to leave openings, obscure from without, distinct in sections longitudinal to them, penetrating to a depth of 6 cm.; the substance above the fruit light colored; fruit dark, elliptical or ovate, nearly homogeneous and showing no structure, subtended by strong involucral bracts and crowded by a mat of chaff probably consisting of the summits of the interseminal scales; seeds not detectable; armor 5 to 8 cm. thick, irregularly joined to the woody axis, the outer or parenchymatous portion of which, to a thickness of 3 cm., is more or less decayed in most of the specimens; fibrous zone divided into two rings, each about 15 mm. thick, the innermost very firm and fine-grained, its inner wall (exposed in two specimens) regularly marked by the scars of the medullary rays, the scars consisting of conspicuous elongated depressions arranged in longitudinal rows at equal distances (1 cm.) from one another; the scars nearly the same distance one above another but alternating so as to form diagonal rows crossing the vertical ones at an angle of nearly 45°; inner face of the second ring of wood (exposed over a small area in one specimen, nearly smooth but faintly striate in a horizontal direction, marked with smaller, more distant scars; medulla (represented only in one small disk-shaped specimen from near the top of a trunk, and here thoroughly crystallized) scarcely known.

Four of the fragments picked up by me belong to this species. They are Nos. 11, 12, 17, and 18. No. 11 is a large block weighing over 7 kilograms, showing considerable of the external surface, which is not very clear. Portions of it have been detached and cut in several directions to show the internal structure. Most of such characters above given are derived from this source. No. 12 is a very small piece, consisting entirely of the fibrous zone of wood, of which it shows the inner wall with the scars identical in character with those of No. 11, of which it is probably only a detached fragment. No. 17 is a crescent-shaped fragment from a small trunk, and weighs 2.27 kilograms. It appears to have come from near the top of the trunk. No. 18 is a thin horizontal zone or disk from near the top of a small trunk. The internal portion is much crystallized.

The specimens on which this species are based, though clearly distinct in their external characters from any of the rest, are still so fragmentary and imperfect that in photographing the material they were overlooked, and no views were taken of the outer surface. One of them, however, No. 11, has furnished an excellent section through the armor and wood, an enlarged view of which is shown on Pl. CXX.

All the specimens are from the Minnekahta region.

CYCADEOIDEA JENNEYANA Ward.

Pls. CXXI–CXXXII.

1894. *Cycadeoidea Jenneyana* Ward: Proc. Biol. Soc. Washington, Vol. IX, April 9, 1894, p. 87.

Trunks large and tall, attaining a height of 130 cm., cylindrical, little compressed, 30 to 40 cm. in diameter, the girth reaching over a meter and a half, firmly silicified, more or less chalcedonized or opalized within, very hard and heavy, light brown or reddish externally, white or reddish, sometimes black within; organs of the armor horizontal except near the summit; leaf scars arranged in intersecting spiral rows, those passing from left to right making an angle of about 40° and those from right to left of about 50° with the vertical axis; scars subrhombic to subtriangular with mostly rounded angles, sometimes kite shaped, large, 20 to 30 mm. wide, 12 to 25 mm. high, partially or wholly filled with the remains of the leaf stalks; vascular bundles in the petioles arranged in an imperfect row all around near the margin with other straight rows, or somewhat scattered in the interior, numerous (40 were counted in one cross section), circular, elliptical, crescent-shaped or kidney-shaped in section; ramentaceous interspaces very thick but somewhat variable (6 to 13 mm.), sometimes roughened or irregularly affected by small pits representing bract scars, a line of which may run through the center, dividing the walls, or by cracks which divide them into plates or small partitions; reproductive organs numerous, large, and well developed, often protruding, sometimes cavitous, scattered over all parts of the surface, axillary to the leaf scars, whose shape and order they distort, elliptical in outline, 25 to 40 mm. in a horizontal and 18 to 26 mm. in a vertical direction, surrounded by concentrically arranged semilunar or somewhat triangular bract scars, which are sometimes continued in a horizontal direction, converging and blending with the rows dividing the walls, the central portion, when exposed at the margin of a fracture, taking the form of an elongated cylindrical spadix or fruit, which, seen in cross section, proves to be made up of four large organs that seem to contain two axes, and seen in longitudinal section, to constitute a convex receptacle from which arise seminiferous peduncles (or filaments) and interseminal (or interstaminate) scales, the seeds (or anthers) having disappeared, leaving a region of amorphous decayed tissue occupied by the matted prolongations of the chaff; armor 8 to 9 cm. thick; liber zone very indistinct; cortical parenchyma 3 to 4 cm. thick; fibrovascular zone about 2 cm., without visible subdivision into rings; medulla slightly elliptical, the major diameter 16 to 17 cm., the minor 13 to 14 cm., black and cherty in all the specimens, showing no structure, giving off rays which may be seen traversing the woody cylinder.

The above description is based mainly on two large trunks, or parts of the same trunk, which, through the intervention of Professor Jenney, were generously loaned to the Smithsonian Institution by Dr. V. T. M'Gillycuddy, director of the State School of Mines of South Dakota at Rapid City, where they had been deposited. There are many reasons for believing that these two pieces belong together, and with a small missing intermediary piece constituted a tall, cylindrical trunk. One of the pieces, about 40 cm. long, represents the true base and the other, 58 cm. long, the true summit. The former is scarcely worn at all while the latter is deeply eroded all round as the result of having been long exposed to adverse influences, probably by having lain in the bottom of a gulch. It is therefore considerably smaller than the normal diminution upward would require. The difference applies, however, wholly to the exterior, and the medulla and woody cylinder are no smaller than would be the case in an entire trunk at different heights. After a careful examination I have arrived at the conclusion that if they are parts of one trunk it would only indicate the loss of about 30 cm., which would give a total height for the trunk of about 130 cm.

Only two other tall, cylindrical species of Cycadeoidea are known to me, viz, the *C. excelsa*, described below, and the *C. gigantea* of Seward from the Purbeck beds of Portland.[1] Specifically, of course, *C. Jenneyana* is very distinct from both of these, but in its straight, erect

[1] On Cycadeoidea gigantea, a new Cycadean stem from the Purbeck beds of Portland, by A. C. Seward: Quart. Jour. Geol. Soc. London, Vol. LIII, February, 1897; pp. 22-39, pls. i-v.

habit it somewhat resembles *C. gigantea*. It is much less compressed laterally, and if my conclusions are correct as to the amount missing between the two sections, it was taller by 11 or 12 centimeters. Mr. Seward does not state the weight of his specimen, but if the material at all resembles that of all other cycads from those quarries its specific gravity is low and the weight would be small in relation to the bulk. He states the girth of the specimen at 107 cm, while that of *C. Jenneyana* is very nearly 130 cm. More exactly, the lower piece, measured at the middle is 129.54 cm, while the upper piece, both at the lower end and at the middle, measures 107 cm. The difference, as explained above, is chiefly due to erosion of the surface of the latter. The lower piece weighs 95.26 kilograms, and the upper 86.18 kilograms, a total of 181.44 kilograms. The entire trunk must therefore have weighed nearly 250 kilograms, which would give it the third rank, from this point of view, among the fossil cycads of the world.

The question whether there are any other specimens in the U. S. National Museum collection that belong to the same species is a more difficult one. In 1893, as stated above (p. 562), an expedition was made to the locality. No other fragments were found by any of our party, although we all searched diligently for several hours and collected a large amount of silicified wood. We were told at the ranch that a man named McBride (not Professor McBride, of course) had been in the region and had gathered and taken away all the specimens he could find.

Later in the summer, when I was in California, Professor Jenney learned the whereabouts of Mr. McBride, who was then in Deadwood, and purchased two fragments of cycads from him that he said came from that locality. He also purchased two other fragments from Mr. L. W. Stillwell in Deadwood, which, as he was informed, came from the same place. All these he sent to Washington, and they constitute a part of the cycad collection in my hands.

Upon careful examination of all four of these fragments I conclude that there is nothing to negative the supposition that three of them belong to the same species as the large trunks, and I have accordingly included them under *Cycadeoidea Jenneyana*. They were numbered in the collection as McBride fragments Nos. 1 and 2 and Stillwell fragment No. 1.

These fragments are irregular and not well preserved, but they evidently came from large trunks, and all the characters that they show agree substantially with those of this species. As they come from the same locality and as a portion of the great trunk is missing, I have examined them carefully to see whether they might possibly belong to that trunk, but I find no evidence of this. These fragments weigh, respectively, 12.25, 11.34, and 7.26 kilograms.

A few days after visiting the locality on Black's ranch I was in Hot Springs, and purchased a number of fragments of cycads from a dealer named Homer Moore. Two of these which fitted together, forming a block weighing a little more than 7 kilograms, evidently belonged to a very large trunk, and these show a number of characters which agree with those of *C. Jenneyana*. In fact they very closely resemble the Stillwell fragment No. 1, so that whatever is done with the one must be done also with the other. Mr. Moore thought that these specimens came from the Minnekahta region, but was uncertain as to their source. They certainly differ specifically from any of the material from that region and agree substantially with most of that from Black's ranch. I shall therefore include them under *C. Jenneyana*.

I had in hand two small slabs belonging to the Woman's College of Baltimore, purchased by Mr. Arthur Bibbins for that college at the World's Columbian Exposition in Chicago and sent over along with the Bibbins collection from Maryland. Mr. Bibbins was informed when he purchased these fragments that they came from the Black Hills in America and that they were cut and polished in Germany. I can well believe this, as, so far as they go, they are substantially identical with the material from Black's ranch, and I am obliged to refer them to the present species. They contain none of the woody cylinder but are confined to the armor, of which they show a thickness of 3 to 5 cm. The exterior is obscure and closely resembles the Stillwell fragment No. 1, and the Homer Moore fragment, but the inner face is cut in a direction transverse to the leaf bases, which are beautifully shown, and also in the opposite direction showing the organs in longitudinal section. Fruiting axes are thus exposed, and much of the above description relating to the structure of these organs is derived from a study of these sections. I have no doubt that the other specimens when similarly cut, as they will be eventually, will furnish the same characters. In fact, they can now be indistinctly seen on a number of fractured surfaces.

These specimens bear the labels of the museum of the Woman's College, Nos. 1501 and 2128. The former weighs 532 grams and the latter 489 grams. They are exactly alike in all essential respects, and may well have belonged to the same trunk.

In the Yale collection there are 24 specimens that appear to belong to this species. These are Nos. 81, 87, 88, 90, 91, 93, 96, 97, 98, 101, 102, 108, 109, 111, 112, 113, 114, 115, 116, 120, 121, 124, 125, and 126. It will be observed that all but the first two of these came with the last two invoices and are from the Blackhawk region, the same from which the original type of the State School of Mines was obtained. The two reported from the Minnekahta region, Nos. 81 and 87, also belong to this species beyond a doubt. No. 81 consists of eight small fragments which all fit together and form an irregular segment from a large trunk similar to those belonging to the State School of Mines of South Dakota. Indeed, they might have belonged to the supposed missing portion of the tall trunk which those two pieces are believed to have so nearly constituted (see Pl. CXXV). The eight fragments together weigh 9.5 kilograms.

No. 87 also consists of a number (five) of small fragments that can be built up into a segment of a trunk, and all together weigh 7.6 kilograms; but these do not so closely resemble the type specimens. Still the characters they possess are those of this species. Professor Marsh thought that these specimens came from the Blackhawk locality, but Mr. Stillwell, from whom they were purchased, states that they were obtained 3 miles southwest of Minnekahta station. This agrees closely with the original locality. I am disposed to believe that there has been some mistake, and that these particular specimens are, after all, from the Blackhawk region.

Of the other 22 from the Blackhawk region Nos. 91, 113, 120, and 124 are somewhat doubtful. No. 91 has a large terminal bud 8 cm. high, elliptical in cross section and 15 by 20 cm. in diameter, studded with polygonal bract scars 5 to 8 mm. in diameter, filled with the bases of the bracts or small leaves matted together and exposed on the sides of the terminal bud, which have suffered from erosion (see Pl. CXXXI). I have not included this bud in the description of the species on account of doubts as to the true affinities of this specimen, which, if it belongs here, is the only one in which the bud is preserved. The surface is so badly worn that all the reliable characters are obscured, except that in general shape the specimen agrees with others of this species. The scars are large and the walls thick, which further confirm this supposition. No. 113 is also badly worn and metamorphosed, but probably belongs to this species. It is a fine trunk, nearly complete, 55 cm. high, and weighs 91.17 kilograms. No. 120 is an interesting specimen, and shows a great number of large fruits, which stand out, having resisted the deep erosion of the surface (see Pl. CXXXII). No. 124 is a mass of quartz and only a fragment, but in all probability came from a trunk of *C. Jenneyana.*

The rest of the specimens, though mostly fragments and segments from large trunks, are not doubtful, as they show surface characters in all cases which are distinctive. Several, however, are fine trunks. No. 101, though in three sections perfectly fitting together, is an almost complete trunk, laterally compressed, 97 cm. high, and weighs 183.71 kilograms, which is a little more than 1 kilogram heavier than both pieces of the type specimen from the State School of Mines of South Dakota. Unfortunately the surface is badly worn and the most important characters are obscured. No. 102 is the lower part (36 cm.) of the largest trunk of the species thus far known. It is nearly circular in cross section, has a diameter of 47 cm., and a girth of 156 cm. Its surface is also in a fair state of preservation (see Pls. CXXVII–CXXIX). No. 121 is a similar but much smaller basal portion. No. 115 is anomalous in many respects and might have been included among the doubtful cases. Though in two pieces it is nearly complete and weighs 87.77 kilograms, having a height of 60 cm. and a girth of 106 cm. Some of the leaf bases are horizontal, while others are strongly declined. The latter are all on one side below the middle, and in the case of certain abnormally small but strongly projecting leaf bases there is the additional peculiarity that they are converted into impure opal or blue quartz (see Pl. CXXX). No. 116 is also a fine, nearly complete trunk 49 cm. high, 42 by 36 cm. in diameter, 120 cm. in girth, and weighs 85.73 kilograms.

Pls. CXXI–CXXV illustrate the great trunks from the State School of Mines of South Dakota. Pls. CXXI and CXXII show the external surface of both trunks on the two opposite sides. Pl. CXXIII shows the true base and true summit, the latter somewhat decayed, forming a depression or "crow's nest." Pl. CXXIV gives a view of the two ends that would have matched each other had nothing been lost. In Pl. CXXV the two segments are placed as nearly as possible in the position in which they stood when living, with an estimated interval between them for the portions lost.

Pl. CXXVI represents the polished surface of No, 1501 of the Museum of the Woman's College of Baltimore and shows the characters above described for that specimen.

Pls. CXXVII–CXXXII represent the specimens of the Yale collection, Nos. 91, 102, 115, and 120, as mentioned above and as fully explained in the descriptions of the plates.

It will be seen from the above that 32 specimens have been referred to this species. Of these, 27, including all the larger trunks, were found with certainty in the Blackhawk region. Two were reported from the Minnekahta region and probably came from there. The source of the other three is uncertain.

CYCADEOIDEA INGENS n. sp.

Pls. CXXXIII–CXLIII.

Trunks large or colossal, ellipsoidal in form, thickest at the middle part, diminishing and more or less rounded off at both base and summit, slightly elliptical or nearly circular in cross section, unbranched or with a few small secondary axes in the form of protuberances, usually of a dark color, hard consistency, and high specific gravity, attaining a maximum height of 85 cm., girth of 170 cm., and weight of over 300 kilograms; organs of the armor slightly declined near the base, horizontal in the middle portion, ascending above, and erect at the apex, producing a large terminal bud consisting of the bases of somewhat flattened leaf-like bracts or scales; leaf scars arranged in two sets of rows passing spirally round the trunk, intersecting each other, and forming each a different angle with the axis, those passing from left to right forming an angle of about 35° to 45°, while those passing from right to left form an angle of 50° to 60°; scars large, 35 to 50 mm. wide, 20 to 35 mm. high, peculiar in shape, the lateral angles drawn out into sharp points by the incurving of the sides, the vertical consisting of mere curves, varying from this to simple gibbosity; leaf bases always present, filling the scars and often projecting, presenting either plane or slightly convex surfaces; vascular bundles in one row closely set together and very near the margin, and an irregular ring at the center inclosing an empty space; ramentaceous interspaces thin, 3 to 10 mm., scaly or laminated, sunk below the leaf bases, forming grooves on the surfaces of the trunk, often white in color, contrasting with other parts; reproductive organs abundant, especially in the upper part of the trunks, very different from the leaf bases, usually large, elliptical, 5 to 6 cm. wide by 3 to 4 cm. high, sometimes solid and projecting, but usually with an opening at the top or cavitous and crater-like, surrounded by numerous bract scars filled with the bases of the bracts, which are usually narrowly triangular or nearly flat; armor 5 to 10 cm. thick, more or less clearly marked off from the underlying tissues; cortical parenchyma 3 to 4 cm. thick; zone of secondary wood 4 cm.; medulla 10 to 20 cm. in diameter.

A perfectly well characterized species differing entirely from any of those based on specimens from the Minnekahta region. It is also very distinct from *C. Jenneyana*, which is the leading form of the Blackhawk region. Still, this species is also common there, and is represented in the collection by eight specimens, viz, Nos. 92, 94, 99, 100, 103, 117, 122, and 123. No. 100 is taken as the type and is the next largest cycadean trunk known in the world, weighing 303.91 kilograms. It slightly exceeds in height the U. S. National Museum type of *C. colossalis*, having a maximum length of 85 cm. Its diameters are respectively 62 cm. and 49 cm., and it has a girth of 170 cm. But, like all other specimens of this species, it diminishes in size toward each end and is somewhat barrel-shaped. Nos. 103 (see Pl. CXXXVI, CXXXVII) and 117 (see Pl. CXXXVIII, CXXXIX) represent the lower part of two other large trunks, and the summit is represented only in No. 100. No. 94 (see Pl. CXL, CXLI) comes next in point of interest in affording most of our knowledge of the internal structure of the species, including the markings on the medulla. No. 123 (see Pl. CXLII, CXLIII) is also instructive from this point of view. The rest are fragments, but all add to the complete conception of the species.

The form of the leaf scars is imitated very closely by two other species, one of which, *C. formosa*, is represented by only one specimen, No. 89. The other is *C. Stillwelli*, and this is made very clear by the new material added by the specimens last sent from the Blackhawk region by Mr. Wells, especially No. 105. In both these cases, however, the scars are much smaller, and this is particularly the case with *C. Stillwelli*.

The species is illustrated by Pls. CXXXIII–CXLIII, which have been commented upon in the foregoing remarks and are further fully explained in the descriptions of the plates.

All the specimens are from the Blackhawk region.

CYCADEOIDEA FORMOSA n. sp.

Pls. CXLIV-CXLVI.

Trunks of moderate size, short-conical, unbranched, dark brown, nearly black within, of average specific gravity, about 25 cm. high, nearly 30 cm. in diameter and having a girth of somewhat less than a meter; organs of the armor, even the lowest, somewhat ascending with a uniform angle; leaf scars arranged in two series of spiral rows, those of both series making an angle with the axis of about 50°; scars large for the size of the trunk, peculiar in shape, the lateral angles very sharp, the vertical ones very obtuse and rounded, the bounding sides usually curving downward and upward on the right and left, causing the scars to be drawn out laterally corresponding to wings of the petioles, lower side more pronounced than the upper in such a manner that a line joining the lateral angles divides the scar into unequal areas, varying to simply gibbous by the absence of the above-described curves; distance between lateral angles 25 to 30 mm., that between highest and lowest points 16 to 20 mm.; leaf bases always present, usually projecting somewhat, sometimes nearly 1 cm., outlines definite, conforming to shape of scars, exposed ends presenting surfaces that are exactly square or tangential to the trunk, never convex nor concave, smooth but not polished, covered by a diaphragm representing a natural plane of disarticulation, this layer, however, sometimes removed, in which case small projecting points are irregularly scattered over the surface of the leaf base; outer row of leaf bundles very close to the margin, faintly visible at the ends, more clearly as striæ on the eroded sides of projecting leaf bases; ramentum walls thin, 1 to 3 mm., thickening at the angles, sunk below the petioles and usually separated from them by a crack, dull colored, loose in structure and somewhat pitted, having the appearance of cracks filled with mud or extraneous matter; reproductive organs numerous and well marked, occurring at all points, but tending to an arrangement in vertical rows, one above another, with a trend different from that of either of the rows of leaf scars, projecting beyond the leaf bases to which they bear no resemblance, rounded or elliptical, 3 to 6 cm. in diameter, never cavitous, usually exhibiting concentrically arranged scars, the circular central portion inclosed in a tube surrounded by involucral bract scars occupied by the bases of the bracts which project in miniature imitation of the leaf bases, the central portion sometimes occupied by small cylindrical bodies or rods 1 mm. in diameter and 1 to 5 mm. long, consisting of nearly pure quartz; armor 5 cm. thick, definitely separated from the axis by a porous liber zone of appreciable thickness; cortical parenchyma 15 mm. thick; secondary wood 4 cm. thick, consisting of two distinct rings of about equal thickness separated by a peculiar scalloped line, apparently caused by the convex edges of woody wedges, 5 mm. thick, separated by thin medullary rays; medulla 9 cm. in diameter, somewhat heterogeneous or chambered in structure.

This species is represented by the single specimen No. 89 of the Yale collection. It has close affinities on the one hand with *C. ingens* and on the other with *C. Stillwelli*, while all these are related to *C. McBridei*, but it is impossible to refer it to any of these species.

Pl. CXLIV shows the side of the trunk with the peculiar shaped scars and two of the vertical rows of fruiting organs. Pl. CXLV shows the remarkable smooth base with its concentric structure. Pl. CXLVI is a view of the top where the thickness of the armor and other features appear to advantage.

The specimen is from the Blackhawk region.

CYCADEOIDEA STILLWELLI n. sp.

Pls. CXLVII-CLII.

Trunks small, cylindrical, or more or less laterally compressed, 30 to 40 cm. high, 15 to 25 cm. in diameter, 40 to 70 cm. in girth, reddish or light colored externally, cherty, flinty, or more or less agatized within, simple, or bearing a few small branches in the form of projections or protuberances, short-conical at the summit, with a natural depression at the apex studded with small polygonal scars and a gentle swelling at the center; organs of the armor nearly horizontal; leaf scars arranged in two series of spiral rows, those from left to right making an angle of 40° to 50°, those from right to left of 30° to 50° with the axis of the trunk; leaf scars normally almost exactly rhombic or diamond-shaped, but with a tendency on the one hand to the rounding of the vertical angles and on the other to the incurving of the sides so as to exaggerate the acuteness of the lateral ones, this sometimes very marked; scars small, 20 to 25 mm. wide, 15 to 20 mm. high, occasionally almost as high as wide, the lateral diagonals about horizontal and the vertical ones perpendicular to them or vertical; leaf bases always present, filling the scars, often projecting, sometimes considerably, the petioles disarticulating at several different points by means of a diaphragm which forms a thin layer over the exposed summits, the occasional absence of which leaves a rough, spongy or porous structure; vascular bundles arranged in two rows, one near the margin and parallel to it, the other forming an elliptical ring at the center 3 by 4 mm. in diameter, both rows usually appearing in the form of denticulate ridges; ramentaceous walls very thin, 1 to 2 mm., often sharp at the surface, generally sunk below the leaf bases, forming grooves or deep channels between them, the surface therefore consisting chiefly of the latter, in the more abnormal forms of scar describing a double curvature and having somewhat the shape of a "line of beauty" in penmanship or one of the parts of a Buddhist cross or "swastika," sometimes, however, projecting so as to leave a groove around the outer edge of the convex summits of the leaf bases; reproductive organs few, more numerous on the narrower sides of the trunk, disposed somewhat in rows or chains, generally parallel to the axis but sometimes running round the trunk, more or less contiguous, consisting of protuberances, some rising above the highest leaf bases, closed, or more commonly open at the top, sometimes crater-like but generally truncated, presenting an irregular surface with numerous pits or pores at the center surrounded by bract scars which are sometimes empty, but usually occupied by the bases of narrowly triangular or flattish bracts projecting and squarely truncated with thin interspaces in miniature imitation of the leaf bases; armor much thicker on the narrower than on the broader sides of the trunk, 3 to 6 cm. thick in the former and 2 to 3 cm. in the latter case, clearly and definitely marked off from the woody axis by a cambium line; cortical parenchyma 15 to 20 mm. thick; secondary wood zone 10 to 20 mm., very fine grained and clearly marked off from the last; medulla somewhat elliptical, 5 to 8 cm. in diameter, marked on its external surface by rows of small rhombic projections of a dark color terminating small longitudinal ridges representing the origin of the medullary rays.

The small cylindrical section of a trunk acquired through Professor Jenney's intervention from Mr. L. W. Stillwell, of Deadwood, exhibited so many good characters, all different from those of any other specimen in the U. S. National Museum collection, that before I had seen the Yale collection—in fact, long before it was made—I had described it as a new species and named it for Mr. Stillwell. It was reported to have been found in the Blackhawk region, and there is every reason to believe that such was the case.

The Yale collection contains six specimens of this species, each of which adds something to our knowledge of it. These are Nos. 16, 36, 56, 105, 107, and 119. The first three of these purport to come from the Minnekahta region, while the others are certainly from the Blackhawk region. The first of these is somewhat smaller than the type and has near its summit two small branches. The leaf scars are normal and confirm my suspicion that the peculiar form which they have in the original specimen is due to lateral compression. It weighs nearly 5 kilograms. No. 36 represents the upper part of a trunk of exactly the same diameter as the Stillwell specimen, but with the outer parts all worn away. The summit, however, is perfect. The transverse fracture has supplied a number of otherwise missing or imperfect characters. This specimen weighs 8.17 kilograms. No. 56 is larger and entire from base to summit, but broken in two near the middle. It is very elliptical in cross section from lateral compression, badly worn like the others, and has a slab scaled off from one side, exposing the outer surface of the medulla and corresponding inner wall of the woody zone. This specimen is 39 cm. high, 15 by 20 cm. in diameter, and has a girth of 54 cm. Its ellipticity is, however, exaggerated by the greater erosion of the flat sides. It weighs 12.7 kilograms.

No. 105 is only a section weighing 12.8 kilograms, with base and summit wanting, also a piece from one side, part of which was saved, but the part that remains shows the outer surface in the most perfect state of preservation, and much of the above description of the phyllotaxy, leaf scars, petioles, vascular bundles, ramentum walls, etc., is derived from it. No. 107 is also an exceedingly interesting specimen, weighing 9.07 kilograms, and is especially valuable as showing the true base. It is obliquely broken through from the top to near the bottom, but one side shows the spiral rows of leaf scars. No. 119, although larger, weighing 14.29 kilograms, is not as well preserved, but also shows the base, which is slightly concave.

Upon the whole, this species may be regarded as one of the best characterized of all that have been based on cycadean trunks alone.

Pl. CXLVII shows the best side of the original Stillwell type with its peculiar scars. Pl. CXLVIII gives views of No. 36 of the Yale collection seen from its best side (Fig. 1) and from the transverse fracture (Fig. 2). In the latter the ring of exogenous tissue can be distinctly seen. Pl. CXLIX shows trunk No. 56 of the Yale collection to good advantage, including the exposed medulla. The small piece on the lower left fits into the upper part of the fracture. It is here turned round so as to exhibit the counterpart of the medulla as impressed on the inner wall of the woody zone. Pl. CL shows at Fig. 1 the most perfect side of No. 105, the regularity of whose scars is scarcely exceeded by any known cycadean trunk. Fig. 2 of the same plate shows the side opposite, on which the leaf bases project to unequal distances above the surface. Pl. CXLI gives two views of No. 107, the peculiar shape of which is described above. Fig. 1 represents the narrow portion between the oblique even base and the plane fractured surface parallel with it. It is over this area that the arrangement of the scars is most definite. Fig. 2 is a good view of the base, but also takes in the broadest side of the inclined trunk above. Pl. CLII shows a side (Fig. 1) and a base (Fig. 2) view of No. 119. The latter is perhaps the best exposure of the base that we have.

CYCADEOIDEA EXCELSA n. sp.

Pls. CLIII–CLV.

Trunks tall, compressed-cylindrical (only specimen known 91 cm. high and truncated) with an enlarged base, 112 cm. in circumference at the base, 80 to 90 cm. at all other points, light ash colored without, whitish or bluish within, soft externally, fine-grained inside and moderately hard, with the specific gravity rather low, unbranched but more or less irregular, crooked, zigzag, and inclined; organs of the armor horizontal, or at right angles to the axis; leaf scars disposed in two series of spiral intersecting rows, those from left to right making an angle of 20°, those from right to left of 50° with the axis; scars imperfectly rhombic or rectangular, the diagonals 16 to 25 mm., the lateral angles nearly alike, the vertical ones usually unlike, the upper consisting of a deep but obtuse sinus, the lower also obtuse but relatively shallow, sometimes reduced to a gentle concave curve formed by the two lower sides; leaf bases generally preserved to within 2 cm. of the surface, disarticulated at a natural joint, their surfaces even and concave but roughened and affected by many small dots of a dark color, irregularly arranged, perhaps representing gum ducts, and some large pits which may have contained leaf bundles; ramentaceous walls thin and frail, 1 to 2 mm., of a light color within, contrasting with the darker leaf bases, thickened at the angles and more or less compound, with a few small pits representing scars of bracts or perulæ; reproductive organs numerous, usually solid, harder than the remaining parts, hence often projecting from the eroded surfaces, of different sizes, the smaller ones probably abortive and occupying angular spaces among the leaves, the walls dividing and surrounding them, circular in section, with or without bract scars, the larger ones lying in interrupted rows running in the same direction as those of the scars which they crowd and distort, elliptical in section, the longer diameter being along the line of the rows, 25 by 38 mm. in diameter, usually solid except their roughened extremities, sometimes open or crater-like at the summit, a few solid and cylindrical (one of which has been detached and will be sliced for microscopic sections); armor 4 to 7 cm. thick, separated from the axis by an even line; parenchymatous zone 2 cm. thick; fibrous zone 3 cm., divided into three rings, one of which exhibits in places a somewhat open structure, crossed by thin medullary rays and inclosed between walls or sheaths of harder material; medulla 13 cm. in diameter and nearly circular, solid, fine-grained, and homogeneous in structure.

The fine specimen upon which the above description is wholly based was purchased by me from Mr. Homer Moore, at Hot Springs, South Dakota, on August 22, 1895, together with the two fragments above described belonging to *C. Jenneyana*. It consists of four pieces which belong together and form a very remarkable trunk, differing greatly from any other from the Black Hills or from any other section.

I inquired carefully into the history of these specimens and learned that some years before they had been found by a railroad employee named A. B. Noble, who was no longer in that region, some 2 miles below Hot Springs in a canyon or ravine which makes into Fall River from the northeast. No further details could be gathered, but as it is 4 miles to Evans quarry, where the true Dakota group is exposed, it is certain that the horizon must be in the Lower Cretaceous, and it is probably substantially the same as that of all the other trunks.

The four pieces or sections which have been numbered from 1 to 4, beginning with the basal one, may be briefly described as follows:

No. 1, which is considerably the largest in all respects, represents the true base and swells out below to a diameter of over 40 cm. and a girth of nearly 112 cm. It is slightly elliptical, the minor axis of a cross section being only 33 cm., but part of this difference is due to the erosion of the armor on the broader sides.

No. 2 is a shorter and smaller piece, but fits perfectly upon the upper fracture of No. 1, which is somewhat oblique. On one side a large elliptical area has decayed, forming a depression which reaches to the bottom of the leaf stalks. This depression is about equally divided between Nos. 1 and 2.

No. 3 is a much shorter piece, the upper fracture of which is very oblique, so as to make it almost wedge shaped. The upper surface of No. 2 and the lower surface of No. 3 do not form a perfect joint. A thin slice or a number of such pieces have apparently scaled off and are wanting. There is, however, abundant evidence of the general agreement of the two sections, and one decayed area extends across the break and reappears on No. 3.

No. 4, which is the uppermost section, fits perfectly upon No. 3. The fracture across the top is oblique in the opposite direction from that of the lower end, thus increasing the cuneiformity of both sections. When superposed upon each other these two upper sections form a sort of crook or bend in the trunk, so that the center of gravity falls considerably on one side and the upper piece falls off unless supported.

The trunk has evidently long lain on one side or the other as determined by the above-mentioned crook or bend and been subject to much erosion on the two exposed sides, while the other two sides have correspondingly escaped. The result is that the leaf scars are deeply worn over much of the surface, while along the protected sides they are preserved or only irregularly broken down, leaving what look like jagged projections.

The weight of the several pieces is as follows:

	Kilograms.
No. 1	50.80
No. 2	21.32
No. 3	17.02
No. 4	18.37
Total weight	107.51

Nothing at all approaching this species was found in the Yale collection.

This species is illustrated by three plates. One side of the specimen is better preserved than the other, and I have given views of both on Pl. CLIII and CLIV, the first of which shows the trunk leaning to the left and the second to the right. Pl. CLV affords a good view of the base.

CYCADEOIDEA NANA n. sp.

Pls. CLVI, CLVII.

Trunks very small, symmetrical, short-conical, laterally subcompressed, 12 cm. high, 15 by 17 cm. in diameter, 49 cm. in girth, dark colored, well silicified, of medium hardness and specific gravity, unbranched, summit not depressed, terminal bud projecting from apex;

leaf bases ascending, even the lowest ones, scars arranged in two series of spiral rows, those from left to right making an angle of 80° and those from right to left of 50° with the axis, very small, subrhombic, averaging 10 mm. wide by 6 mm. high, smaller near the summit, empty to considerable depth; ramentaceous interstices 1 to 3 mm. thick, firm in texture, usually consisting of three layers, which may be regarded as a lining to each of the adjacent scars, with a thicker membrane between; reproductive organs few, poorly defined, slightly projecting, with irregular markings on their outer surfaces, probably for the most part immature or abortive; armor 3 to 5 cm. thick; axis 8 cm. in diameter, somewhat clearly marked off from the armor but without clear boundaries between the cortical parenchyma and fibrous zone or between the latter and the medulla, so far as the single known specimen shows without cutting.

This species differs from all others in a number of characters besides its small size.

The only specimen is No. 84 of the Yale collection, a small, almost perfect trunk, weighing only 2.95 kilograms. At first glance it recalled the *C. pygmæa* of England, from the Lias of Lyme Regis, figured by Lindley and Hutton in the Fossil Flora of Great Britain, Vol. II, pl. cxliii, but on confronting the specimen with that figure the differences are obvious. Except for its small size it might be compared to *C. marylandica*, from the iron-ore clays of Maryland, and of all the specimens of that species it most resembles the fragment which Professor Fontaine designated as No. 2,[1] and which I have described as Johns Hopkins Cycads, No. 3.[2] That specimen, however, has a large secondary axis, which, with better material, might take it out of that species.

Of all the forms from the Black Hills, it most resembles in the character of the scars, etc., some of the smaller branches of *C. Marshiana*, in which these are considerably reduced in size. I have therefore had a faint suspicion, which I would not leave the subject without expressing, that it might be one of these secondary axes or knots, as it were, wrenched from the larger trunk and found in an isolated position. With this thought in my mind I have examined a great many such cases, but I can find none in which the fracture at the point of separation at all resembled the base of this specimen, they all showing the break to have been due to some extraneous cause, whereas the base of this specimen is perfectly natural, not torn nor cracked, and shows the medulla at the center. Nevertheless, there is something a little anomalous in the way the armor surrounds the axis.

The specimen is nearly uniform on all sides, as shown by the two figures of Pl. CLVI, which afford side views of two of the sides. Pl. CLVII is a view of the base, which shows no depression, but simply

[1] Potomac or Younger Mesozoic Flora. Monogr. U. S. Geol. Surv., Vol. XV, 1890, p. 192.
[2] Proc. Biol. Soc. Washington, Vol. XI, March 13, 1897, p. 11.

a convex surface with the medulla near the center, and elongated leaf scars ascending in all directions from it.

The above arrangement of the species of Cycadeoidea from the Black Hills is not wholly without method. It is true that there is no lineal arrangement that can be regarded as satisfactory, and yet there are decided affinities among the species. These affinities, however, are shown in particular characters, and the same species may have some characters almost in common with two or more other species that are otherwise very different. This is specially the case with branching species in which other characters resemble those of unbranched species. For example, *C. turrita*, except in its branching habit, is closely allied to *C. McBridei*, which never branches; *C. Marshiana*, but for its branching, would be nearly related to *C. colossalis;* and *C. Wellsii* may be almost regarded as an unbranched form of *C. minnekahtensis*.

In view of these and many other more subtle peculiarities, I have sought, since the arrangement must be lineal, to compromise in such a manner as to bring those species most akin as near together as possible, but it is clear that any arrangement would widely separate species that are similar in one respect or another.

C. dacotensis and *C. colossalis* are obviously very closely allied species. *C. Wellsii* can scarcely be said to form a transition from *C. colossalis* to *C. minnekahtensis*, but it resembles the former at least in the one fact of being simple. *C. pulcherrima* is somewhat close to *C. minnekahtensis*. *C. cicatricula* can not be said to form a transition from *C. pulcherrima* to *C. turrita*, but it has considerable affinity to the former. *C. turrita* is related to *C. minnekahtensis* and *C. pulcherrima*, and from it to *C. McBridei*, as already remarked, the distance would be very small but for the branching habit of the former.

Between *C. McBridei* and *C. Marshiana*, however, there is scarcely any bond, and it might have been as well to place the latter immediately after *C. colossalis*. We virtually begin a new series here and pass naturally through *C. furcata* to *C. Colei* and *C. Paynei*. *C. Wielandi* has so much affinity to *C. Paynei* that it was first placed in that species. *C. aspera* also closely resembles *C. Paynei* in external aspect, but the two anomalous characters noted clearly distinguish it from all others. It fits in here, however, and *C. insolita* and *C. occidentalis* belong to this same general group.

C. Jenneyana, *C. ingens*, *C. formosa*, *C. Stillwelli*, and *C. excelsa* may also be said to form a group. The first and the last two constitute the only cylindrical forms known in America. The shape of the scars in *C. ingens*, *C. formosa*, and *C. Stillwelli* unite these three from that important point of view, while those of *C. Jenneyana* and *C. ingens* tend to approach each other. *C. excelsa* has little in common with any other species, and *C. nana* almost nothing. These two are therefore properly made to close the series.

2. THE FOSSIL FORESTS.

In the historical introduction to this paper (p. 529), and again in the chapter on the Minnekahta region (p. 552), the remarkable fossil forests of that section of the Black Hills were unavoidably discussed. In the chapter on the Blackhawk region (p. 562) the occurrence of silicified wood in great abundance was noted. Professor Jenney, in his very full treatment of the Hay Creek region, lays proper stress on the great quantities of fossil wood at many of the localities and horizons where he worked. It is much to be regretted that this important department of the present section on the Flora of the Black Hills could not have received full treatment. This deficiency is not due to any lack of material for such a treatment, but almost wholly to the special difficulties attending the elaboration of this class of material. A good collection was made from the original forest, some of the specimens being broken from the great fossil log described, others picked up among the branches. A short distance northwest of this spot wood was also very abundant, and many specimens were taken. This wood usually has the outward appearance of showing the internal structure well, and two of the most promising specimens were cut and microscopic slides mounted for determination; but when these were examined by Dr. F. H. Knowlton with the compound microscope they were found to be too obscure to show any characters. It is evident that a large number of specimens will have to be examined before one is found that will yield the desired results. This there has not been time to do, and Dr. Knowlton has been too much occupied with other pressing work to undertake such a systematic study of this material as will be necessary to test its value.

A fine collection of silicified wood was made from the Blackhawk region, partly from the particular spot where Mr. Getchell told us the cycad trunks lay and partly from the general vicinity, particularly from a locality half a mile east of the ranch house. As showing how deceptive a microscopic examination of such material often is, I may add that by far the finest looking specimen found in this region, in which the grains of the wood are seen with great distinctness, was cut in all necessary directions and slides were made from it, in full confidence that they would clearly indicate the nature of the timber of that region in Lower Cretaceous time, but to our great disappointment no detailed structure was revealed.

Professor Jenney collected a considerable amount of fossil wood at a number of horizons in the Hay Creek region, but none of it looked promising, and after so many failures with much better appearing material it was not thought worth while to attempt its study, although it is quite possible that some of it may prove much better than it looks.

While our party were gathering up the fragments of cycads on the slope where so many fine trunks were found, a peculiar block attracted the attention of Mrs. Jenney, who brought it to my notice. I first thought it might be the internal portion of a cycadean trunk, but upon examination I was convinced that it was a piece of silicified wood. It was thrown into the wagon with the rest and shipped to Washington. No other fossil wood was seen by me at the cycad locality. Coming as it did from the very same spot as the cycads, its importance was greatly increased, and at my request Dr. Knowlton took it up, marked it for sectioning, and had some slides made. To our great delight it was found to be in an admirable state of preservation and perfectly determinable. It belongs to the genus Araucarioxylon—i. e., it is the ancient representative of the Araucarian pines of the Southern Hemisphere, which have long since disappeared from all our Western forests.

Dr. Knowlton furnished me a brief report upon this species for my early paper, and, although he has now described and figured it thoroughly, it will be of interest to reproduce his original and less technical account of it as follows:

The structure of this wood is very finely preserved, and a glance suffices to show that it possesses the Araucarian type and represents, with little question, an undescribed species of the genus Araucarioxylon. The wood cells are provided with two rows of alternating hexagonal pores on the radial walls, which nearly or, in some cases, quite cover the walls. The medullary rays are composed of a single layer of thin, short, cells, each of which is covered on the radial side with numerous fine dots or punctations. The rays are from 1 to about 20 cells high, the average number being perhaps 8 or 10. A large number are composed of only 1 or 2 cells. The annual rings are rather indistinct, yet can be made out.

As far as I now know, only two species of Araucarioxylon have been described from the United States, *A. arizonicum* Kn., from the Triassic or Lower Jurassic of New Mexico and Arizona, and *A. virginianum* Kn., supposed at first to belong to the Potomac formation, but now known to be from the Trias of Virginia. These species differ markedly from the one under discussion. With the *A. arizonicum* it has almost no points in common, while it differs from the *A. virginianum* in important particulars.

To this I added the following comment:

The only sections of the fossil wood that have yet been made were cut from a specimen taken from the cycad bed proper, and not from the principal fossil forest, but it often happens that only one species can be found in such a forest. It is therefore probable that the same structure would be shown by the other specimens. I confess to a little surprise at finding that this structure represents the Araucarian rather than the Sequoian type of conifers, since, in the East at least, these two types characterize the Trias and Potomac, respectively, no Araucarian specimens having been found in the Potomac and no Sequoian specimens in the Trias. And generally the Araucarian type is more ancient. This evidence therefore points to a lower instead of a higher horizon.[1]

[1] Jour. Geol., Vol. II, No. 3, April-May, 1894, pp. 260-261.

The following is Dr. Knowlton's revised description of the species:

SUBKINGDOM SPERMATOPHYTA (Phanerogams).

Subdivision GYMNOSPERMAE.

Class CONIFERÆ.

Family PINACEÆ (ARAUCARIACEÆ) Engler.

Genus ARAUCARIOXYLON Kraus (1870).

ARAUCARIOXYLON HOPPERTONÆ Knowlton n. sp.

Pls. CLVIII, CLIX.

1894. *Araucarioxylon* sp. Kn. in Ward: The Cretaceous rim of the Black Hills; Jour. Geol., Vol. II, pp. 260–261.

Diagnosis.—Annual rings very distinct, or 4 to 8 rows of very thick-walled fall wood; spring wood of large but thick-walled cells; medullary rays in a single series of from 3 to 12 or 15 cells; these short, covering the width of some 4 to 6 or 8 wood cells, provided with a single series of small punctations; wood cells with 1 or 2 rows of hexagonal or rarely nearly round punctations.

Discussion.—Transverse section: This section shows the annual rings to have been very plainly maiked. The spring wood is made up of very large although thick-walled cells, which begin very abruptly at the fall wood. The cells gradually decrease in size until the last 5 or 8 rows of cells are very thick.

Tangential section: The medullary rays as seen in this section are quite numerous, in a single series of from 3 to sometimes as many as 15 superimposed cells. The wood cells as seen in this section do not seem to have been provided with punctations or other markings (Pl. CLIX, Fig. 3).

Radial section: As the material has been very finely preserved, this section shows remarkably well. The wide cells of the spring wood are provided with usually 2 longitudinal rows of hexagonal pores, which quite cover the walls (Pl. CLVIII, Fig. 1). Occasionally in cells of unusual width the pores while in 2 series are only slightly compressed (Pl. CLIX, Fig. 4). Usually when but 1 row is present they are hexagonal and occupy the center of the cell (Pl. CLVIII, Fig. 2).

The inner pores in these punctations are relatively small and slightly elongated in a direction at right angles to the cells.

The medullary rays as seen in this section (Pl. CLVIII, Fig. 4) are short, covering the width usually of 4 or 5 wood cells, although occasionally longer and covering as many as 8 cells. They are provided with a single row of small bordered pores so arranged that one comes over each wood cell, or occasionally there may be two over a wood cell (Pl. CLIX, Fig. 1). The inner pore is minute.

This is the third species of Araucarioxylon thus far described from the United States, and it is quite unlike either of the others. From *A. arizonicum* Kn.,[1] a species found in the Triassic or Lower Jurassic, it differs in having a clearly marked annual ring, usually hexagonal pores and no markings in the tangential walls of the wood cells. From *A. virginianum* Kn.,[2] a species of the Trias of Virginia, it differs in the annual rings, in the less number of medullary ray cells, and in having the cells of the ray short punctate.

At Professor Ward's suggestion I take pleasure in naming this very distinct species in honor of Mrs. Jenney, who discovered this block of wood among the fragments of cycadean trunks.

Locality.—Cycad bed 2 miles southwest of Minnekahta Station, South Dakota. Collected by Mrs. Mary Hopperton Jenney, September 7, 1892.

3. LOWER CRETACEOUS FLORA OF THE BLACK HILLS, OTHER THAN CYCADEAN TRUNKS AND SILICIFIED WOOD.

As already shown, the principal contribution to the Lower Cretaceous flora of the Black Hills was made by Prof. Walter P. Jenney in 1895 from the Hay Creek coal field of Crook County, Wyoming. The present chapter therefore consists chiefly of Professor Fontaine's report upon this collection. The only other forms included in it are the few that were collected by Professor Jenney and myself on the western slope of Red Canyon, about 3 miles southwest of Minnekahta station, half a mile southwest of Matties Peak, and immediately over the ridge to the west of the principal fossil forest. These were also determined by Professor Fontaine and reported upon in a letter dated January 10, 1894, which report was embodied almost entire in my paper on the Cretaceous Rim of the Black Hills.[3] His remarks on the species will be introduced in their systematic place.

Professor Fontaine's report on the Jenney collection from the Hay Creek coal field is as follows:[4]

NOTES ON LOWER CRETACEOUS PLANTS FROM THE HAY CREEK COAL FIELD, CROOK COUNTY, WYOMING.

By WM. M. FONTAINE.

In the summer of 1894, Prof. W. P. Jenney collected a considerable number of fossil plants in Wyoming, and sent them to Mr. Lester F. Ward, who referred them to me for examination.

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[1] Proc. U. S. Nat. Mus., Vol. XI, p. 4, pl. i.

[2] Bull. U. S. Geol. Surv. No. 56, p. 50, pl. vii, figs. 2-5.

[3] Journal of Geology, Vol. II, No. 3, Chicago, April-May, 1894, pp. 259-260.

[4] The only modifications that it has been found necessary to make in this report relate to the purely systematic part. Mr. Seward in his Wealden Flora has made a careful revision of the principal Wealden genera and has changed many of the names, substituting modern ones for the older Carboniferous genera to which the species had been improperly referred. In most such cases I have adopted his suggestions, but have introduced full synonymy, so that no possible confusion can arise.

Professor Fontaine simply described the species and arranged them in a general way under the heads Equiseta, Ferns, Cycads, Conifers, etc. I have changed his arrangement very little, and only to make it conform as nearly as possible to the system of Engler and Prantl. The higher subdivisions have been supplied by me. I am also responsible for all the footnotes.—L. F. W.

Professor Jenney in the same summer wrote a number of letters to Mr. Ward, giving the localities and horizons of the fossils, along with other points necessary to throw light on their occurrence. In order to give an intelligible account of these fossils it will be necessary for me to quote from these letters. As Professor Jenney states that his subdivisions of the formation containing the fossils are subject to change if called for by further field study, this qualification must be borne in mind.

Professor Jenney made his collections of plant fossils in the Hay Creek coal field of Crook County, Wyoming, a region located 40 miles northwest of Deadwood, South Dakota. A number of his localities are found on Pine Creek and Oak Creek. In one of his letters he says regarding these creeks: "Pine Creek and Oak Creek are two small streams entering the Belle Fourche, draining the area between that river and Hay Creek, and are part of the Hay Creek coal field of which Barrett post-office is the center." This statement, with the data given for each locality where plants were collected, will fix their position with sufficient accuracy. Before the examination made by Professor Jenney of this region, Newton's Dakota group was supposed to extend down to and rest upon the Jurassic. Professor Jenney, as the result of his field work, and influenced by geological data alone, was led to subdivide the Dakota of Newton into several horizons. These will be given later.

Mr. Ward, on examining the plants, recognized their striking resemblance to Lower Potomac and Kootanie plants. As I had studied the former, he sent Professor Jenney's plants to me for determination. Professor Jenney, on stratigraphical and lithological grounds, was led to make the following provisional subdivisions of the Dakota group of Newton, as exhibited in the Hay Creek region of Wyoming. I quote from his letter to Mr. Ward:

THE DAKOTA GROUP OF NEWTON.

Upper surface probably somewhat eroded, overlain by Fort Benton shales.

	Feet.
1. The Dakota sandstone, with characteristic plant remains, the base a massive sandstone of variable character with respect to hardness, per cent of iron, etc	100
2. Clay shales, sandstone shales, and soft sandstones, with, locally, beds of carbonaceous shale and plant remains. Plants of modern type. * * * At base of this member a massive cross-bedded sandstone 50 feet in thickness.	150
Contact stratum, a breccia of clay and sandstone, marking unconformity.	
3. Massive sandstone, 40 feet, underlain by drab clay shales and carbonaceous shales with plant remains (ferns, etc.)	100
4. Soft sandstones, clay shales, and clays, with one workable seam (3 to 5 feet thick) and several smaller local seams of coal. Plant remains, peculiar forms of cycad life, etc	100
5. Ash-colored clays with calcareous nodules, no fossils observed; near top, at contact with No. 4, occur, locally, fossil bones	50
(This member may be Jurassic.)	
6. Jurassic clays and shell limestone, with marine fossils, Belemnites, Ostrea, Exogyra, etc.	

Professor Jenney, in another letter, states that his later investigations led him to conclude that No. 5 of the preceding section is composed of Jurassic shallow-water deposits, and that they are not Lower Cretaceous. He says the beds carry often large trunks and limbs of fossil wood, and, in the layers of impure limestone, a few small Ammonites, but near the top of No. 5, just below the contact with the base of No. 4 Cretaceous, occurs a bone-bearing bed with large elongated vertebræ and fragments of leg and thigh bones, all in a poor state of preservation.

He goes on to say that there are evidences that the land was rising at the close of the Jurassic, that some of the beds of No. 5 may be of brackish- or fresh-water origin, and before the deposition of the lowest beds of the coal series (those of division No. 4) the land was above water and had suffered quite an extensive denudation. The evidence also indicates that the workable and lowest beds of coal were deposited in basins, channels, or valleys in the eroded Jurassic.

Professor Jenney states that he found in the Dakota group of Newton evidences of unconformity between No. 1 and No. 2, and between No. 2 and No. 3, but was unable to find any between No. 3 and No. 4, while there is great unconformity between No. 4 and the Jurassic.

These extracts from Professor Jenney's letters show that, from stratigraphical evidence, the Dakota group of Newton, which has hitherto been supposed to contain no strata older than the typical Dakota with dicotyledons, and to extend as a unit down to the Jurassic, is really divided by two marked unconformities into at least three members. The strata of division No. 1 contain the dicotyledons of the typical Dakota, while those of No. 2 and the lower divisions do not show these, but a quite different flora, whose age will be discussed in this paper.

If Professor Jenney is right, as he no doubt is, in his conclusion that the land rose after the Jurassic submersion, and then, after an interval, vegetation established itself on it finally in amounts sufficient to form coal beds, it follows that even the oldest of the plants described in this paper are decidedly younger than Jurassic. Here we have a flora that established itself after the retreat of the Jurassic sea. But in the case of plants in the Trinity group of Texas, as Professor Hill shows, we have a different condition of things, for the sea advanced upon the land, finding an established flora, whose remains it swept away and preserved in the beds then formed. The same is true of the Lower Potomac fossil plants of Virginia. In the case of these two groups of fossil plants, the *geological* conditions do not indicate positively that they are younger than Jurassic, for we may have the remains of a Jurassic flora preserved in the lowest beds of the Lower Cretaceous. Professor Jenney's discovery of fossil plants is especially fortunate in the fact that, according to the stratigraphy, they are clearly and distinctly younger than the Jurassic, for they are found in strata that rest upon Jurassic beds, and in addition an erosion interval separates the two. When we take into consideration the want of conformity of the Jurassic and these Lower Cretaceous beds, as well as the lapse of time required for a flora to establish itself on the land newly emerged from the Jurassic sea, it is surprising to find so many Jurassic types surviving in this lower division of the Lower Cretaceous.

As Professor Jenney collected his plants from several horizons, and at different localities, it will be necessary, before passing to the description of the species, to give some account of the geological horizon of the different localities from which the plants were obtained. The following statements give the localities from which plant fossils were obtained, with their position in the Lower Cretaceous group, as given by Professor Jenney on labels accompanying each package of fossils. It will be noted that he fixes their geological position by referring the horizon in some cases to the Jurassic below, and in others to the typical Dakota sandstone above, with dicotyledons as the predominant plants. This latter will be mentioned simply as the Dakota sandstone.

Professor Jenney determines the following localities as lying 60 feet below the base of the Dakota sandstone:

1. Bed of carbonaceous shales in a cliff in the east bank of Oak Creek, 2 miles below Robbin's ranch, Crook County, Wyoming. This horizon is in his division No. 2 of Newton's Dakota group, which is the uppermost of the divisions made by Professor Jenney of the strata underlying the typical Dakota. This horizon is the highest in division 2 which has yielded fossil plants. In the description of the species it will be referred to as Cliff in east bank of Oak Creek.

2. Cliffs along the north side of Red Water Valley, about 4 miles south of Larrabee's coal mine. These localities will be designated Cliff along the north side of Red Water Valley.

3. The next lower horizon at which plant fossils were found is located by Professor Jenney at 100 feet below the base of the Dakota sandstone. On this horizon, and still in division No. 2, plants were found at a cliff on north side of Pine Creek, 2 miles above (west of) Mrs. Dorsett's ranch. This will be referred to as Cliff on north side of Pine Creek.

4. Cliff on the south side of Pine Creek, 2½ miles above (west of) Mrs. Dorsett's ranch. This will be referred to as Cliff on the south side of Pine Creek.

5. Bed of carbonaceous shales in Rollin's tunnel, 1½ miles southeast of Robbin's ranch, on Oak Creek. This will be referred to as Carbonaceous shales in Rollin's tunnel.

6. Cliff on Oak Creek at Robbin's ranch, 6 miles northeast of Barrett, Wyoming. This will be designated as Cliff on Oak Creek, at Robbin's ranch.

The following localities, lying in Professor Jenney's third division of Newton's Dakota, were located by him about 150 feet above the top of the Jurassic, and about 170 feet below the base of the typical Dakota, or his division No. 1:

1. Bed of shales in cliff on the north side of the valley of the South Fork of Hay Creek, 2½ miles west of Barrett post-office, Crook County, Wyoming. This locality will be designated as Cliff on the north side of the valley of the South Fork of Hay Creek.

2. Bed of shales under the third sandstone, Barrett, Wyoming. This locality was not given so precisely as some of the others, and it will be referred to as Shales under the third sandstone, Barrett.

3. From John Barr's tunnel, 1 mile north of Forks of Hay Creek post-office, Crook County, Wyoming. This will be designated as John Barr's tunnel.

4. Locality not given. The package of fossils was marked simply as coming from the third division of Newton's Dakota group, 150 feet above the top of the Jurassic. The locality is probably the same as No. 2 of this list, and it will be referred to as Locality unknown. Horizon 150 feet above the Jurassic.

The next horizons in descending, at which fossils were found, according to Professor Jenney, occur in his division No. 4, of Newton's Dakota group, and they are probably essentially the same, but from the distances given by Professor Jenney for them above the Jurassic, there is some variation in their height above that formation. This variation, however, is not greater than might be expected from varying thickness in the beds underlying them, which are superposed immediately on the Jurassic. I give the localities and the distances determined by Professor Jenney at each, from the plant-bearing bed down to the Jurassic:

1. Shale over the lowest coal bed, Larrabee's shaft, Barrett, Crook County, Wyoming. This stands from 50 to 75 feet above the top of the Jurassic, and the locality will be referred to as Shale over the lowest coal, Larrabee's shaft.

2. Bed of shales over coal, T. 54, R. 61, sec. 36, 2 miles southeast of Barrett, Crook County, Wyoming, about 30 to 50 feet above the top of the Jurassic. This will be referred to as Shales over coal, 2 miles southeast of Barrett.

3. Bed of highly carbonaceous shale 50 feet above the top of the Jurassic, Webster's ranch, 4 miles northeast of Beulah, Crook County, Wyoming. This will be referred to as Carbonaceous shale, Webster's ranch.

4. The lowest horizon in No. 4 that promised fossil plants is a bed of shales at the contact of the Cretaceous with the Jurassic, at Lon Cottle's ranch, 1 mile southwest of Barrett, Crook County, Wyoming. This bed of shales is the lowest bed in division 4. The locality will be referred to as Bed of shales, Lon Cottle's ranch.

DESCRIPTIONS OF THE SPECIES.

Subkingdom PTERIDOPHYTA (Ferns and fern allies).

Class EQUISETALES Engler.

Family EQUISETACEÆ (Joint rushes).

Genus EQUISETUM Linnæus.

EQUISETUM VIRGINICUM Fontaine.

Pl. CLX, Fig. 1.

1889. *Equisetum virginicum* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 63, pl. i, figs. 1-6, 8; pl. ii, figs. 1-3, 6, 7, 9.

A single good specimen of a small Equisetum was obtained from the horizon 100 feet below the base of the Dakota sandstone, and another doubtful one from the horizon 150 feet above the Jurassic. It belongs to the small type of Equisetum, with many branches and narrow teeth, that is so characteristic of the Lower Cretaceous, and which contains the species of *E. Burchardti* from the Wealden of Germany, and *E. virginicum* from the Lower Potomac (Neocomian) of Virginia.

The plant is decorticated and does not show plainly the nodes and sheaths in any place. What indications may be seen point to the possession of narrow acute teeth, like those of *E. virginicum.* The size of the branches, their number, and the general facies of the plant are features which strongly indicate that this is a species which can not be separated from the Virginia plant.

The species was evidently a copiously branching one, for the best specimen, that from the horizon 100 feet below the Dakota sandstone, shows a number of small stems diverging as if from insertion on a common stem. The insertion, however, is not visible.

The plant was found in one good specimen, that figured, in the cliff on the north side of Pine Creek and in a single stem of doubtful character at the horizon 150 feet above the Jurassic, at the cliff on the north side of the Valley of the South Fork of Hay Creek.

Class FILICALES Engler.[1]

FERNS.

Genus WEICHSELIA Stiehler.[2]

WEICHSELIA RETICULATA (Stokes & Webb) Ward n. comb.

Pl. CLX, Figs. 2 to 4.

1824. *Pecopteris reticulata* Stokes and Webb: Trans. Geol. Soc. London, 2d ser., Vol. I, p. 424, pl. xlvi, fig. 5; pl. xlvii, fig. 3.
1828. *Lonchopteris Mantelli* Brongn.: Prodrome, p. 60, 199; Histoire, Vol. I, p. 369, pl. cxxxi, figs. 4, 5.
1836. *Polypodites Mantelli* (Brongn.) Göpp.: Syst. Fil. Foss., p. 341.
1838. *Lonchopteris Huttoni* Presl in Sternberg: Flora der Vorwelt, Vol. II, p. 166.
1844. *Pecopteris* sp. Auerbach: Bull. Soc. Imp. Nat. de Moscou, Vol. XVII, Pt. I, p. 148, pl. v, figs. 10, 11.
1845. *Polypodites reticulatus* (Stokes and Webb) Ung.: Synops. Pl. Foss., p. 93.
1845. *Pterophyllum Murchisonianum* Göppert in Murchison's Géologie de la Russie, Vol. II, Pt. III, Paléontologie, p. 501, pl. G, figs. 5, 6a (non fig. 3).
1845. *Pterophyllum filicinum* Göppert in Murchison's Géologie de la Russie, Vol. II, Pt. III, Paléontologie, p. 501, pl. G, figs. 4a, 4b.
1846. *Pecopteris Murchisoniana* (Göpp.) Auerbach and Freers: Bull. Soc. Imp. Nat. de Moscou, Vol. XIX, Pt. I, p. 495, pl. ix.
1846. *Pecopteris Auerbachiana* Rouillier: Bull. Soc. Imp. Nat. de Moscou, Vol. XIX, Pt. II, p. 412.
1849. *Pecopteris Auerbachiana* Rouillier: Op. cit., Vol. XXII, p. 16, pl. J, fig. 55.
1852. *Alethopteris recentior* Ett.: Abh. d. k. k. geol. Reichsanst., Vol. I, Abth. III, No. 2, p. 16, pl. iii, figs. 17, 18.
1854. *Anomopteris* sp. Stiehler: Zeitschr. d. deutsch. geol. Gesellschaft, Vol. VI, p. 661.
1855. *Anomopteris Ludowicæ* Stiehler: Bericht d. naturwiss. Vereins d. Harzes f. 1853 and 1854, p. 14.
1857. *Weichselia Ludovicæ* Stiehler: Zeitschr. d. gesammt. Naturwiss. z. Halle, Vol. IX, p. 454.
1858. *Weichselia Ludovicæ* Stiehler: Palaeontographica, Vol. V, Lieferung 3, p. 73, pl. xii, xiii.
1865. *Pteris reticulata* (Stokes and Webb) Ett.: Die Farnkräuter der Jetztwelt, p. 117.
1869. *Alethopteris Ettingshausii* Schimp.: Traité de Pal. Vég., Vol. I, p. 569.
1869. *Lonchopteris recentior* (Ett.) Schenk: Palaeontographica, Vol. XIX, p. 4, pl. i, figs. 2–6, 6a.
1870. *Asplenites klinensis* Trautschold, in pt.: Nouv. Mém. Soc. Imp. Nat. de Moscou, Vol. XIII, p. 209 (Livraison 3, p. 21), pl. xx, figs. 1, 5–8 (non figs. 2–4).
1883. *Cladophlebis nebbensis* Geinitz-Rostock [non (Schouw) Schimp.]: Arch. Ver. Freund. Nat. Mecklenb., Jahrg. XXXVI, p. 50.
1890. *Pecopteris Geyleriana* Nathorst (in pt.): Denkschr. Wien. Akad., Vol. LVII, p. 48, pl. iv, f. 3.

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[1] In view of the imperfect state of our knowledge of fossil ferns no attempt will be made in this paper to assign the genera to the now recognized families, Osmundaceæ Hymenophyllaceæ, Schizæaceæ, Polypodiaceæ, etc., especially as Engler and Prantl's great work has not at this writing embraced this part of the vegetable kingdom.

[2] The genus Weichselia was founded in 1858 (Palaeontographica, Vol. V, p. 73) by August Wilhelm Stiehler for the species *W. Ludowicæ*, which Mr. Seward regards as identical with *Lonchopteris Mantelli* Brongn. (Histoire, Vol. I, p. 369, pl. cxxxi, figs 4, 5.) Lonchopteris is a Paleozoic genus and this form had to be called by a different name.

1891. *Weichselia erratica* Nathorst: Arch. Ver. Freund. Nat. Mecklenb., Jahrg. XLIV, p. 24.

1894. *Weichselia Mantelli* (Brongn.) Seward: Wealden Flora, Pt. I, p. 114, figs. 12, 13 on p. 120, pl. x, fig. 3.

The horizons in division No. 2 made by Professor Jenney in Newton's Dakota, lying 60 and 100 feet below the Dakota sandstone, contain in abundance a fern that is so close to Schenk's *Lonchopteris recentior*, referred by Seward to *Weichselia Mantelli*, that it can not be separated from that species.

Schenk in his work, Die fossilen Pflanzen der Wernsdorfer Schichten (Palaeontographica, Vol. XIX), p. 4, pl. i, figs. 2–6, describes and figures fragments of a fern with reticulate nervation that was obtained from the Wernsdorf beds of the northern Carpathians, which are of Urgonian age. In the size, shape, and mode of insertion of the pinnules, in the character of the nervation, and, indeed, in all important points, the agreement between the Wyoming and European plants is very close.

Schenk is no doubt correct in his supposition that this fern is bipinnate. It is a rather peculiar fact that in all the numerous specimens coming from the Hay Creek coal field and examined by me there are none that show the insertion of the ultimate pinnæ on a primary one. The specimens are all small bits of ultimate pinnæ, as were those of Schenk, and show only a few pinnules. From the imprints left on the stone, and the amount of carbonaceous matter left by the pinnules, we must conclude that they were thick and leathery in nature. Owing to this, in most of the specimens it is difficult to see the details of the nervation. Some of the pinnules approach in shape very near to *Lonchopteris Mantelli* Brongn., from the Wealden of England and France, for there is some variability in them, although for a fern this is surprisingly small. Schenk says of his form that it is with difficulty to be separated from the Wealden species, and the Wyoming forms make still more doubtful the propriety of making two species of them. I have in Pl. CLX, Figs. 2 to 4, endeavored to give average forms. Fig. 2 represents the terminal portion of an ultimate pinna with pinnules of average size. Fig. 3 gives this enlarged three diameters, to show the nervation. Fig. 4 gives a portion of an ultimate pinna lower down than the portion given in Fig. 2 and represents pinnules somewhat larger than those of Fig. 2, being the average of the larger pinnules possessed by this fern. It should be noted that in the Hay Creek pinnules their margins are often bent under and the lamina on each side of the midrib is convex in form, giving the pinnule something of the aspect of an Alethopteris, a feature mentioned by Schenk as shown in the Wernsdorf plant.

Weichselia reticulata is one of the most common plants in Jenney's second division, and forms nearly all of the material obtained at certain localities. This is the case with the collections made from cliffs along the north side of Red Water Valley, cliff on the south side of

Pine Creek, carbonaceous shales in Rollin's tunnel, and cliff on Oak Creek at Robbin's ranch. Besides these localities, numerous specimens occur at the cliff in east bank of Oak Creek.

It thus seems to be abundant on both plant-bearing horizons in division No. 2 of Jenney, that 60 feet and that 100 feet below the base of the Dakota sandstone, and it is without doubt one of the most characteristic plants of this division. No trace of it has so far been found in the divisions of the Lower Cretaceous lying under No. 2. Its great abundance in division No. 2 and its absence in the underlying divisions indicate a change in the flora which is in keeping with the differences seen in the other plants of the two portions of the Lower Cretaceous.

Both the specimens figured are from the black carbonaceous shales in Rollin's tunnel.

Genus MATONIDIUM Schenk.

MATONIDIUM ALTHAUSII (Dunker) Ward n. comb.

Pl. CLX, Figs. 5–8.

1844. *Cycadites Althausii* Dunker: Programm d. höheren Gewerbschule in Cassel, 1843–1844, p. 7.
1846. *Pecopteris Althausii* Dunker: Mon. d. Norddeutsch. Wealdenbildung, p. 5, pl. ii, fig. 2.
1846. *Pecopteris polydactyla* Göppert in Dunker: op. cit., p. 5, pl. vii, fig. 4.
1846. *Pecopteris Conybeari* Dunker: op. cit., p. 7, pl. ix, figs. 8, 8a.
1846. *Alethopteris elegans* Göppert in Dunker: op. cit., p. 8, pl. vii, figs. 7, 7a.
1849. *Pecopteris elegans* (Göpp.) Brongn.: Tableau, p. 107.
1852. *Alethopteris Gœpperti* Ett.: Abh. d. k. k. geol. Reichsanst. Wien, Vol. I, Abth. III, No. 2, p. 16, pl. v.
1869. *Laccopteris Gœpperti* (Ett.) Schimp: Traité de Pal. Vég., Vol. I, p. 582; Atlas, pl. xxxi, figs. 5–8.
1870. *Pecopteris explanata* Trautschold: Nouv. Mém. Soc. Imp. Nat. de Moscou, Vol. XIII, p. 220 (Livraison 3, p. 32), pl. xix, fig. 7.
1871. *Matonidium Gœppevti* (Ett.) Schenk: Palaeontographica, Vol. XIX, p. 220, pl. xxvii, fig 5; pl. xxviii; pl. xxx, fig. 3.
1888. *Alethopteris polydactyla* (Göpp.) Schenk: Die fossilen Pflanzenreste, p. 39.
1891. *Laccopteris polydactyla* (Göpp.) Sap.: Plantes jurassiques, Vol. IV, p. 384.

This fern, described by Schenk as abundant in the Wealden formation of northern Germany, and found by Heer in the Wealden of Portugal, is one of the most common plants at the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek. It occurs also very rarely in the carbonaceous shales in Rollin's tunnel. It has not yet been found at any other localities or on any other horizon. Schenk's specimens as described and figured in Die Foss. Flora der Norddeutsch. Wealdenformation, pp. 17, 18, pl. vi, fig. 5; pl. vii, figs. 1, 1a–c, 2, 2a (Palaeontographica, Vol. XIX, pp. 220, 221, pl. xxxvii, fig. 5; pl. xxxviii, figs. 1, 1a–c), show much more of the plant than can be seen in the fossils from the Hay Creek beds. These are always fragments of ultimate pinnæ. They are pinnæ of both the sterile and fruiting forms of the fern. In their dimensions the pinnules are in most cases larger than those figured by Schenk, and smaller than those of Heer, given on pl. xv of his Contributions à la Flore Fossile du Portugal. The agreement in all essential points of the Hay Creek fossils with those from both European regions is exact. The fructified pinnules mostly carry sori from their tips, and they are proportionally very large, so as to cover the entire lamina on each side of the midnerve. The sori show a proportionally large and distinct depression in their center. Fig. 5 gives average sterile pinnules, and Fig. 6 represents these enlarged two diameters, to show the character of the nerves. Fig. 7 represents the fertile pinnules, and Fig. 8 gives these enlarged two diameters, to show the sori.

Both the specimens figured are from the cliff on the north side of Pine Creek.

Genus PECOPTERIS Brongniart.[1]

PECOPTERIS GEYLERIANA Nathorst.

Pl. CLX, Figs. 9–13.

1890. *Pecopteris Geyleriana* Nath.: Denkschr. d. Wien. Akad. d. Wiss., Vol. LVII, p. 48, pl. iv, fig. 1; pl. vi, fig. 1.

This fern, coming from the Lower Cretaceous of Japan, was first described and figured by Nathorst in his Beiträge zur Mes. Flora Japans (Denkschr. Wien. Akad., Vol. LVII), p. 48, pl. iv, fig. 1; pl. vi, fig. 1. It was later found by M. Yokoyama at additional localities in the same country and formation, who noticed the plant in the Journal of the College of Science, Imperial University of Japan, Vol. VII, Pt. III, 1894, pp. 219–220, pl. xxi, fig. 12; pl. xxiii, fig. 1, 1a; pl. xxviii, fig. 5, giving some excellent figures. The figures of both Nathorst and Yokoyama show that the plant possesses some characteristic features that render it rather easy to identify. The Japanese forms are far more complete than those of the Hay Creek beds, but fortunately the peculiarities are found mostly in the pinnules, and these are well shown in the American fossil.

In the Hay Creek strata *Pecopteris Geyleriana* is always found in detached fragments of ultimate pinnæ and mostly associated with *Weich-*

[1] There are probably no true representatives of the genus Pecopteris in the Cretaceous, but in default of the fruiting organs a large number of forms of Mesozoic age have from time to time been referred to this genus on account of the similarity of the fronds and their nervation. In recent times there has been a strong movement in the direction of assigning such forms to more modern genera, and in due time all will probably be so referred. They are found to fall under several different genera, but the majority of them probably belong to the genus Cladophlebis, established by Brongniart himself in 1849 (Tableau, p. 25), for the reception of a number of those that he had formerly included under Pecopteris. Among other Mesozoic genera to which these forms have been referred are Weichselia of Stiehler, Matonidium of Schenk, and Scleropteris of Saporta. A number have also been placed in the living genera Pteris, Thyrsopteris, and Gleichenia. This, however, is probably going almost as far to the opposite extreme. Until the subject shall have been properly monographed we shall be obliged to follow the authorities we have.

selia reticulata. While it is much less abundant than this latter, both occur in the same condition of preservation, which shows that the fragments had been transported some distance from the place of their growth. The specimens of this Pecopteris are nowhere very abundant and the fragments of ultimate pinnæ are never very large. Still the pinnules show their character very distinctly and the number of different parts is great enough to indicate almost all the variations mentioned and illustrated by Yokoyama. The pinnules of all the Hay Creek specimens are quite small. They must have been thick and leathery, as is indicated by Yokoyama's figures. They must have been quite durable, for they leave a thick layer of carbonaceous matter that obscures the nerves. Yokoyama mentions as a peculiar feature that the lowest pinnules on the front of the rachis of the ultimate pinnæ are often falcate backward instead of forward, and he says that they are mostly blunt and that the views are in most cases indistinct. All these features are seen in the specimens from the Hay Creek beds. The midnerve is generally persistent to near the tip and it sends off on each side forking lateral nerves, which, owing to the thickness of the carbonaceous film, are not often seen. Another peculiarity seen in both the Japanese and Hay Creek specimens is the rounding off of the pinnules at their base, so as to form ears, and the posterior ear is usually larger than the anterior one. The pinnules are more or less triangular in shape.

Pl. CLX, Fig. 11, represents a fragment of an ultimate pinna with pinnules of the largest size that were seen. Fig. 12 gives those of intermediate size, while Fig. 9 gives the smallest size. The enlargement of Figs. 9 and 12 and in Figs. 10 and 13 are four diameters.

This plant has been found on the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek, one specimen; and a number of specimens on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek; carbonaceous shales in Rollin's tunnel, and cliff on Oak Creek at Robbin's ranch.

The specimen represented by Figs. 9 and 10 of Pl. CLX is from Rollin's tunnel; that by Fig. 11 is from the cliff on the north side of Pine Creek, and that by Figs. 12 and 13 from the east bank of Oak Creek, 2 miles below Robbin's ranch.

PECOPTERIS BOREALIS Brongniart.

Pl. CLX, Figs. 14, 15.

1828. *Pecopteris borealis* Brongn.: Histoire des Végétaux fossiles, Vol. I, p. 351, pl. cxix, figs. 1, 2.

A single specimen of a plant so much like the *Pecopteris borealis* of Brongniart that it may be identified with it was found on the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek. It shows a considerable portion of an ultimate pinna with a number of pinnules that are quite well preserved. These are shown in

Fig. 13. The ultimate pinnæ must have been quite long and have had closely set pinnules that were separate near their bases. The lower surface of the rachis seems to have had a corded appearance, from the existence of the rachis in the midst of a wing on each side, caused by the union of the bases of the pinnules. The pinnules have the aspect of those of Cladophlebis of the Jurassic type. They are small, broadest at their bases, inclined forward, more or less ovate and subacute toward their tips. The nerves are very distinct, as shown in Fig. 14. The general aspect of the pinnules is much like those of the pinnules of the specimen figured by Heer in Flor. Foss. Arct., Vol. I, pl. xliv, figs. 5a, 5b. The rigid wing on each side of the rachis in the Hay Creek plants makes the rachis of the ultimate pinna appear much thicker than it really is. Only two specimens were found.

Genus CLADOPHLEBIS Brongniart.

CLADOPHLEBIS WYOMINGENSIS n. sp.

Pl. CLX, Figs. 16, 17.

A single mutilated specimen of a fern was found on the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek, that is probably a new species. The specimen shows only a fragment of an ultimate pinna with pinnules more or less distorted by pressure. Some of them, however, show their original character pretty well. The description of the plant is as follows: Frond bipinnate, pinnules remote, obliquely attached, falcate and acute, slightly decurrent, midnerve slender and continuous to near the tip of the pinnules, where it splits up into branches. Lateral nerves going off obliquely, forking once, the forking taking place near their insertion.

Although not enough material of this plant was obtained to permit the determination of its full character and the establishment consequently of a good species, it is not near enough to any species known to me to justify its being identified with any hitherto described. Where a plant from some new region possesses only a slight resemblance to one previously described from some remote locality it appears to be better usage to regard them as different species. Still more is this true if the two belong to different geological formations. It is true that this involves a multiplication of species, but the making of species, which can be easily merged into others if necessary, involves possible errors of less importance than the unjustified assumption that the same plant existed in widely separated localities and survived through different geological periods.

The plant now in question is a good deal like *Pecopteris virginiensis*, which I have described in Monograph XV of the U. S. Geological Survey, from the Lower Potomac of Virginia; but it lacks the toothing, which is a very persistent feature on the pinnules of that plant, being shown on them even high up toward the ends of the ultimate pinnæ.

It is also like the narrower forms of the pinnules of *Cladophlebis acuta*, which is found in the Lower Potomac formation (see Mon. U. S. Geol. Survey, Vol. XV, pl. xi, fig. 7), but the pinnules of this form are closely placed and united at bases. A larger amount of material would very probably justify its identification with *Cladophlebis acuta*. Our plant has an obvious resemblance to the fern from the Kootanie formation of British America which Sir William Dawson considers as identical with Heer's *Asplenium distans* from the Jurassic of Siberia (see Dawson on the Mesozoic floras of the Rocky Mountain region of Canada: Trans. Roy. Soc. Can., Sec. IV, Vol. III, 1885, p. 5, pl. iii, fig. 7). But the Kootanie plant is a fern with larger pinnules. Whatever its specific order may be, our plant belongs to a type which is quite characteristic of the later Jurassic and basal Cretaceous.

CLADOPHLEBIS PARVA Fontaine?

Pl. CLX, Fig. 18.

1899. *Cladophlebis parva* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 73, pl. iv, figs. 7, 7a; pl. vi, figs. 1, 1a, 2, 2a, 3, 3a.

At the cliff on the north side of the valley of the South Fork of Hay Creek and on the horizon 150 feet above the Jurassic a small fragment of a fern was found that appears to be identical with *Cladophlebis parva* of the Lower Potomac. For description of this species see Mon. U. S. Geol. Survey, Vol. XV, p. 73. The amount of material is much too small to permit its true character to be made out. However, the pinnules, which are well preserved, are exactly like those of *Cladophlebis parva*. These look much like Jurassic forms of Cladophlebis, and are probably survivors from the Jurassic. Several imperfect specimens, which may also be placed doubtfully in this species, were found on the horizon 100 feet below the Dakota sandstone, at the cliff on Oak Creek, Robbin's ranch.

Genus SPHENOPTERIS Brongniart.[1]

SPHENOPTERIS PLURINERVIA Heer?

Pl. CLX, Figs. 19, 20.

1881. *Sphenopteris plurinervia* Heer: Contributions à la Flore fossile du Portugal; Section des Travaux géologiques du Portugal, 1881, p. 13, pl. xi, figs. 6, 6b; pl. xv, figs. 8, 8b, 8c.

The specimen identified doubtfully with Heer's species is a portion of an ultimate pinna of a small fern. It shows a number of minute pinnules that have lost their tips, but were evidently elliptical in form

[1] Sphenopteris is another mainly Paleozoic genus of ferns to which Cretaceous forms probably ought never to have been referred. Many of them have gone into Onychiopsis, Cladophlebis, Scleropteris, Dichopteris, Cyathea, Dicksonia, and Thyrsopteris, but a considerable number still remain and it will be impossible in this paper to assign them to their proper genera. They will therefore be left in this genus until a thorough revision can be made of the group.

and narrowing to their base in such a manner that they were attached to the rachis almost by a petiole. They resemble *Sphenopteris plurinervia* enough to justify a doubtful identification with the species. There is not enough material to permit the determination of a full specific character. Heer describes his plant in Contr. à la Flor. Foss. du Portugal, pp. 13–14, pl. xi, fig. 6; pl. xv, fig. 8, as coming from the Lower Cretaceous of Portugal. The plant in the Hay Creek series occurs on the horizon 150 feet above the top of the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek, in only two specimens.

Genus THYRSOPTERIS Kuntze.[1]

THYRSOPTERIS PINNATIFIDA Fontaine?

Pl. CLXI, Figs. 1, 2.

1889. *Thyrsopteris pinnatifida* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 136, pl. li, fig. 2; pl. liv, figs. 4, 5, 7, 7a, 7b; pl. lvii, figs. 7, 7a.

On the horizon 150 feet above the Jurassic and at the cliff on the north side of the valley of the South Fork of Hay Creek a small fragment of a fern was found, having a character unlike the others, and resembling *Thyrsopteris pinnatifida* of the Lower Potomac of Virginia. As there is not enough material to permit its full character to be made out, its identification must be doubtful. The fragment shows a piece of an ultimate pinna carrying several fragmental pinnules which have all the character of those of *Thyrsopteris pinnatifida*. They have the same size, shape, and lobing of the pinnules of that plant when they occur toward the ends of ultimate pinnæ, being quite small, elliptical in shape, and cut obliquely into minute lobes and teeth.

THYRSOPTERIS CRASSINERVIS Fontaine.

Pl. CLXI, Figs. 3, 4.

1889. *Thyrsopteris crassinervis* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 130, pl. xli, figs. 1, 1a, 1b, 2, 2a, 2b, 3, 3a, 3b.

At the same locality and on the same horizon with the doubtful specimen of *Thyrsopteris pinnatifida* another small specimen of a different fern was found. This has pretty strongly shown the features of *Thyrsopteris crassinervis* of the Lower Potomac of Virginia, but in this case also the amount of material does not justify a positive identification with that form. The specimen is very distinct in the features shown. It is a portion of a penultimate pinna from toward its tip, that contains several short ultimate pinnæ. These have broadly elliptical pinnules that are united at the base. The upper basal pinnules, as is

[1] Professor Fontaine has referred a large number of Potomac ferns to this living genus, perhaps correctly, but it would probably have been better to place them in Brongniart's extinct genus Coniopteris. For a brief account of the general subject see the Fifteenth Annual Report of the U. S. Geological Survey, p. 383.

the case with *Thyrsopteris crassinervis*, are a good deal larger than the others, but it is not lobed as is the case with the corresponding pinnules of the Potomac plant. This is probably owing to the fact that the ultimate pinnæ of the Hay Creek specimen come from a portion of the penultimate pinna nearer its end than those of the Potomac form that show lobed basal pinnules. The nerves are strong and distinct.

THYRSOPTERIS ELLIPTICA Fontaine.

Pl. CLXI, Fig. 5.

1889. *Thyrsopteris elliptica* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 133, pl. xxiv, figs. 3, 3a; pl. xlvi, figs. 1, 1a; pl. l, figs. 6, 6a, 9; pl. li, figs. 4, 6, 6a, 6b, 7; pl. liv, fig. 6; pl. lv, fig. 4; pl. lvi, figs. 6, 6a, 7; pl. lvii, figs. 6, 6a; pl. lviii, figs. 2, 2a.

This plant, which is abundant in the Lower Potomac strata of Virginia, and has been described in Monograph XV, p. 133, is rather rare in the Hay Creek beds. So far as yet found it occurs on the horizon 150 feet above the Jurassic at two localities: Cliff on the north side of the valley of the South Fork of Hay Creek, and shales under the third sandstone, Barrett, with one doubtful small fragment at the contact of the Jurassic with the Cretaceous, Lon Cottles' ranch. At all the localities only small, imperfect fragments were obtained, showing portions of ultimate pinnæ. At the first-named locality the fragments are larger, but the pinnules are not so well preserved. At the second locality the small bits of pinnæ, with often very distinct pinnules, go to help form a mat of vegetation along with small fragments of *Pinus susquaensis* and *Czekanowskia nervosa*, that covers the cleavage surfaces of the shale. The plants here seem from some cause to have been torn into small bits, which, however, are very distinct in character.

The shale under the third sandstone at Barrett deserves a careful and prolonged search. It would no doubt yield many beautifully preserved specimens of those plants already made out and some new species, for very suggestive fragments, too small to give any positive character, may sometimes be seen. The shale is well fitted to preserve plants and is full of fragments. It is very fine-grained, gray in color, with a tinge of buff. It splits into laminæ as thin as paper, and the surface of these takes a perfect imprint of a plant. Unfortunately, only a very small amount of this material was obtained. It is a noteworthy fact that this shale is physically strikingly like the carbonaceous shale at Webster's ranch, which Professor Jenney places geologically 100 feet below it. *Czekanowskia nervosa* and *Pinus susquaensis* occur in both. The only difference, as shown by the plants, is that the small Zamites, *Z. borealis*, is common on the lower horizon, while it is not found on the upper, and *Thyrsopteris elliptica* occurs on the upper and not on the lower horizon.

The specimen figured was found at the cliff on the north side of the valley of the South Fork of Hay Creek, 2½ miles west of Barrett.

THYRSOPTERIS DENTIFOLIA n. sp.

Pl. CLXI, Figs. 6-9.

Frond bipinnate; only the terminal portions of some of the ultimate pinnæ were seen. The ultimate pinnæ have their terminal portions long and narrow, with an unusually gradual reduction in the size of the lobes and teeth which they carry, and which represent the pinnules of lower portions of the pinnæ and frond. The lowest pinnules seen on the ultimate pinnæ (Fig. 6) are united at base, very obliquely inserted on the rachis, oblong in form, with margins notched as if for incipient lobes. Toward the end of the pinnæ the pinnules pass very gradually, by diminution in size and increasing union, into lobes and then into teeth. These lobes and teeth are narrowly ovate, acute, and very oblique, diverging from the rachis (Fig. 8). The lobes have each a single nerve, which sends a branch to the upper margin or tooth. In the notched lower pinnæ a midnerve sends off on each side a branch into each incipient lobe.

It is obvious that not enough material is possessed to give certainly the character of this small fern. The long drawn out tips of the ultimate pinnæ, with small dentate lobes and acute diverging teeth, appear to be a new and constant character. The tips of the pinnæ look like portions of a twig of some conifer. These terminal portions seem to have been rather easily broken off, for they form most of the imprints found. One of these bits, 18 mm. long, shows only the tooth-like lobes, the width from tip to tip of which is only 2.5 to 3 mm. The plant looks much like *Sphenopteris Mantelli* Brongn. [*Onychiopsis Mantelli* (Brongn.) Sew.], and would have been so regarded were it not for the passage in the lower portions of the pinnæ of the lobes into Thyrsopterid pinnules. At any rate it belongs to the kind of fern with narrow, rigid pinnules which appears common in the Lower Cretaceous, and of which *Onychiopsis Mantelli* may be taken as the type.

This fern occurs sparingly on the horizon 50 feet above the Jurassic, at the shales over coal 2 miles southeast of Barrett.

THYRSOPTERIS BREVIFOLIA Fontaine.

Pl. CLXI, Figs. 10-15.

1889. *Thyrsopteris brevifolia* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 121, pl. xxiv, figs. 5, 5a, 5b, 5c, 5d, 10.

This pretty little fern is one of the most common plants on the horizon 50 feet above the Jurassic at the shale over coal 2 miles southeast of Barrett, where its fragments cover thickly some of the cleavage surfaces of the shale, being mingled with fragments of *Thyrsopteris dentifolia* and *T. pecopteroides*. It never shows, in any imprint, more than detached fragments of ultimate pinnæ. These, however, are numerous enough to give a pretty full representation of various portions of these pinnæ from different parts of the frond. At the same time gradations show connecting links between the detached portions. This plant was found in the Lower Potomac of Virginia, occurring at the Dutch Gap Canal, in a ball of red clay or shale, which was embedded in the layers of bluish-gray clay and sand that form the banks of the canal. It was found nowhere else in that formation, and it is interesting to note that it occurs in the Hay Creek region, at only one locality, in a shale that resembles that containing it at the Dutch Gap. Its description was given in Mon. XV, p. 121, pl. xxiv, figs. 5, 5a–d, and 10.

The larger number of imprints occurring in the Hay Creek beds enable us to see parts not shown in the Potomac fossils. These are portions from lower down on the ultimate pinnæ and parts of ultimate pinnæ from higher up toward the summit of the frond. All the parts indicate a fern somewhat more robust than the Dutch Gap plant. The pinnules from the lowest portion of the pinnæ and frond are still more like *Sphenopteris hymenophylloides* Brongn. than any of the Potomac specimens. The ultimate pinnæ from both regions were evidently very long and slender, and the Hay Creek specimens show that they ended in long drawn out and attenuated terminations. Especially is this true of the pinnæ from the upper part of the frond, as shown in Figs. 12 and 14 of Pl. CLXI. The deeply incised pinnules, Fig. 10, graduate into elliptical lobes and teeth toward the ends of the pinnæ. These are shown in Figs. 12 and 14, Fig. 12 giving the lobed forms and Fig. 14 those with teeth. All this is clearly shown in the enlarged Figs. 11, 13, and 15.

THYRSOPTERIS PECOPTEROIDES Fontaine.

Pl. CLXI, Figs. 16–19.

1889. *Thyrsopteris pecopteroides* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 135, pl. li, figs. 1, 1a.

This small, delicately incised fern was found by the writer in the Lower Potomac of Virginia at Fredericksburg, where it occurs quite rarely. It occurs in the Hay Creek beds, on the horizon 50 feet above the Jurassic, at the shales over coal 2 miles southeast of Barrett, along with *Thyrsopteris brevifolia* and *T. dentifolia*, being almost as common as the former. The specimens show only portions of the ultimate pinnæ, but some of these appear to come from parts of the frond lower down than any seen in the Potomac fossils. Hence some of the pinnules are somewhat larger than any belonging to the Virginia specimens and show a greater tendency to lobing. These are given in Figs. 16 and 17. At the same time pinnæ from parts of the frond higher up than those seen in the Potomac specimens were obtained. These are very minute. They are shown in Figs. 18 and 19.

It is a noteworthy fact that the three ferns last described, viz, *Thyrsopteris dentifolia*, *T. brevifolia*, and *T. pecopteroides*, occur together in comparative abundance on the horizon given by Professor Jenney at 30 to 50 feet above the Jurassic, at shales over the coal 2 miles southeast of Barrett, while they are found nowhere else in the Hay Creek region. Only one small collection from this locality was placed in my hands, and it is much to be desired that additional collections should be made there. The shale preserves the plants well, it cleaves nicely, and seems to be rich in fossils. Some bits indicate that other and new forms may be found there. It is peculiar that so many parts of detached, ultimate pinnæ are found at this locality with their terminal portions perfectly preserved, while in no case were the pinnæ seen attached to a rachis. The terminal portions of pinnæ of delicate ferns like these are usually the parts most poorly preserved.

THYRSOPTERIS BREVIPENNIS Fontaine?

Pl. CLXII, Fig. 1a.[1]

1889. *Thyrsopteris brevipennis* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 124, pl. xxxiv, figs. 3, 3a; pl. xxxvi, figs. 2, 2a; pl. xxxvii, figs. 3, 9; pl. xxxviii, figs. 1, 1a, 1b; pl. xli, figs. 4, 4a.

This species was described by the writer from the Lower Potomac in Monograph XV of the U. S. Geological Survey, page 124. In the Hay Creek beds were found several small fragments of ultimate pinnæ, carrying a few pinnules, of a fern that is apparently the same species, but the amount of material is not sufficient to permit positive identification. They occur only on the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek.

Genus SCLEROPTERIS Saporta.[2]

SCLEROPTERIS DISTANTIFOLIA n. sp

Pl. CLXII, Figs. 2, 3.

This is apparently a new Scleropteris that occurs at the same locality and horizon as *Thyrsopteris pinnatifida* and *T. crassinervis*, on the South Fork of Hay Creek, 170 feet below the Dakota sandstone. It occurs in only one specimen, but that is characterized well enough to justify its being provisionally made a new species.

The specimen shows a fragment of a long, slender ultimate pinna. The lobes, or rather pinnules, are remote from one another and very obliquely directed toward the ends of the pinna, so that they diverge very slightly from the rachis to which they are attached. They are very small, narrowly ellipitical in form and decurrent at base, so as to

[1] Where the material was scarce and doubtful, Professor Fontaine did not always select specimens for illustration. It seemed to me all the more important that such cases should be illustrated in order that the occurrence of the species in the Black Hills might be fully attested. I have therefore had figures made, however imperfect, to support his notes.

[2] This genus was established by the Marquis Saporta in 1872 (Plantes Jurassiques, Vol. I, p. 364) to embrace a number of forms of Mesozoic ferns previously referred to Sphenopteris, Loxopteris, Pachypteris, and Dichopteris, but without wholly absorbing these genera. The Lower Cretaceous of America contains some forms that fall distinctly within the limits of the genus.

form a comparatively wide wing. The nervation consists in each pinnule of a parent nerve that splits up into several branches which are directed very obliquely upward toward the tip of the pinnule. One or more of the branches may be forked.

The shale which yields these plants at the cliff on the north side of the valley of the South Fork of Hay Creek is a fine-grained fissile material, gray in color, with a slight brownish shade. It preserves the plants beautifully, although most of those obtained are in small bits, owing to the small fragments of the shale obtained. This is no doubt due to the fact that the specimens come from weathered shale of surfaces long exposed. From the character of this material there is little doubt that if specimens be taken from fresher rock, farther in from the surface, larger and more complete imprints of the plants would be found. Only a small amount of the rock was obtained, and no doubt prolonged and careful search would result in finding other plants. Occasionally to be seen on the specimens are small bits and fragments that indicate the existence of other plants besides those mentioned in this paper. In addition a number of the plants found here are not found elsewhere, so that it is very desirable that additional collections should be made at this spot.

SCLEROPTERIS ROTUNDIFOLIA n. sp.

Pl. CLXII, Figs. 4, 5.

Frond probably tripinnatifid. The ultimate pinnæ or pinnules are very small. Their tips are not preserved, but they were probably not more than 5 mm. in length. They are alternate and attached at an angle of about 45° with the principal rachis. They carry minute circular lobes or pinnules that are united at base by a proportionally broad wing. This latter is thick in texture and rigid, so that when the rachis is seen from above the wing seems to be a part of it. Hence the rachis appears abnormally strong. When the underside of the rachis is presented it is seen to be very slender. The pinnules or lobes become more and more united toward the tips of the ultimate pinnæ. They are not more than three-fourths of a millimeter wide. In each lobe a nerve ascends from a very oblique insertion and splits in a flabellate manner into two or more branches.

This minute Scleropteris is not near any described plant known to me. The best preserved specimens do not show enough to enable the character of the plant to be made out fully, but enough may be seen to indicate that it is a pretty well marked new species. Pl. CLXII, Fig. 4, gives the most complete imprint found.

It occurs in several specimens on the horizon 150 feet above the Jurassic at the cliff on the north side of the valley of the South Fork of Hay Creek, and has been found as yet nowhere else.

Genus ASPLENIUM Linnæus.

ASPLENIUM DICKSONIANUM Heer?

Pl. CLXII, Figs. 6-8.

1874. *Asplenium Dicksonianum* Heer: Die Kreide-Flora der arctischen Zone, K. Svensk. Vet.-Akad. Handl., Vol. XII, No. 6 (Fl. Foss. Arct., Vol. III, Pt. II), p. 31, pl. i, figs. 1 (excl. b, c), 1aa, 2, 3, 3b, 4, 5 (excl. a, b, c).

The specimens represent the summits of ultimate pinnæ of a fern which is decidedly like *Asplenium Dicksonianum* Heer, from the Kome beds of Greenland. It has also something of the character of the widely diffused Potomac plant *Thyrsopteris rarinervis*. but is, I think, nearer Heer's plant.[1]

Genus GLEICHENIA Smith.

GLEICHENIA ZIPPEI (Corda) Heer?

Pl. CLXII, Fig. 9.

1846. *Pecopteris Zippei* Corda in Reuss: Versteinerungen d. böhm. Kreideformation, Abth. II, p. 95, pl. xlix, figs 2, 3.
1868. *Gleichenia Zippei* (Corda) Heer: Fl. Foss. Arct., Vol. I, p. 79, pl. xliii, figs. 4, 4b.

Some ends of the ultimate pinnæ of a small fern with the facies of Gleichenia occur in the collection. This is nearest to Heer's *G. Zippei* from the Kome beds, but the pinnules are rather more acute than most of those of that plant, and indicate that those on this plant lower down are somewhat larger than those of *G. Zippei*. The form is also something like *Aspidium heterophyllum* of the Potomac formation, but seems to be smaller and more delicate. It may, however, be the same.[2]

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[1] The above is all that Professor Fontaine says in his letter of January 10, 1894, about the three small fragments figured on Pl. CLXII, Figs. 6-8, which were collected by Professor Jenney and myself on the slope of Red Canyon in the Minnekahta region. After examining the specimens he returned them with labels, on all of which he wrote: "Probably *Asplenium Dicksonianum*." It is a significant fact that neither this species nor the Potomac fern *Thyrsopteris rarinervis* Font., occurs in the Hay Creek collection. A comparison of these fragments with the fine specimens of *Asplenium Dicksonianum* collected by us near Evans quarry, in the true Dakota group (see infra, p. 704, Pl. CLXX, Fig. 1), will be of interest.

[2] The above description by Professor Fontaine was based chiefly on the specimen figured on Pl. LXXX, Fig. 9, but of which, at the time he examined it, scarcely more than 2 cm. were visible of the upper part of the pinna. After its return I observed that the impression passed into the rock below the exposed portion, and by a little skillful manipulation I succeeded in scaling off a piece of rock and exposing the remainder that we here see, amounting to considerably more than 5 cm. The lower lobes are somewhat more toothed than the upper ones, thus differing from Heer's figures. They are not pointed like *Aspidium heterophyllum* Font., and it seems to me probable that the impression may represent a pinnule of *Thyrsopteris pecopteroides* Font.

Subkingdom SPERMATOPHYTA (Phanerogams).

Subdivision GYMNOSPERMAE.

Class CYCADALES Engler 1897.[1]

Family CYCADACEÆ.

No unequivocal cycadaceous plants occur above the horizon lying 150 feet above the Jurassic. The only possible exceptions are the one or two small fragments of leaves that occur at higher horizons, and that look more like Zamites than any other plant. They show, however, neither basal nor terminal portions, and may be Nageiopsis. Cycads of the type of Zamites described by Heer, so characteristic of the Kome beds of Greenland, are the only certain ones found in the Hay Creek strata. On the horizon 150 feet above the Jurassic at John Barr's tunnel they are the most common plants. Elsewhere they are rare. It is a noteworthy fact that this type of cycad seems to be the most characteristic one in the Kootanie beds, as made known by Sir William Dawson, and in the strata of similar age at Great Falls, Montana. Taking all these occurrences into consideration, it seems that this type is highly characteristic of the Lower Cretaceous, at least of North America.

Genus ZAMITES Brongniart.

ZAMITES BREVIPENNIS Heer.

Pl. CLXII, Figs. 10–13.

1874. *Zamites brevipennis* Heer: K. Svensk. Vet.-Akad. Handl., Vol. XII, No. 6 (Fl. Foss. Arct., Vol. III, Pt. II), p. 67, pl. xv, figs. 8–10.

Several well-preserved specimens of a small Zamites occur on the horizon 150 feet above the Jurassic at John Barr's tunnel, and nowhere else, which are identical with *Z. brevipennis* obtained by Heer from the Kome beds of Greenland and described by him in Vol. III of Fl. Foss. Arct., Pt. II, Die Kreide-Flora des Arctischen Zone, p. 67, pl. xv, figs. 8, 9, 10. They agree so far that even Heer's largest and smallest forms of this plant can be duplicated from the Hay Creek beds. Fig. 10 agrees well with Heer's larger forms, and Fig. 12 with his smaller. The nerves could not be made out, for it appears that they are not visible in this type when the upper surface of the plant is presented uppermost.

The plants must have had a coriaceous and double-leaf texture, for in the shale the leaf substance is to a large extent preserved, and may be peeled off so as to remove all trace of the plant.

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[1] The class Bennettitales (see supra, p. 598) does not include the foliage, fruits, etc., of cycadean vegetation found in a fossil state, but only petrified trunks. We are, therefore, compelled to refer the former still to the class Cycadales and family Cycadaceæ. There is evidently an inconsistency in this, as it is altogether probable that the impressions from the same horizon represent the foliage, etc., of the forms whose trunks were entombed at other localities under different conditions.

The shale at John Barr's tunnel deserves careful examination, and additional collections should be made from it. Only one small bundle of specimens was placed in my hands as coming from this locality, and it contained at least one species not found elsewhere, while it gives promise of well-preserved specimens from a critical horizon in the Lower Cretaceous. Besides it is of a nature to preserve in great perfection the plants that it contains. Even in the apparently weathered fragments obtained the points were shown with a distinctness rarely found. The shale is very fine-grained and fissile, splitting into thin and smooth laminæ.

ZAMITES BOREALIS Heer.

Pl. CLXII, Fig. 14.

1874. *Zamites borealis* Heer: K. Svensk. Vet.-Akad. Handl., Vol. XII, No. 6 (Fl. Foss. Arct., Vol. III, Pt. II), p. 66, pl. xiv, figs. 13, 14; pl. xv, figs. 1, 2.

A Zamites, which is identical in all respects with Heer's *Z. borealis* from the Kome beds of Greenland, is one of the most common fossils at some of the localities yielding plants from the lower horizons of the Hay Creek beds. It occurs on the horizon 150 feet above the Jurassic, at John Barr's tunnel, where it is the most common fossil, and appears to be abundant. On the horizon 50 feet above the Jurassic, it occurs also in carbonaceous shale; Webster's ranch, where it is rather common, and from which the specimen figured on Pl. CLXII, Fig. 14, was obtained; also at the shales over lowest coal, Larrabee's shaft, where it is not so common. The nerves were not seen, as they are probably immersed in the rather thick leaf substance.

This Zamites seems to me to be identical with that coming from the Kootanie beds and described by Sir William Dawson in his paper on the Mesozoic floras of the Rocky Mountain region of Canada: Trans. Roy. Soc. Can., Sec. IV., Vol. III, p. 7, pl. i, fig. 5. This he has identified with Heer's *Z. acutipennis*, from the Lower Cretaceous of Greenland. This Zamites is evidently widely diffused in the Lower Cretaceous of North America, and is highly characteristic of it. On this account, the entire absence in the Lower Potomac of the type of Zamites to which it belongs is all the more noteworthy.

ZAMITES? sp.

Pl. CLXII, Fig. 15.

On the horizon 100 feet below the base of the Dakota sandstone, at the cliff on Oak Creek at Robbin's ranch, a small fragment of a leaf was found, which looks like a portion of a Zamites. It has pretty strong, closely placed, and numerous nerves. As it shows neither base nor termination, its character can not be determined. It may be Nageiopsis or Podozamites. If it be a Zamites it does not belong to the type of *Z. borealis* Heer, but rather to that of *Z. tenuinervis* Font., of the Lower Potomac.

The above constitute all the occurrences of possibly cycadaceous foliage in the Hay Creek strata.

Genus GLOSSOZAMITES Schimper.

GLOSSOZAMITES FONTAINEANUS Ward n. sp.

Pl. CLXII, Figs. 16-18.

1894. *Glossozamites?* sp. Font.: Journal of Geology, Vol. II, p. 260.[1]

The most common fossils are fragments of detached leaflets and one entire leaflet of a plant which is strikingly like a Neuropteris of the Coal Measures (*N. flexuosa*). I am pretty sure, however, that it is a Glossozamites, a form of cycad that has leaflets which closely resemble Neuropteris in form and nervation. This, if a Glossozamites, has leaflets proportionately broader and shorter than any known to me, and it is probably new. I wish that you would compare it with the figures of Glossozamites in your library.[2]

Genus CYCADEOSPERMUM Saporta.

CYCADEOSPERMUM ROTUNDATUM Fontaine.

Pl. CLXII, Fig. 19.

1889. *Cycadeospermum rotundatum* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 271, pl. cxxxvi, fig. 12.

A single specimen of a round, nut-like seed was found on the horizon 100 feet below the Dakota sandstone, at the cliff on Oak Creek, at Robbin's Ranch. This in all respects is exactly like the seed found in the Lower Potomac of Virginia, and described under the name *Cycadeospermum rotundatum*, in Mon. U. S. Geol. Survey, Vol. XV, p. 271. A similar seed was found in the Trinity division of the Comanche series of the Lower Cretaceous of Texas. The Hay Creek seed has the shape and size of *C. rotundatum*, with also its characteristic epidermis, which is smooth, parchment-like, and durable.

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[1] As this species is very well characterized and evidently new, I thought it deserved a specific name, and have therefore dedicated it to Professor Fontaine, who determined its generic affinities and described it.

[2] I have complied with the last suggestion in the above, which is contained in his report on the small collection made by Professor Jenney and myself from the slope of Red Canyon, west of the fossil forest containing these specimens. I have examined all the figures of Glossozamites and of the forms originally referred to other genera (Podozamites, Pterophyllum) that Schimper referred to that genus when he established it. The pinnules are generally more elongated and narrow, conforming to Schimper's character (Traité de Pal. Vég., Vol. II, p. 128) "*folia linealia, obtuse acuminata, foliolis lingulatis.*" This, however, has not been consistently adhered to. The figure that approaches ours most nearly is that of Kurr in his Beiträge z. foss. Fl. d. Juraform. Württemburgs, 1845, pl. i, fig. 5, called by him *Pterophyllum oblongifolium*, and referred to Glossozamites by Schimper.

In their short, rounded form they approach much more closely to some species of Otozamites (cf. *O. Beanii*) (L. & H.) Brongn. in Saporta, Plantes Jurassiques, Vol. II, pl. xcv, Fig. 2), and our Fig. 17 even shows a slightly auriculate base. That genus passes in some of its species into Sphenozamites, in which the pinnules are wedge-shaped at the base, and either sessile or raised on a short stalk. Our forms may be compared with *S. latifolius* (Brongn.) Sap. (cf. op. cit., pl. cxiii, figs. 2, 3).

Genus WILLIAMSONIA Carruthers.

WILLIAMSONIA ? PHŒNICOPSOIDES Ward n. sp.[1]

Pl. CLXII, Fig. 20.

An imperfectly preserved imprint of a portion of a plant was found on the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek. This, owing to its strong resemblance to Williamsonia, is placed doubtfully in that genus.

It consists of the summit of what seems to have been a thick, fleshy stem, from which radiate flabellately the basal portions of what were probably thick, fleshy bracts, having the character of those of Williamsonia. The nature of these can not be made out, as only their bases are preserved, and these seem to be distorted from compression by crowding. This gives them less width than is shown in the bracts of most Williamsonias. The fossil looks something like a palm leaf, which preserves only the portion immediately around the summit of the petiole. It resembles, also, some of the forms of Jurassic Phœnicopsis, which Heer has described in his Fl. Foss. Arct., Vol. IV, Pt. II (Beiträge zur Juraflora, Ostsib.), p. 112, pls. xxix, xxx, and it is not impossible that it may belong to this genus. If it is a Williamsonia, it is probably a new species.

Class CONIFERÆ (Conifers).[2]

Conifers form the most abundant plants in the Hay Creek strata. They surpass in species any other great group, and far exceed in the number of individuals of some species any other plants. They are, as a rule, the best preserved specimens that are found at the several localities. While they are the most abundant forms in the higher strata, there is a noteworthy scarcity of them in the lower.

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[1] Whatever may be the objections to giving names to defective objects, it is found in practice that to designate them merely "sp." after assigning them even doubtfully to a genus leads to great confusion and involves much more labor on the part of all who may subsequently have anything to do with them than to give them specific names. Such a designation is a name. It has to be credited to the namer, and the awkward combination thus produced becomes a permanent part of the synonomy. But it involves the possibility that several different objects may have the same combination throughout. Some papers are so burdened with these names, falsely supposed to obviate the objection of *nomina nuda* or of undue definiteness, that it becomes necessary to number them and refer to them as Nos. 1, 2, 3, etc., or even to count the lines on the page where the particular one in question is mentioned and refer to them in this way. If they are not described they are *nomina nuda*, and if described they are names, and must be identified in some way. The evils of this practice have become so great that it might almost be given as a rule that if a form is worth mentioning at all it is worth a specific name.

In view of the above I have given names to most such objects treated in this paper, and the name here employed is justified by Professor Fontaine's comparison of it with Heer's genus Phœnicopsis.

[2] I have not attempted in this paper to classify the Coniferæ according to the latest systems, but have left the arrangement substantially as Professor Fontaine drew it up. The forms enumerated, however, embrace not only the families Taxaceæ and Pinaceæ but also the class Ginkgoales.

Genus ARAUCARITES Presl.

ARAUCARITES WYOMINGENSIS n. sp.

Pl. CLXIII, Figs. 1–9.

A number of cone scales and seeds were found in the lower strata of the Hay Creek Lower Cretaceous series which seem to belong to a new species of conifer closely resembling Araucaria. The fossils occur as cone scales and seeds on the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek. A cone scale (Pl. CLXIII, Fig. 7) was discovered with traces of a seed on it at the contact of the Cretaceous with the Jurassic, at the bed of shales, Lon Cottles's ranch; also a number of detached seeds (Pl. CLXIII, Figs. 1–6, 8, 9). Some seeds attached to scales and some scales without seeds were found. These fossils form pretty much all that were obtained from this locality. Some of the seeds and scales are remarkably well preserved, and show very well the relation of the seeds to the scales, as well as the form of the latter. The scales, like those of the true Araucaria, were evidently very deciduous, for no indication was found of their attachment to an axis. Both the seeds and the scales vary a little in shape, which is no doubt due to distortion from pressure. The seeds are hard and bony or nut-like in structure, and have an ovate-cuneate to nearly cuneate form. They are 4 to 5 mm. long, and have a width of 3 to 3.5 mm. in their widest portion. The forms of these seeds, differing somewhat in shape, are given on Pl. CLXIII, Figs. 1–9. Fig. 1 (enlarged 2 diameters in Fig. 2) gives the most common and normal form. This seed shows on its margin a remnant of the cone scale to which it was once attached. Fig. 3 (enlarged 2 diameters in Fig. 4) shows a seed somewhat larger and narrower than that given in Fig. 1. Fig. 5 (enlarged 2 diameters in Fig. 6) gives a shape that is more ovate than the normal, more enlongated, and narrower proportionally than common. This shape nears that of *Carpolithus fœnarius*, described below, and suggests the idea that this latter may be an abnormal form of the Araucarites now being described. These variations are most probably due to distortion from pressure.

The cone scales are strikingly like those of Araucaria. They are broadly cuneate in outline, and leaving out their terminal part, are not unlike the seeds borne on them. In their widest portion they are about 9 mm. wide. Including their beak-like tips, they have a length of about 12 mm. Their free ends or summits are thickened and carry a beak-like projection, as in Araucaria. They show, as might be expected, more distortion from pressure than do the seeds. They were apparently leathery, firm in texture, and very durable. Fig. 7 shows a cone scale that has indications of the thickening at its summit. Fig. 8 (enlarged 2 diameters in Fig. 9) gives the most complete and undistorted scale found. It has a seed partly embedded in its surface, and this embed ding of the seed in the inner surface of the scale appears to have been the normal mode of attachment of the seed to the cone scale. Judging from this specimen the seeds were borne singly under each scale, embedded in its inner surface. They were flattened, and in shape resembled the scale to which they were attached. These features remind one strongly of the cones of *Araucaria Cunninghamii* Aiton, the Moreton Bay pine, which contains similar seeds in the same way in its cone scales.

ARAUCARITES CUNEATUS Ward n. sp.[1]

Pl. CLXIII, Fig. 10.

This is a single cone scale found at John Barr's tunnel, on the horizon 150 feet above the top of the Jurassic. It is too poorly preserved and there is too little material to enable one to fix the character. It is, however, a cone scale of some Araucarites, and it is clearly a different species from *Araucarites wyomingensis*, for it is much longer than any of the cone scales of that plant, and it tapers more gradually. It is spatulate-cuneate in form, rounded at the free end, and widest here, having the width of 9 mm. in this portion. It is 2 cm. long and tapers very gradually to the end by which it was attached, where it shows a width of 2 mm. It shows no trace of a beak at the free end, and none of a seed, as it has evidently suffered from maceration.

Genus PINUS Linnæus.

PINUS SUSQUAENSIS Dawson.

Pl. CLXIII, Figs. 11a, 12, 13.

1883. *Pinus susquaensis* Dn.: Trans. Roy. Soc. Can., Sec. IV, Vol. I, p. 23, pl. iii, fig. 36.

Sir William Dawson, in his paper on the Cretaceous and Tertiary Floras of British Columbia and the Northwest Territory (1883) and on the Mesozoic Floras of the Rocky Mountain Regions of Canada (1885), p. 9, pl. ii, figs. 6, 6a, has described very narrow and long Pinus leaves, which he has named *P. susquaensis*. Fragments of precisely similar leaves occur mostly in the lower strata of the Hay Creek Lower Cretaceous. This gives another connecting link with the Kootanie flora. The specimens found in the Hay Creek beds are much more imperfect than those described by Sir William Dawson. They are never found entire or grouped, but are fragments sufficient to show that they must have been quite long. Their fragmentary and scattered condition indicate that they must have drifted some distance. It is not always easy to distinguish leaves like these from those of *Leptostrobus longifolius*, which they much resemble, especially when no nerves are visible. The possession of a midnerve, when this is visible, is decisive. Otherwise the decidedly greater thickness and rigidity of the Pinus leaves points

[1] Professor Fontaine did not give this a specific name, and I have supplied it on the principle stated in the last footnote. It is perhaps better than to reject it altogether.

to their presence. The Hay Creek leaves are one-nerved, about 1 mm. wide, quite thick and rigid. They occur on the horizon 100 feet below the Dakota sandstone, in small bits, which are rather rare and of doubtful character. They may be leaves of Leptostrobus, which by wrinkling from pressure, appear to have a midnerve. The locality showing these doubtful forms is the cliff on the north side of Pine Creek, where a multitude of Leptostrobus leaves occur with them.

On the horizon 150 feet above the Jurassic, at the shales under the third sandstone, Barrett, it is more certainly shown; still, however, in rather rare and small fragments. These are thick in texture, one-nerved, and rigid. On the horizon 50 feet above the Jurassic, at the carbonaceous shales, Webster's ranch, it is quite common in pretty large, well characterized fragments.

The specimen figured in Pl. CLXIII, Fig. 11a is from the cliff on the east bank of Oak Creek; that in Fig. 12 is from the shales under the third sandstone above the coal at Barrett, and the large leaves shown in Fig. 13 are from the cliff on the east bank of Oak Creek, 2 miles below Robbin's ranch.

Genus ABIETITES Hisinger.

ABIETITES ANGUSTICARPUS Fontaine.

Pl. CLXIII, Fig. 14.

1889. *Abietites angusticarpus* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 263, pl. cxxxiii, fig. 1.

A specimen of a narrow cone was found on the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek. This is apparently identical in species with the cone of a similar character found in the Lower Potomac of Virginia and described as *Abietites angusticarpus* in Mon. U. S. Geol. Survey, Vol. XV, p. 263, pl. cxxxiii, fig. 1. It has the same form with the Potomac plant and the same kind of cone scales, which, in their lower portions at least, are thin and at the same time are closely imbricated.

Genus LEPTOSTROBUS Heer.

LEPTOSTROBUS LONGIFOLIUS Fontaine.

Pl. CLXIII, fig. 15; Pl. CLXV, Fig. 3.

1889. Leptostrobus longifolius Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 228, pl. ci, figs. 2, 3; pl. cii, figs. 1–4; pl. ciii, figs. 6, 6a–e, 7, 7a, 8, 8a, 9, 10, 10a, 11, 12; pl. civ, fig. 6.

This species, described by the writer from the Lower Potomac of Virginia in Mon. U. S. Geol. Survey, Vol. XV, pp. 228–230, is one of the most common plants in Professor Jenney's division No. 2, of the Hay Creek beds. Hardly a specimen at some localities is found without imprints of fragments of the leaves, and on some fragments of rocks they are piled upon one another. It is not found at all below the horizon 100 feet beneath the Dakota sandstone. With only one probable exception the leaves are found unattached to a stem. They occur mostly as scattered fragments and show neither base nor summit. In cases where the specimens are very numerous and lie one upon another there is no means of determining the original length of the leaves. They must, however, have been very long, for some of the fragments are 8 cm. long. The texture was thin, a good deal thinner than that of the leaves of Pinus. This thinness of texture and the absence of a midnerve are the most obvious differences between this plant and Pinus.

This plant occurs on the horizon 100 feet below the Dakota sandstone at the cliff on the north side of Pine Creek, which furnished the specimens figured on Pl. CLXIII, Fig. 15, and Pl. CLXV, Fig. 3. Here it is the most common plant, scattered leaves occuring on nearly all the specimens, while on some they are piled up or matted together. They occur more rarely on the same horizon, at the cliff on Oak Creek, at Robbin's ranch. On the horizon 60 feet below the Dakota, at the cliff on the east bank of Oak Creek, they are found also, but not very abundantly. The leaves are mostly 1 mm. wide, rarely attaining the width of 1.5 mm. Most of the best preserved imprints show, with the help of a good lens, a varying number of fine parallel nerves, looking like striæ, up to the number of 6, which is probably the true number. Some, however, of the exceptionally well preserved imprints with the same help disclose two comparatively strong parallel nerves, one near each margin with a flat space between, in which fine nerves like those shown on most of the leaves are visible up to about 4 in number. Heer in Fl. Foss. Arct., Vol. VI, Abth. I, Pt. I (Nachträge zur Juraflora Sibiriens) p. 25, has given these last-named characters for some of the leaves of his *Leptostrobus rigida*. The character given by Heer was not seen in any of the leaves of the Lower Potomac of Virginia, no doubt because none of these were as well preserved as are some of the Hay Creek specimens. The fact that some only of the Hay Creek leaves show the two stronger nerves seems to indicate that these are visible as such—that is, as prominent veins—only on the under side of the leaves, whereas on the upper side, if seen at all, they appear as fine nerves. On some of the best preserved imprints, with the help of a lens, these stronger nerves appear to be formed by the close approximation or consolidation of several fine nerves.

One of the specimens from the cliff on the north side of Pine Creek shows a great number of leaf fragments, and among them a number converging so as to appear to form or be attached to a short twig. This is a feature seen in some of the Lower Potomac specimens. From the great number of leaf fragments in some cases, and from the almost total absence of attachments of these, they must have been quite deciduous. From the additional facts found in the Hay Creek specimens we may amend the description of the species given in Mon. U. S. Geol. Survey, Vol. XV, as follows: Leaves thin in texture, showing on the upper surface, with the help of a lens, fine parallel nerves up to 6 in number; on the under surface 2 stronger parallel veins and between them fine nerves up to 4 in number.

It seems to the writer that some Lower Cretaceous plants described under other names should be identified with this species. Heer has described as *Pinus Petorseni* in Fl. Foss. Arct., Vol. I, Kreideflora, p. 84, pl. xliv, fig. 19, a, b, leaves which he gives as being thin in texture, about 1 mm. in width, although in fragments showing considerable length and having several nerves—in a word, as having most, if not all, of the characteristic features of *Leptostrobus longifolius.* This plant, coming from the Kome beds of Greenland, is most probably *Leptostrobus longifolius.* Heer gives as *Czekanowskia dichotoma*, also from the Kome beds, leaves which he describes in Fl. Foss. Arct., Vol. VI, Abth. II, Flora der Komeschichten, p. 14, pl. ii, fig. 12b, pl. iii, fig. 1, and which he identifies with his *Sclerophyllina dichotoma.* It, however, in its leaves appears a more delicate plant than *S. dichotoma*, and with narrower forms. The leaves do not appear to fork at all, the apparent forking, as given by Heer, being due to the fact that the ends of some of the apparent branches, really independent leaves, are hidden by the other superposed leaves. The leaves of this specimen are exactly like those of *Leptostrobus longifolius* in their general character and their arrangement on the stem, as shown in Heer's pl. iii, fig. 1, and much like some of the forms of this species shown in the Potomac specimens, for example, those in pl. cii, figs. 1, 2, of the Potomac flora.

LEPTOSTROBUS? ALATUS Ward n. sp.[1]

Pl. CLXIII, Figs. 16, 17.

A small winged seed was found on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek. It reminds one of the winged seed obtained from the Brown Jura and assigned by Heer to Leptostrobus (see Fl. Foss. Arct., Vol. VI, Abth. I, Pt. I, Nachträge zur Juraflora Sibiriens, p. 23). The seed now in question is about 4 mm. long and less than 2 mm. in width. It is elliptical in shape and appears to retain only a portion of the wing, showing on the left-hand upper portion a part of it in the form of an elliptical projection like a beak. The seed is entire, but the appendage is too poorly preserved to give any reliable indication of its true character. Its true position is quite doubtful, but it may provisionally, and for the sake of a name, be placed with Leptostrobus. *Leptostrobus longifolius* is the most common fossil at this locality.

[1] No specific name was given by Professor Fontaine to this seed. I have therefore employed the leading character in assigning it a name.

Genus ATHROTAXOPSIS Fontaine.

ATHROTAXOPSIS TENUICAULIS Fontaine.

Pl. CLXIV.

1889. *Athrotaxopsis tenuicaulis* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 241, pl. cxiv, figs. 4, 4a, 5; pl. cxv, figs. 4, 4a; pl. cxvi, fig. 6; pl. cxvii, figs. 2, 2a.

In Professor Jenney's division No. 2 of the Hay Creek beds are found some specimens of a conifer that agree well with *Athrotaxopsis tenuicaulis* as described by the writer, from the Lower Potomac of Virginia, in Mon. U. S. Geol. Survey, Vol. XV, p. 241. The fossils are in the form of fragments of alternate twigs of varying length, as shown on Pl. CLXIV, Figs. 1-3. The thickness of these will, on an average, somewhat surpass the average of the Potomac *Athrotaxopsis tenuicaulis* and will lie between it and that of *A. grandis*. This, however, does not seem to indicate a new species, but rather a more vigorous habit of growth for the Hay Creek plants, a feature shown also in the *Sequoia Reichenbachi*, from these strata. In the Hay Creek beds *Athrotaxopsis tenuicaulis* occurs on the horizon 100 feet below the Dakota sandstone rather commonly, but in small fragments at the cliff on the north side of Pine Creek. On the horizon 60 feet below the Dakota sandstone it occurs not very commonly, but in well-preserved large twigs at the cliff in the east bank of Oak Creek, from which all the specimens here figured were obtained. One of the specimens bears a cone, represented by Fig. 4 of the same plate.

Genus SEQUOIA Endlicher.

SEQUOIA REICHENBACHI (Geinitz) Heer.

Pl. CLXV, Figs. 1, 2; Pl. CLXVI, Fig. 1.

1842. *Araucarites Reichenbachi* Gein.: Characteristik d. Schichten u. Petrefacten d. sachs.-böhm. Kreidegebirges, Heft III, p. 98, pl. xxiv, fig. 4.
1849. *Araucaria Reichenbachi* (Gein.) Debey: Entwurf. z. einer geogn.-geogenet. Darstellung d. Gegend v. Aachen, pp. 63, 64 (Nachträge).
1868. *Sequoia Reichenbachi* (Gein.) Heer: Fl. Foss. Arct., Vol. I, p. 83, pl. xliii, figs. 1d, 2b, 5a, 5d, 5dd, 8, 8b.[1]

Fine leafy branches of a Sequoia, having all the characters of *S. Reichenbachi*, occur at the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek, along with the cones that probably belong to the same species.

At the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek, several cones of a similar kind are found. These latter are poorly preserved, but they retain character enough to justify identifying them with cones of *S. Reichenbachi*.

[1] The synonomy here given is only partial, as a complete one would involve the decision of a number of knotty questions, for which this is obviously not the place. The only omission that concerns us here is that of *Geinitzia cretacea* Endl., which will be considered a little later.

The fine, leafy twigs distinguished by Professor Jenney as specimens A and B are the most complete of the leafy branches. The largest of these, specimen A, shows a portion of an ultimate twig that is 15 cm. long and 3 mm. wide. It has a number of the characteristic curving leaves of *S. Reichenbachi*, which are widest at base and narrow at their ends to an acute tip. The longest of these were 16 cm. in length. The leaves that are retained are attached laterally. The upper face of the twigs show occasional elongate elliptical scars left by the bases of the leaves that have fallen off.

The slab marked B by Professor Jenney has been photographed and forms Pl. CLXV. Fig. 1, on the left, shows the leafy branch above mentioned, while Fig. 2, on the lower right, is the imprint of a small cone which may have belonged to the same branch or individual. All across the slab lie the long two-nerved leaves of *Leptostrobus longifolius* Font. (Fig. 3). This specimen is from the cliff on the north side of Pine Creek, 100 feet below the Dakota sandstone in division No. 2 of Professor Jenney.

The fine cone given in Pl. CLXVI, Fig. 1, comes from the same horizon and locality. It is almost certainly the cone of *S. Reichenbachi*, for it has attached to it a portion of the twig on whose summit the cone was borne, and this has elliptical scars like those seen on the upper surface of leafy branches of *S. Reichenbachi*. Besides, it agrees very well with the cones griven by Heer for this species in Fl. Foss. Arct., Vol. III, Pt. II (Die Kreide-Flora des Arctischen Zone) pl. xx, figs. 1a, 2, 3. The cone scales are, however, longer than those of Heer, probably on account of differences in the mode of preservation. Those of Heer seem to be compressed vertically, while in the Hay Creek specimens they may be elongated by pressure.

These cones are comparatively large for those of a Cretaceous Sequoia. With the scales closed, this one was probably broadly elliptical in shape, having a length of 30–35 mm. and a maximum thickness of 20–25 mm.

SEQUOIA GRACILIS Heer.

Pl. CLXVI, Fig. 2.

1874. *Sequoia gracilis* Heer: Die Kreide-Flora des Arctischen Zone, K. Svensk. vet.-Akad., Handl., Vol. XII, No. 6 (Fl. Foss. Arct., Vol. III, Pt. II), p. 80, pl. xviii, fig. 1c; pl. xxii, figs. 1a, 1b, 1c, 2–4, 5a–e, 7, 8, 8b, 9, 10, 10b, 10c.

Small, round cones of a Sequoia occur sparingly on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek and at the cliff on the south side of Pine Creek. The specimens here figured were obtained at the latter locality. These cones are evidently of a different species from those that occur with them, and which I have identified with *Sequoia Reichenbachi*. They are much smaller, and are round in shape. One of them is depicted in Fig. 2, Pl. CLXVI. They have not been found attached to any leafy branches, hence the character of the leaves with which they belong can not be determined. In size, shape, indeed in all features, they agree well with the cones that Heer determines as those of *S. gracilis*, and which he depicts in Fl. Foss. Arct., Vol. III, Pt. II, pl. xxii, figs. 5a, 5b, 5d.

Leafy branches of *Sequoia gracilis* have not been identified by the writer from the Hay Creek strata, but the plant identified with *Sphenolepidium parceramosum* is not uncommon in the strata containing the cones now in question. The leaves and twigs of this are so much like those of *S. gracilis* that I would not hesitate to identify these Hay Creek fossils with it were it not that the leaves contain a midrib, whereas Heer says those of *S. gracilis* are without it.

SEQUOIA sp. Fontaine (immature cone).

Pl. CLXVI, Figs. 3, 4.

An immature cone of some Sequoia was obtained on the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek. It is 8 mm. long, 6 mm. wide, and nearly globular in form. On its surface it shows, rather vaguely, rhombic imprints of the character of those made by the terminations of Sequoia cone scales. There is nothing to show with what leafy branches it belongs. It is shown natural size on Pl. CLXVI, Fig. 3, and enlarged two diameters in Fig. 4.

Genus GEINITZIA Endlicher.[1]

GEINITZIA JENNEYI n. sp.

Pl. CLXVI, Figs. 5-11; Pl. CLXVII.

Certain remarkable imprints of the stems of a conifer, which seems to be a new species of the genus Geinitzia, are found in Professor Jenney's division No. 2 of the Hay Creek beds. They occur in smaller specimens on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek (Pl. CLXVI, Figs. 5-11), and on the horizon 60 feet below the Dakota, at the cliff in the east bank of Oak Creek, in larger ones (Pl. CLXVII). The stems leaving the imprints were fragments of much larger parts, for they are broken at both ends and show no appreciable change in thickness from one end to the other. In no case was any of the vegetable matter of the stem or leaf preserved, but all the fossils are in the form of flattened molds of the stem. The molds on their inner surface bear imprints in the

[1] This genus was founded by Endlicher in his Synopsis Coniferarum, 1847, p. 280, to include certain forms referred by Geinitz to Sedites and Araucarites and by Corda to Cryptomeria. Among the former was the *Araucarites Reichenbachi* of Geinitz, which Heer in 1868 identified with the living genus Sequoia, of which Endlicher was also the author. Since the latter date this well-known fossil plant has been almost uniformly called *Sequoia Reichenbachi*, and many place Endlicher's *Geinitzia cretacea* under it as a synonym. Others retain the older forms under Geinitzia, and this has been done by Professor Fontaine, while still recognizing *Sequoia Reichenbachi*. It will be allowed to stand thus, although it seems to me that the retention of the genus Geinitzia logically carries the *S. Reichenbachi* with it into that genus as the type, while, on the other hand, the recognition of *S. Reichenbachi* logically abolishes the genus Geinitzia.

inclosing shale, which are the reverse of the markings shown on the surface of the stem. The molds are so flattened by pressure that they are almost completely collapsed. In splitting the shale the cleavage took place along these collapsed molds, so that the imprint on the specimen shows the inner surface of more or less than one-half of the mold. In some of the imprints both margins of the half mold are more or less preserved, so that the original width may be detected, and in some places a narrow portion of the other half, next to the margin, is obtained, so that one can get an idea of the thickness of the stem after its flattening. When we take into consideration the considerable thickness of some of the stems, as indicated by the width, the amount of compression is surprising. Molds having a width of 15 mm. show a hollow only 2 to 3 mm. thick. This indicates that comparatively old branches were still soft and succulent. On one of these flattened molds may be seen imprints of short portions of the basal parts of a number of leaves. These leaves were a portion of those attached to the stem on the parts that, in the crushing, formed the margins of the collapsed molds, and hence were in the most favorable position to be preserved.

The stems.—In describing the stems I will give first the character of the imprints in the shale, and then from these deduce the nature of the markings on the stem that made them.

The smallest imprint seen of what seems to be a series of stems of the same plant, and the one here named *Geinitzia Jenneyi*, is that depicted in Fig. 5 of Pl. CLXVI enlarged two diameters in Fig. 6. It is 35 mm. long and 4 mm. wide, being made by a fragment of what was originally a much longer stem. If it belongs to the same plant with that making the impressions to be described further on, then it is the youngest of the series. The imprints of the leaf scars have considerable interspaces, but still are pretty thickly set on the imprint of the stem. They are rhombic in form, with the greater dimensions in the direction of the axis of the stem. Their lateral angles are more or less rounded off. The superior angle is acute and the inferior one similar in form, but this latter is generally not defined well enough to be seen. Toward the upper part of the imprint there is a vague indication, on the best preserved imprints, of a furrow running in the direction of the axis of the stem, with a pit, as if made by the entrance of the vascular bundle of the leaf. If these imprints were stretched at right angles to the axis of the stem, which would occur in the case that they are made by permanent leaf scars on stems that increase in thickness, they would graduate in shape into the forms represented on Pl. CLXVII, Figs. 1, 2.

Pl. CLXVII, Fig. 1, depicts the largest and most complete imprint found. It was evidently made by a stem that was much larger and longer than that making the imprint given in Fig. 5 of Pl. CLXVI, and apparently was correspondingly older. That it is a fragment of a much longer stem is shown by the fact that it is broken short off at both ends, and, although 16 cm. long, shows, from one end to the other, no appreciable deviation from a width of 15 mm. This is the imprint that shows traces of leaves along the margins. This imprint is thickly set with depressions made by leaf scars. These imprints of leaf scars are more closely placed and much larger and more distinct than those of Pl. CLXVI, Fig. 5. With the increased thickness of the stem, the leaf scars seem to have had their dimensions at right angles with the stem increased more than those in the direction of the axis.

The imprints of the leaf scars shown on this specimen are deep and very distinct. In contour they are approximately rhombic, with the transverse dimensions slightly greater than those in the direction of the length of the stem. The upper margin, however, is a curve, and the lower one shows a more or less obtuse angle. The right and left ends, or lateral angles, are acute and more or less drawn out into points that are directed downward, as shown in Fig. 2 of Pl. CLXVII, which represents an enlarged and restored imprint. Within the depressed area forming the imprint of the leaf scar there is a boss or protuberance, more or less elliptical in shape, with its major axis at right angles with the axis of the stem. This boss is often distorted by pressure, and varies then somewhat in shape, being sometimes even round. The boss is bounded by a depressed line or furrow that is slightly deeper than the rest of the imprint. From the right and left ends of the furrow a similar furrow, one on each side, in perfectly formed imprints, runs toward the lateral angles of the imprint of the leaf scars. But these are rarely seen. The boss is placed, not centrally, but somewhat nearer the angle of the lower margin of the imprint of the leaf scar. As indicated in the best preserved imprints, the original and normal shape of the boss and of the furrow which bounds it and determines its form was approximately that of the entire imprint—that is, rhombic—but with the difference that the lower angle, instead of the upper, is rounded out more or less into a curve. However, as stated, distortion usually destroys this form. There are sometimes indications that the central portion of the boss was raised into a sort of mamma or teat.

The imprint given in Fig. 8 of Pl. CLXVI seems to have been made by a stem older and larger than that depicted on Pl. CLXVII. Its width is about 15 mm., but one margin is not preserved, so that the imprint does not show the true size of the stem. The imprints of the leaf scars here are larger and more crowded than in the form represented on Pl. CLXVII, Fig. 1. Owing to their crowding, their upper margin no longer shows the curvature seen in that figure, but tends to become angular, giving the contour more truly a rhombic shape. The lateral angles are more rounded off, and the lower angle is prolonged to form a kind of tail, as represented in Fig. 9 of Pl. CLXVI. Between these imprints of scars there are no interspaces, as were still to be seen on the specimen figured on Pl. CLXVII, but they crowd one another. The stem, whose imprint is depicted in Fig. 8 of Pl. CLXVI, must have been larger than that figured on Pl. CLXVII, for it shows a width of 15 mm., with only one margin preserved. The amount of woody matter in the stems making the imprints must have been small, for in the specimens enough of the mold is shown to indicate that it was flattened to a thickness of only 2 or 3 mm. This leads us to infer that these imprints could not have been made by cones, and that if by stems they must have remained succulent a long time.

The imprint depicted in Fig. 10 of Pl. CLXVI, if not larger than that represented by Fig. 8, seems to have been older. As one margin of the imprint is not shown, we can not determine the true size of the stem. The imprint of the stem in this case is rather more than 15 mm. wide. The imprints of the leaf scars are larger, more crowded, and more distinct than those of any of the previously described specimens. In their shape they show still further modification. The upper margin is more decidedly angular, the tail from the lower angle is nearly or quite obliterated and the imprints are more elongated transversely. The scar imprints have here more of the true rhombic form than any of those described in the preceding pages. The imprints are deep and very distinct. The central protuberance is more distinct than any of the others, and the furrows running from its right and left ends to the lateral angles of the imprint of the leaf scar are deeper and more sharply defined than in any others.

The imprints described in the preceding account are seen in the rock material that surrounded and entombed the original stems. They are markings imprinted on the inner surfaces of the collapsed molds, and of course in character they are the reverse markings on the stems which imprinted them. Convexities on the surface of the stems form concavities in the surrounding sediment, and, vice versa, concavities correspond to convexities. It may be concluded, then, that the stems forming these fossils had on their surface prominences or cushions approximately of rhombic form, but varying in the manner described with the age and thickness of the stem. These had within their margins a rim or ridge, also approximately rhombic in form, and this inclosed a depressed, transversely elongated area which contained a circular, still deeper depression, which was caused by the entrance of the vascular bundle from the leaf into the stem. From the lateral angles of the central ridge inclosing the depression there passed, one on each side, a raised line or ridge to the lateral angles of the leaf scar. These cushions seem to have been permanent, and they were probably left by the disarticulation of the leaf bases from the stems, like the scars of Lepidodendron, which they resemble in form. They seem to have grown in size with the increasing thickness of the stem which bore them and to have become more crowded and pronounced in character. A comparison of the imprints depicted in the figures given in the preceding seems to show that they were made by stems belonging to the same species, and that the differences in their forms are caused by the fact that the scars in enlarging with age increased more in their dimensions at right angles to the axis of the stems than in the direction of that axis. At the same time they became more crowded.

The leaves.—Unfortunately, no imprints of entire leaves were seen attached to the fossils. On the margins of the imprints given on Pl. CLXVII there may be seen imprints of small portions of the lowest parts of a number of leaves. These imprints indicate that the leaves that made them are narrow, curved upward, keeled, pretty thick at their bases, and very rigid. In fact the imprints are such as would be made by leaves similar to those which Velenovský gives as those of *Geinitzia cretacea*, and which he has figured and described in Die Gymnospermen der böhm. Kreideformation, p. 15, pl. viii, figs. 11, 12; pl. ix, figs. 1, 2. The leaves referred to are given in pl. ix, fig. 1.

At first sight the imprints of the leaf scars look, in their general form, like Brachyphyllum, but the leaves of that genus have a boss in their center instead of a pit. The other markings also are too regular for those of Brachyphyllum, and are not of the same pattern. The imprints are strikingly like those made by the terminal surfaces of the cone scales of some Pinus, but to make them the scales must have stood at right angles with the axis of the cones. This is true of the cones of Geinitzia, which are also long and cylindrical. But the markings on the terminal surfaces of the cone scales of Geinitzia are totally different. Besides it would seem impossible to compress any cone into the thinness indicated by the molds, especially cones with scales at right angles to the axis. The forms represented in Fig. 5 of Pl. CLXVI and on Pl. CLXVII are obviously impossible for cones. Those given in Figs. 8 and 10 of Pl. CLXVI might more probably pass for imprints of cones, but they are clearly made by portions of long cylindrical bodies, too long for cones. Then, too, the impressions on these are clearly essentially the same in character as those on Pl. CLXVII. The impressions made by the leaf scars in these stems are so strikingly like those shown on fig. 1, pl. ix, of Velenovský, referred to above, that we can not resist the belief that if not of the same genus they must be closely allied to it. The resemblance between Velenovský's fig. 1 and Fig. 1 of Pl. CLXVII is essentially strong, extending not only to the shape of the imprints of the leaf scars, but also to the depression within it. The same gradation in shape is also indicated. The younger branches of *Geinitzia cretacea*, as given in pl. ix, fig. 2, of Velenovský's work, have the rhombic imprints with the greater dimensions in the direction of the axis of the stem, as in Fig. 5 of Pl. CLXVI. Another fact that indicates that our plant is nearly allied to that of Velenovský is the number, persistence, and distinctness of the imprints of the leaf scars. I know of no conifer except Geinitzia that shows these features. Heer's *Geinitzia formosa* shows crowded, persistent rhombic leaf scars.

Lesquereux, in his Tertiary Flora, pl. lxi, figs. 28, 29, represents stems with crowded, persistent scars of what he calls *Sequoia longifolia*. On pl. lxii, figs. 15–18, he gives representations of stems with similar scars, which he calls *Sequoia biformis*. These scars closely resemble those on our Pl. CLXVI, Fig. 5. On pl. vii, in fig. 19, he gives a similarly marked stem for *Abietites dubius*. All of these plants Schenk states he regards as Geinitzia. See Zittel's Handbuch der Palæontologie, Abth. II, pp. 299–300. On pl. vii, of the above-cited work of Lesquereux, in fig. 31, there is a representation of a stem of what he regards as *Pinus palæostrobus* (Ett.) Heer. The scars on this are strikingly like those on the older stems of the Hay Creek plant.

The resemblance between the Hay Creek forms and Geinitzia is so strong that we are justified in placing them in that genus, at least provisionally. As Geinitzia is hitherto known from no strata older than the Younger Cretaceous, it may be found that our plant is an ancestral form of the true Geinitzia. In that case it would be fittingly named *Geinitzites Jenneyi.*

Genus SPHENOLEPIDIUM Heer.

SPHENOLEPIDIUM KURRIANUM (Dunker) Heer.

Pl. CLXVI, Figs. 12, 13.

1846. *Thuites (Cupressites?) Kurrianus* Dunk.: Monographie d. norddeutsch. Wealdenbildung, p. 20, pl. vii, fig. 8.
1846. *Lycopodites?* sp. Dunk.: Op. cit., pp. 20, 85, pl. viii, fig. 8.
1847. *Widdringtonites Kurrianus* (Dunk.) Endl.: Synopsis Coniferarum, p. 272.
1849. *Brachyphyllum? Kurrianum* (Dunk.) Brongn.: Tableau, p. 107.
1852. *Widdringtonites Haidingeri* Ett.: Beitrag z. Flora d. Wealdenperiode, Abh. d. k. k. geol. Reichsanst., Vol. I, Abth. 3, No. 2, p. 26, pl. ii, fig. 1.
1852. *Araucarites Dunkeri* Ett., in pt.: Op. cit., p. 27, pl. ii, fig. 10 (non figs. 2–9).
1870. ? *Araucarites hamatus* Trautsch.: Der Klin'sche Sandstein, Nouv. Mém. Soc. Imp. de Moscou, Vol. XIII, p. 225 (Livraison 3, p. 37), pl. xxi, figs. 3, 3a, 3b, 3c.
1871. *Sphenolepis Kurriana* (Dunk.) Schenk: Foss. Fl. d. nordwestdeutsch. Wealdenformation, Palaeontographica, Vol. XIX, p. 243, pl. xxxvii, figs. 5-8, 8a; pl. xxxviii, fig. 1 (non fig. 2).
1881. *Sphenolepidium Kurrianum* (Dunk.) Heer: Contr. à la Fl. Foss. du Portugal, Section des Travaux géologiques du Portugal, p. 19, pl. xii, fig. 1b; pl. xiii, figs. 1b, 8b; pl. xvi, fig. 5c; pl. xviii, figs. 1–8 (excl. figs. 5b, 5c).
1881. ? *Thuites Choffati* Heer, in pt.: Op. cit., p. 11, pl. x, figs. 7, 8.

Specimens were obtained of a conifer that can not be distinguished from the widely diffused Lower Cretaceous plant *Sphenolepidium Kurrianum.* They occur on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek, rather commonly, and sometimes in well preserved branching specimens. On the same horizon, at the cliff on the south side of Pine Creek, and the cliff of Oak Creek, at Robbin's ranch, the fossils are rarer and not so well preserved. The best specimens are found on the horizon 60 feet below the Dakota, at the cliff in the east bank of Oak Creek. Here some very fine, freely branching specimens were obtained. The scale-like leaves of this plant in the Hay Creek beds are a little broader than those found in the Potomac, probably indicating a more luxuriant growth, which feature is seen in a number of the other Hay Creek plants.

The specimen represented by Fig. 12 of Pl. CLXVI is from the cliff on the north side of Pine Creek, and that by Fig. 13 from the shales on the south side of Pine Creek.

SPHENOLEPIDIUM PARCERAMOSUM Fontaine.

Pl. CLXIII, Fig. 11b; Pl. CLXVIII, Figs. 1-3.

1889. *Sphenolepidium parceramosum* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 257, pl. cxxix, figs. 7, 7a, 7b; pl. cxxx, figs. 8, 8a; pl. cxxxi, fig. 2.

This plant, also first found in the Lower Potomac of Virginia, occurs in the Hay Creek beds. It is confined, like *Sphenolepidium Kurrianum*, to the upper member, Jenney's No. 2 of the Hay Creek Lower Cretaceous, and occurs mostly with that plant and *Sequoia Reichenbachi*.

It is found on the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek (Pl. CLXIII, Fig. 11b), rather commonly, and sometimes in fine specimens. On the horizon 100 feet below the Dakota, it is found at two localities: Cliff on the north side of Pine Creek, from which were obtained the specimens figured on Pl. CLXVIII, Figs. 1-3, and cliff on the south side of Pine Creek, being rather common at the first-named locality on Pine Creek.

This plant was described by the writer in Mon. U. S. Geol. Survey, Vol. XV, pp. 257-258. It is well characterized by its long, sparingly branched, slender twigs, thickly clothed with leaves, of which the laterally attached ones have an ovate or elongate elliptical shape and rather long acute tips. They also have a midnerve. The leaves of this plant are in shape much like those that Heer has depicted for *Sequoia gracilis*, but are generally more slender. Were it not for the midnerve I would conclude that it is that Sequoia, showing only a varietal difference. Heer, however, states that *Sequoia gracilis* has no midnerve in its leaves. I would be all the more inclined to identify it with this Sequoia, because small, round Sequoia cones, exactly like those of *S. gracilis*, occur with it. This plant is highly characteristic of the upper portion of the Lower Potomac strata, such as is found near Brooke Station, Virginia, which group is called by Mr. Ward the Aquia Creek series. It forms another of the plants that indicate a similar geological age for the Brooke strata and Jenney's division No. 2 of the Hay Creek beds.

Genus GLYPTOSTROBUS Endlicher.

GLYPTOSTROBUS BROOKENSIS (Fontaine) Ward.

Pl. CLXV, Fig. 4; Pl. CLXVIII, Fig. 4.

1889. *Taxodium* (*Glyptostrobus*) *brookense* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 254, pl. cxxii, figs. 1, 1a, 1b; pl. cxxiv, figs. 3, 3a, 4, 4a, 5, 6, 7, 7a, 8, 9; pl. cxxxi, figs. 5, 5a; pl. clxv, figs. 1-3; pl. clxvi, figs. 4, 4a, 7; pl. clxvii, fig. 3.

1895. *Glyptostrobus brookensis* (Font.) Ward: Fifteenth Annual Report U. S. Geol. Survey, pp. 359, 377, 380.

Several good specimens of this plant, first described by the writer from the Lower Potomac of Virginia in Mon. U. S. Geol. Survey, Vol. XV, p. 254, occur on the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek (from which the specimen here figured on Pl. CLXVIII, Fig. 4, was obtained), along with *Athrotaxopsis tenuicaulis* and *Sphenolepidium parceramosum.* It occurs also, but rarely, on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek, as seen in faint impressions on the large slab, Pl. CLXV, Fig. 4. In the Lower Potomac of Virginia this form is highly characteristic of the upper or Brooke group. Like many of the Hay Creek fossils, the twigs of this conifer are a little stouter than those of the same species found in the Lower Potomac. The leaves also diverge rather more from the stem than do most of those from the Potomac. This, however, is probably due to differences in the modes of preservation.

Genus NAGEIOPSIS Fontaine.

NAGEIOPSIS LONGIFOLIA Fontaine?

Pl. CLXVIII, Figs. 5, 6.

1889. *Nageiopsis longifolia* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 195, pl. lxxv, figs. 1, 1a, 1b; pl. lxxvi, figs. 2-6; pl. lxxvii, figs. 1, 2; pl. lxxviii, figs. 1-5; pl. lxxix, fig. 7; pl. lxxxv, figs. 1, 2, 8, 9.

In the Hay Creek series detached fragments of leaves occur that are so much like *Nageiopsis longifolia* that they may, with little hesitation, be identified with that species. *N. longifolia* occurs in the Lower Potomac of Virginia, in some fine specimens. It was described by the writer in Mon. U. S. Geol. Survey, Vol. XV, p. 195. The distinctive characters of Nageiopsis as compared with Podozamites are found in the basal and terminal portions of their leaves; that is, the characters that may be seen in the detached leaf. As the Hay Creek specimens nowhere show these portions of the leaves, we can not be certain that these fragments are Nageiopsis; but the texture, shape, size, and other features of the fragments, as well as the nervation, agree so well with *N. longifolia* that the identification is justified.

Sir William Dawson, in his paper on the "Mesozoic floras of the Rocky Mountain region of Canada" (Trans. Roy. Soc. Can., Sec. IV, Vol. III), p. 6, pl. i, fig. 3, describes a plant from the Kootanie series of Canada which he identifies with *Podozamites lanceolatus.* This is in most respects much like *Nageiopsis longifolia,* being the termination of a leaf. It is hardly possible that this Podozamites has ranged all over the Northern Hemisphere in its geographical distribution, and from the Triassic into the Lower Cretaceous in its geological age. Schenk's *Zamites Göpperti,* also from the Urgonian of the Wernsdorf beds, seems to be *Nageiopsis longifolia.* The form he gives in Die foss. Pflanzen der Wernsdorfer Schichten (Palaeontographica, Vol. XIX), pl. iii, fig. 6 is just what would be seen in *N. longifolia* if the lower surface of a large leaf be presented uppermost, so that the stem partially hides the insertions of the leaflets.

N. longifolia occurs, so far as yet seen, only at the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek, and also at shales under the third sandstone, Barrett. It is quite common at the former locality and rather rare at the latter.

Both the specimens figured are from the bed of shales under the third sandstone, 50 to 100 feet above the coal at Barrett.

NAGEIOPSIS ANGUSTIFOLIA Fontaine?

Pl. CLXVIII, Fig. 7.

1889. *Nageiopsis angustifolia* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 202, pl. lxxxvi, figs. 8, 9; pl. lxxxvii, figs. 2, 2a, 3, 4, 5, 5a, 6, 6a; pl. lxxxviii, figs. 1, 3, 4, 6–8; pl. lxxxix, figs. 2, 2a.

A single leaflet of a plant that appears to be identical with *Nageiopsis angustifolia* occurs on the horizon 150 feet above the Jurassic, at the shales under the third sandstone, Barrett. This species was described by the writer in Mon. U. S. Geol. Survey, Vol. XV, p. 202. It is one of the most widely diffused species of the Virginia Potomac formation. Although the leaflet is well characterized, and can hardly be anything but this Nageiopsis, I do not make the identification positive, as the amount of material is so small.

Genus BAIEROPSIS Fontaine.

BAIEROPSIS ADIANTIFOLIA Fontaine.

Pl. CLXVIII, Fig. 8.

1889. *Baieropsis adiantifolia* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 211, pl. xcii, figs. 8, 8a, 9; pl. xciii, figs. 1, 1a, 2, 3; pl. xciv, figs. 2, 3.

Fragments of detached leaves of a plant which seems to be identical with *Baieropsis adiantifolia* occur not very abundantly in the Hay Creek beds, and only at the horizon 150 feet above the Jurassic. This plant was found by the writer in the Lower Potomac of Virginia, and was described in Mon. U. S. Geol. Survey, Vol. XV, p. 211. The Potomac specimens yield some forms that are much more complete than any found in the Hay Creek beds. Still, as the leaves are of peculiar shape and have a lobing not found in any others, and as these points are clearly indicated in the specimens drawn, there does not seem to be much room for doubt that the Hay Creek forms are really *B. adiantifolia*. Most of the Hay Creek specimens do not show the margins of the leaves, or, indeed, their shape. On one of these, however, the characteristic nervation of *B. adiantifolia* was visible. This nervation is marked by fine but sharply defined and closely placed nerves that fork so as to spread in a fan-shaped manner. In the specimen figured we have a more complete fragment of a leaf. It shows enough to indicate that the shape of the leaf was the characteristic one of the species now in question, and it has in addition preserved, in the right-hand lower corner of the leaf, two of the characteristic lobes and teeth of *B. adiantifolia.* The teeth are not preserved well enough to show the spike-like tips in which they terminate. These, however, are hardly ever visible, even in the best preserved Potomac specimens.

In the Hay Creek beds this plant occurs in a considerable number of fragments, at the cliff on the north side of the valley of the South Fork of Hay Creek, and in one specimen (that here figured) at the shales under the third sandstone, Barrett.

BAIEROPSIS PLURIPARTITA Fontaine?

Pl. CLXVIII, Figs. 9–12.

1889. *Baieropsis pluripartita* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 208, pl. lxxxix, fig. 4; pl. xc, figs. 2, 2a, 3, 4, 4a, 5; pl. xci, figs. 1, 3, 3a, 4, 7.

Two specimens of a plant that is much like *Baieropsis pluripartita* were found on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek. *B. pluripartita* was found by the writer in the Lower Potomac of Virginia in fine specimens, and was described in Mon. U. S. Geol. Survey, Vol. XV, p. 208. While the Hay Creek specimens are quite fragmentary, they show enough to strongly indicate their identity with the Potomac species. We may rely more fully on conclusions drawn from a small amount of material in the case of such leaves as this than where leaves are concerned that belong to a type common to many different plants. Still, as we have only two imperfect specimens, I make the identification doubtful.

Genus CZEKANOWSKIA Heer.

CZEKANOWSKIA NERVOSA Heer.

Pl. CLXIX, Figs. 1, 2.

1881. *Czekanowskia nervosa* Heer: Contr. à la Fl. Foss. du Portugal, Sect. des Trav. Géol. du Portugal, p. 18, pl. xvii, figs. 5, 5b, 6, 7a, 8, 10, 10b, 11, 11b.

A fossil not to be distinguished from Heer's *Czekanowskia nervosa*, first found in the Wealden of Portugal, occurs in the lower members of the Hay Creek series, Lower Cretaceous. It is found not rarely. A good many fragments are found on the horizon 150 feet above the Jurassic, in shales under the third sandstone, Barrett. On the horizon, 50 feet above the Jurassic, in carbonaceous shales, Webster's Ranch, it is common, occurring there in better preserved and more complete forms than at the higher horizons. The two specimens figured were found at this locality. The leaf of this plant is of the Baiera type, and I think it, as well as Heer's plant, is a true Baiera. Heer describes his forms in Contr. à. la Flore Foss. du Portugal, p. 18. The description that Heer gives applies to the Hay Creek plant, viz, the leaves are divided into laciniæ in a dichotomous manner. The laciniæ are from 1 to 2 mm. wide and have several nerves. The figures of Heer represent that the leaf had at base a single narrow lacinia, and this, by repeated dichotomous subdivision, gave origin to the leaf. The basal lamina, as in the Hay Creek plants, probably passed downward into a petiole. Heer's figures represent the laciniæ more crowded together and looking as if the leaf had been stretched by pressure in the direction of its length. In the Hay Creek specimens the pressure seems to have operated to spread out the lobes. Heer's fig. 11 of pl. xvii represents the specimen of his plant that is nearest to our forms. He says of the nerves of his plant that they are distinct, but in the Hay Creek specimens they are seen with difficulty. Probably this distinction is caused by differences in the mode of preservation. The ultimate laciniæ of the Hay Creek plants are only 1 mm. in width, and it is possible that the subdivision was carried further than was seen.

The shale of the two localities furnishing this plant, although given by Professor Jenney as separated by 100 feet of strata and as occurring at different places, is strikingly alike, being very fine grained and fissile, the substance of the plant peeling off from the stone like paper. It preserves the plants well, and additional collections should be made from it.

Genus CEPHALOTAXOPSIS Fontaine.

CEPHALOTAXOPSIS MAGNIFOLIA Fontaine.

Pl. CLXII, Fig. 1b; Pl. CLXIX, Figs. 3, 4.

1889. *Cephalotaxopsis magnifolia* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 236, pl. civ, figs. 4, 5; pl. cv, figs. 1, 1a, 1b, 2, 4; pl. cvi, figs. 1, 1a, 3; pl. cvii, figs. 1, 2, 4, 4a; pl. cviii, figs. 1, 3, 4.

Leaves that are identical with those of *Cephalotaxopsis magnifolia*, as described in Mon. U. S. Geol. Surv., Vol. XV, p. 236, from the Lower Potomac of Virginia, are found sparingly on the horizon 150 feet above the Jurassic, at the cliff on the north side of the Valley of the South Fork of Hay Creek, and in shales under the third sandstone, Barrett. They are found also on the horizon 100 feet under the Dakota, at the cliff on the north side of Pine Creek. At these localities they are by no means common. With the larger leaves, corresponding to those of *C. magnifolia*, are others that agree better with those of *C. ramosa*. As, however, none of the leaves are attached to stems, the data are not sufficient to justify their separation into two distinct species. The probabilities, however, are that two species are present. The leaves of Cephalotaxopsis seem to have been drifted some distance. As the nut-like fruit *Carpolithus montium-nigrorum* occurs at the same locality with these leaves, and as this is much like *C. fasciculatus*, which is found in the Potomac strata with many fine specimens of Cephalotaxopsis, and as also Cephalotaxus has similar fruit, it is probable that this Carpolithus is the fruit of some Cephalotaxopsis.

The specimens represented on Pl. CLXII, Fig. 1b, and Pl. CLXIX, Fig. 4, are from the north side of the valley of the South Fork of Hay Creek, 2½ miles west of Barrett. The other specimen (Pl. CLXIX, Fig. 3) is from the shales under the third sandstone above the coal at Barrett.

Male Ament of a Conifer.

Pl. CLXIX, Fig. 5.

A small ament was found on the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek, which is probably the male ament of some conifer. It is quite well preserved, and shows a length of 1 cm., with a width of 4 mm., including the deflected bracts. The form is cylindrical, with both ends obtuse. The bracts on the upper face are mostly removed, being taken off in the splitting of the shale along the plane of the ament. Hence the axis is exposed for most of its length. It is comparatively stout. The lateral bracts are preserved, and show comparatively long and slender tips, which are strongly deflected.

Subdivision ANGIOSPERMAE.

Class DICOTYLEDONEÆ (Dicotyledons).

In the Lower Cretaceous series of the Hay Creek region dicotyledons occur only in the highest portion in Professor Jenney's division No. 2. In the strict confinement of this type of vegetation to the upper portion, the Hay Creek Lower Cretaceous differs from the Lower Potomac, as shown in Virginia. This latter formation shows in its older portion a few dicotyledons of peculiar archaic type, unlike anything found in the Hay Creek Lower Cretaceous, or in that of any region. There is, however, a marked resemblance between the Hay Creek dicotyledons and those of the upper Brooke beds of the Virginia Potomac. In both cases the type of dicotyledons is more modern in facies than the element found in the older beds of the Lower Potomac. At present it is impossible to say whether or not there is really a difference in the occurrence of dicotyledons in these two widely separated terranes of Lower Cretaceous. The collections made thus far in the Hay Creek region are very scanty, and it may be true that more persistent search will disclose dicotyledons of ancient type in the lower Hay Creek beds. It is from these beds that the collections are most scanty. Conclusions, based on the failure to find certain forms, are at best uncertain, and they are especially so when the collections can not be taken as fairly representing the flora.

In the case of the Hay Creek Lower Cretaceous flora we may fairly conclude that dicotyledons were relatively not very abundant on any horizon, and, granting that they existed in the time of the deposition of the lower beds, they formed proportionally a much smaller element of the vegetation than during the era of the formation of the upper strata. The collections show that even in division No. 2 the ferns and conifers far surpassed the dicotyledons. The case is very different when we pass above No. 2 into the true Dakota formation. Here conifers, cycads, and ferns become insignificant in numbers, and dicotyledons attain an overwhelming predominance. The facts that are indicated by the Hay Creek dicotyledons, so far as the evidence now attained goes to show, are similar to those made out from the study of the Lower Potomac beds. Dicotyledons of modern aspect appear in some force in the upper strata of the Hay Creek Lower Cretaceous, but they do not form the dominant element in the flora.

Family FAGACEÆ (Beech and Oak family)

Genus QUERCOPHYLLUM Fontaine.

QUERCOPHYLLUM WYOMINGENSE n. sp.

P. CLXIX, Fig. 6.

A fragment of a small dicotyledonous leaf was found on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek. The fragment shows intact the left side of the base, a lobe, and the sinus between this and the next higher lobe, which is only partially preserved. The indications are that this latter is similar in character to the lowest lobe, which is fully preserved. The basal portion of the leaf is rounded off and passes into the lowest lobe with a considerable convexity in the margin of the leaf. The lobe that is preserved is oblong, with an elliptical-shaped tip that is turned slightly outward away from the midrib. One of the primary veins of the leaf passes into this lobe to its tips. The sinus between this and the next lobe forms a narrow, acute, inverted triangle. A similar primary nerve passes into the second partially preserved lobe. The upper portion of this latter lobe and of the leaf, as well as nearly all of the right-hand half of the leaf, are wanting. Not enough of the leaf is preserved to fix its true position. It may belong to any one of several genera. As, however, it seems to be nearer some of the forms of Quercus than to any other genus, I place it provisionally in the allied genus Quercophyllum. It should be noted that it has the facies of a recent type of leaf. Its importance as a fossil lies in the fact that it is distinctly a dycotyledon that is different from the others found in the Hay Creek Lower Cretaceous, and that the archaic features are not shown in it.

Family ULMACEÆ (Elm family).

Genus ULMIPHYLLUM Fontaine.

ULMIPHYLLUM DENSINERVE n. sp.

Pl. CLXIX, Fig. 7.

A fragment of a small leaf quite different from the other Hay Creek dicotyledons was found on the horizon 100 feet below the Dakota sandstone, in the Carbonaceous shales at Rollin's tunnel. It is 2 cm. long and 11 mm. wide, with but little variation in the width from end to end. The entire leaf was probably oblong in shape, or lanceolate. The leaf texture seems to have been firm and durable, and the nerves are but faintly shown. The midrib is slender. The secondary or lateral veins go off from the midrib almost at right angles. They are parallel, placed at equal distances, and slightly arched in the middle, with their ends directed toward the end of the leaf. They are all of equal strength and are placed about 1.5 mm. apart. No nervation other than the midrib and lateral veins was seen.

The general aspect of this leaf is much like that of a fern of the Angiopteridium type, and it resembles some of the pinnules of *Angiopteridium strictinerve*, as, for example, that given in Mon. U. S. Geol. Survey, Vol. XV, pl. xxix, fig. 8; but this leaf has a much slenderer midrib, and the lateral nerves do not fork. Besides, these nerves have the appearance of the nerves of a dicotyledon rather than of a fern.

Not enough of the plant has been found to determine positively its true position. It may belong to any one of several genera of dicotyledons. The nerves are closer than is usual in dicotyledons of this type. It is perhaps nearest to Ulmus, and I place it provisionally in the allied genus Ulmiphyllum.

Family MORACEÆ (Mulberry and Fig family).

Genus FICOPHYLLUM Fontaine.

FICOPHYLLUM SERRATUM Fontaine.

Pl. CLXIX, Fig. 8.

1889. *Ficophyllum serratum* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 294, pl. cxlv, fig. 2; pl. cxlix, fig. 9.

Ficophyllum serratum was found in the Lower Potomac of Virginia and described by the writer in Mon. U. S. Geol. Survey, Vol. XV, p. 294, pl. cxlv, fig. 2; pl. cxlix, fig. 9. A fragment of a dicotyledonous leaf was obtained in division No. 2 of the Hay Creek beds that so strongly resembles this that it may safely be identified with it. The fossil now in question occurs on the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek. Only one specimen was found. It shows a portion of the lower part of the midrib and a large part of the right-hand half of the leaf. The fossil indicates a leaf of the same size and character as that shown on pl. cxlix in fig. 9 of Mon. U. S. Geol. Survey, Vol. XV. The tendency to form double teeth seen in the leaf depicted in fig. 9 does not appear here. That, however, is not a persistent feature in the Potomac plant.

Family SAPINDACEÆ (Soapberry family).

Genus SAPINDOPSIS Fontaine.

SAPINDOPSIS VARIABILIS Fontaine.

Pl. CLXIX, Fig. 9.

1889. *Sapindopsis variabilis* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 298, pl. cli, figs. 1, 1a; pl. clii, figs. 1, 4, 4a; pl. cliii, fig. 3; pl. cliv, figs. 2-4, 4a; pl. clv, figs. 2-5.

Sapindopsis variabilis was first found by the writer in numerous well-preserved specimens in the upper or Brooke group of beds belonging to the Lower Potomac. It is described in Mon. U. S. Geol. Survey, Vol. XV, pp. 298-300. It is highly characteristic of the upper portion of the Lower Potomac in Virginia, and great numbers of its fossils are found at some localities. It is by far the most common dicotyledon at the localities where it occurs.

Precisely similar leaves occur in division No. 2 of the Hay Creek beds. They are found on the horizon 60 feet below the Dakota sandstone, at the cliff in the east bank of Oak Creek, where it is the most abundant dicotyledon, and is quite common, and where the specimen here figured was obtained. It is, in fact, the only abundant dicotyledon in the Hay Creek Lower Cretaceous. It occurs also on the horizon 100 feet below the Dakota sandstone at the cliff on Oak Creek, at Robbin's ranch. Here it is found sparingly, but in well-preserved forms. This plant is a valuable one for the determination of the age of the beds in which it occurs, for it has a number of features that render it easy to identify, and which cause it obviously to differ from others. The leaves have a thick, very durable texture, that causes them to be much better preserved than most dicotyledons. The odd-pinnate leaves, owing to the persistence of the leaflets at their summits, frequently show them attached, and sometimes even the terminal leaflets. The nervation is strongly marked and characteristic. Indeed, these leaves can hardly be mistaken for others. It is significant to find that this plant, which is the most abundant in the Brooke group of the Virginia Lower Potomac, is the most common dicotyledon in the upper member of the Hay Creek Lower Cretaceous. As indicating similarity of age, such a plant is much more important than any single species, which is vaguely characteristic and represented by few individuals. This Sapindopsis is "at home" and well established in the upper portion of the Lower Cretaceous of both the Hay Creek region and of Virginia.

MALE AMENT OF A DICOTYLEDON?

Pl. CLXIX, Fig. 10.

A male ament or catkin of what was probably some dicotyledon was obtained on the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek. This differs from the compactly built, chaffy aments ascribed to conifers. It has a length of about 1 cm. and a width of about 3 mm. The axis is slender and shows remotely placed bracts scattered along it. The bracts are slender and have long slender tips. For the greater portion of their length they are coiled up like a watch spring. Its true place is doubtful.

These few species are all the possible dicotyledons found thus far in the Hay Creek Lower Cretaceous.

INCERTÆ SEDIS.

FRUITS.

The following fruits have not been found connected with any foliage in a way to indicate where they belong in the various groups established from stems and leaves. It is quite possible that some of them should be placed in species described in the preceding pages.

Genus CARPOLITHUS Artis.

CARPOLITHUS FASCICULATUS Fontaine.

Pl. CLXIX, Figs. 11, 12.

1889. *Carpolithus fasciculatus* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 265, pl. cxxxiv, fig. 1.

On the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek, a single imprint, as from a nut-like fruit, was obtained. This in shape and size is identical with one of the fruits of *Carpolithus fasciculatus* from the Lower Potomac of Virginia. This species was described by the writer in Mon. U. S. Geol. Survey, Vol. XV, p. 265, pl. cxxxiv, fig. 1. *Carpolithus fasciculatus*, as found in the Potomac of Virginia, shows a group of nut-like fruits borne on a common stem. The fruit now in question agrees well with the single nuts of the Virginia plant. As Cephalotaxus has a plum-like fruit, two or three in a head, and as *Cephalotaxopsis magnifolia* occurs at this locality, this fruit may belong to the latter. *Nageiopsis longifolia* also occurs at this locality, and the fruit now described may belong to it.

The genus Nageiopsis, which is abundant in the Lower Potomac of Virginia, and highly characteristic of it, was established by the writer for certain leaves and leafy branches that agreed closely with the living genus Nageia Gaertner, generally regarded as a subgenus of

Podocarpus Endlicher, now surviving in the East Indies and Japan. When the description of the genus was written I had not seen either the foliage or fruit of Nageia. Since that time, however, through the kindness of a friend in Japan, specimens of both have been obtained. My conclusion as to the close resemblance of the foliage of Nageia and and Nageiopsis has been strongly confirmed by an inspection of these. The fruits of the living Nageia are so much like some of those of the Lower Potomac of Virginia, which I described as belonging to the groups Carpolithus and Cycadeospermum, especially the latter, that I think it quite probable that some of the Carpolithus forms and perhaps all of Cycadeospermum are fruits of Nageiopsis. It is true that most of the Nageias have single nut-like fruits, but *Nageia Blumei* Endl. (*Podocarpus Blumei* Endl.) is described as having its fruit, after the fall of the floral leaves, grouped in bunches at the ends of the branchlets. Hence it may be that even branched nutlets, like those of *Carpolithus fasciculatus* may belong to Nageiopsis.

Fig. 11 of Pl. CLXIX shows this nut natural size, and Fig. 12 is enlarged 2 diameters.

Carpolithus montium-nigrorum Ward n. sp.[1]

Pl. CLXIX, Fig. 13.

A nut-like fruit, which is probably a new species of Carpolithus, was obtained on the horizon 150 feet above the Jurassic, at the cliff on the north side of the valley of the South Fork of Hay Creek. It is ovate in shape, 15 mm. long, and, including the rind or margin, 10 mm. wide at the widest part, which is close to its base. It has a distinct wing-like margin, which is flat, while the body of the seed is strongly convex, indicating that the margin was thinner than the seed proper. In shape and size it resembles *Cycadeospermum spatulatum* Font., of the Lower Potomac of Virginia. This latter was figured in Mon. U. S. Geol. Survey, Vol. XV, pl. cxxxv, figs. 11, 21. The Potomac fruit, however, has no wing, and is a thinner seed with a less firm texture. This seed may be the fruit of *Cephalotaxopsis magnifolia* Font., for this plant occurs at this locality, and the fruit of Cephalotaxus is fleshy, with a hard woody seed within.

The figure shows the specimen natural size.

Carpolithus barrensis Ward n. sp.[2]

l. CLXIX, Figs. 14, 15.

The fossil here named *Carpolithus barrensis* was obtained on the horizon 150 feet above the Jurassic, at John Barr's tunnel. It has an ovate shape and is 9 mm. long, with a maximum width at its lower portion of about 4 mm. As it leaves a pretty deep imprint in the shale,

[1] Professor Fontaine in his manuscript designates this form by a name that had been twice used before and therefore it was necessary to change it.

[2] The name that Professor Fontaine gave this form in his manuscript has already been given to three different objects by different authors. As it was found at Barr's tunnel it may be called *C. barrensis*.

it was probably quite thick and firm in texture. It is a good deal like *Carpolithus virginiensis* Font., but it is more elliptic in form than that and proportionally narrower, and had apparently a less woody texture. It may prove identical with the seed of *Araucarites wyomingensis*, but the differences seem to justify its doubtful separation as a new species.

Fig. 15 is enlarged 2 diameters.

Carpolithus virginiensis Fontaine.

Pl. CLXIX, Fig. 16.

1889. *Carpolithus virginiensis* Font.: Potomac Flora, Mon. U. S. Geol. Survey, Vol. XV, p. 266, pl. cxxxiv, figs. 11, 11a, 12, 13, 14, 14a; pl. cxxxv, figs. 1, 5; pl. clxviii, figs. 7, 7a.

Several detached nut-like seeds were found on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek. They are not attached to a stem, as were some of the forms of *Carpolithus virginiensis*, which were found in some abundance in the Lower Potomac of Virginia, and described in Mon. U. S. Geol. Survey, Vol. XV, p. 266, but they resemble strikingly the detached seed of this plant. The resemblance is strong enough to justify the identification of the Hay Creek seed with those of the Potomac. Like the Potomac seeds, those of Hay Creek seem to have had a firm woody texture. One of the seeds has a short pedicel, indicating that it was attached to a stem after the manner of the Potomac specimens.

The figure shows one of these seeds natural size.

Carpolithus fœnarius Ward n. sp.[1]

Pl. CLXIX, Figs. 17, 18.

This is a narrowly elliptical or fusiform seed, occurring in the strata at the junction of the Jurassic with the Cretaceous at Lou Cottle's ranch. It is 5 mm. long, with a maximum width of 1.5 mm. It has attached to it what looks like a portion of a wing. Possibly this is an abnormal seed of *Araucarites wyomingensis*, but more probably it is the seed of a different species of Araucarites, as it is proportionally too narrow for *A. wyomingensis*.

Fig. 17 of Pl. CLXIX represents it natural size, and Fig. 18 enlarged 2 diameters.

Genus FEISTMANTELIA Ward n. gen.

Feistmantelia oblonga Ward n. sp.

Pl. CLXIX, Fig. 19.

Fusiform or cigar-shaped markings.—Certain peculiar oblong and fusiform markings are found not rarely on the horizon 100 feet below the Dakota sandstone, at the cliff on the north side of Pine Creek.

[1] The name given to this form by Professor Fontaine in his manuscript was preoccupied. The one I have chosen is derived from the Latin word for hay, in vague allusion to the Hay Creek coal field.

They appear on the surface of the rock as convex forms that are casts of concave shapes that existed apparently on woody stems of considerable size in the cambium layer under the bark. They are not arranged in a strictly definite manner or with unvarying pattern. They have their longer dimensions in the direction of the length of the stem on which they occur, and are arranged mostly in interrupted rows, with the individual markings more or less en échelon, with their ends sometimes overlapping. Sometimes they are close together and touch for most of their length. Some are curved, but most of them are straight. These markings have a sufficiently constant and definite character to enable one to recognize them at a glance. They occur only at certain horizons. Hence we must infer that they are not the results of mere accident. Another fact that gives them significance is their occurrence in the same way and with the same shapes in the Lower Potomac of Virginia. In this they are found on the same horizon at Fredericksburg and at Cockpit Point. I can offer no satisfactory explanation of them, but they are worthy of description, for they clearly belong to the wood of a particular kind of tree occurring only in the Lower Cretaceous on a definite horizon.

NOTE.—The above was Professor Fontaine's description of these objects, and Fig. 19 of Pl. CLXIX is a fairly good illustration of their appearance. I was with him when the specimens of this plant referred to by him from Cockpit Point, on the Potomac River, in Virginia, were found on the occasion of our visit to that locality on July 27, 1893, and the specimens we then collected now lie before me, as do also those from the Hay Creek coal field. Professor Fontaine states that others were obtained from Fredericksburg, but these I have not seen. The Fredericksburg horizon is the same as that of Cockpit Point, viz., his Fredericksburg or my Rappahannock series of the Potomac formation.

In addition to these three localities, I last summer found the same plant in the Cheyenne sandstone of Kansas. It is quite abundant in what Professor Cragin has called the Lamphier shales, and also occurs in the more carbonaceous portions of his Stokes sandstone. Referring to my notes, I find first the mention of broad stems resembling bamboo and subsequently of these peculiar "cigar-shaped markings identical with those from the Black Hills and Cockpit Point," so associated with the broad bamboo-like stems "that it was easy to be sure that they belong to the stems and occur in the interior as a part of the internal structure." These specimens are now in temporary storage and I can not confront them with the others, but I was too familiar with them to have been mistaken, as the Cockpit Point specimens had greatly interested me and led me to make a prolonged search for similar objects previously figured by other authors. I will now give the result of that investigation supplemented by some later discoveries.

Of all the figures thus far found that which Feistmantel gives in his Flora of Kach (Foss. Fl. Gondw. Syst., Vol. II, Pt. I, 1876, pl. x, fig. 2) comes the nearest to the American forms. In fact, it is substantially identical and must represent the same genus. It is for this reason that I dedicate this new genus to the late Dr. Ottokar Feistmantel, for whom, notwithstanding his numerous and important contributions to paleobotany, no genus of fossil plants has been named, and very few species.

Of this plant Feistmantel, on page 61 of the work quoted, says:

"Portion of a stem of a coniferous plant.—The specimen which I have figured here seems to me to be undoubtedly a fragment of the stem of a coniferous plant. The scars, it is true, remind one very much of a lycopodiaceous plant, but no Lycopodiaceæ have been found anywhere in Mesozoic strata. The scars are spirally disposed, oblong, with the broader portion above, where, I believe, leaves were inserted. The lower portion is narrower and elongate, but no other structure is to be seen. If we compare these specimens, however, with stems of living coniferous plants, we shall find that the structure of the young branches is similar. But to describe and determine them more exactly is, I believe, not possible, because it is always very difficult to recognize a plant only from a fragment of the stem. We can only say that the stems belong, perhaps, to one of the coniferous plants found in the same locality, and two especially may be suggested, the Pachyphyllum, or the plant to which the scales I shall next describe belonged. I believe this stem can not be referred to Echinostrobus Schimp., as the leaves are quite different." In the description of the plate of fig. 2 he simply says: "Stem of a coniferous plant, with leaf scars.—From Kukurbit."

Next to this in point of similarity to our forms I place three figures of Stokes and Webb in their report on Mantell's collection from the Tilgate Forest in Sussex (Wealden), contributed to the Geological Society of London and published in its Transactions in 1824 (Trans. Geol. Soc. London, 2d Ser., Vol. I, pp. 421–424, pl. xlv–xlvii). These are the figs. 8 of pl. xlvi and figs. 4b and 4c of pl. xlvii, all of which are regarded as parts of their *Clathraria anomala*, and the first of them is still included by Seward (Wealden Flora, Pt. II, p. 123) in *Bucklandia anomala*, which is the modern name of that same plant. It is generally admitted that these are the piths of cycadean trunks, and for this class of objects Saporta proposed the name Cycadeomyelon (Plantes Jurassiques, Vol. II, p. 331).

Saporta did not, however, deal with the English Wealden forms, and only included under his new genus so much of the plant described by Schimper (Traité de Pal. Vég., Vol. II, p. 183) under the designation *Clathraria liasina* as related to certain pith casts found at Hettanges near Metz. Schimper thought that these objects represented the woody cylinder of cycadean trunks (he does not say the medulla), and he suggested that they might belong to *Otozamites major*. He did not figure any of the specimens, and the only figure I have seen of this plant, which Saporta called *Cycadeomyelon hettangense*, is that of the Plantes Jurassiques, Vol. II, Atlas, pl. cxix, fig. 5. This also presents a remarkable similarity to the American Lower Cretaceous forms under consideration, and I was at first tempted to refer these to Cycadeomyelon and class them with the Cycadales; but certain weighty considerations deter me from this course.

The only other figures that I have thought it worth while to compare are those of Germar's *Omphalomela scabra* (Palaeontographica, Vol. I, pl. iii), which are without much doubt pith casts of cycads, and were referred by Schimper to Clathraria and called *Clathraria? Germari* (Traité, Vol. III, p. 554). The markings here are quite different from those heretofore considered and approach more closely to those seen on the medulla of other cycadean trunks of which we have knowledge, some of which are described in this paper (cf. *Cycadeoidea Stillwelli*, supra, pp. 636, 637, Pl. CXLIX), and others elsewhere (see Proc. Biol. Soc. Washington, Vol. XI, p. 13).

The principal objection to regarding the American forms as distinct from Cycadeomyelon and for seriously doubting that they really represent the medulla of cycadean trunks is that the markings appear in all cases to be on the inner wall of the hollow cylinder of some vegetable trunk, and not on the outer surface of the medullary axis, i. e., in precisely the reverse position from those of Cycadeomyelon. In the case of the Indian plant, although Feistmantel supposed that the markings were leaf scars on the surface of coniferous stems, there is nothing in his figures to negative the idea that they might be internal. He speaks as if he had considerable material, and this question could perhaps be settled by an examination of it. In many of our specimens it would be difficult to decide whether the scars occupied an outer or an inner surface, and Professor Fontaine, in his description given above, does not clearly indicate what his view of the matter is by saying that "they appear on the surface of the rock as convex forms that are casts of concave shapes that existed apparently on woody stems of considerable size in the cambium layer under the bark." This, it seems to me, might admit of either interpretation. As I now examine the specimen figured by him I think I see evidence that the projections were inward, and other material that he did not figure confirms this impression. The specimens from Cockpit Point present the same difficulty, but one of these pretty clearly indicates that it forms the thin edge of a flattened hollow due to pressure, and represents itself the investing layer of whatever may have once occupied this hollow space. Put with this my observations in Kansas, which left no doubt in my mind that the bamboo-like stems on parts of which these markings occur were the interior parts of large hollow trunks, and the evidence becomes strong that our plant is not a Cycadeomyelon or any other "myelon" or pith, but part of a hollow mold with the elevations directed toward the center of the trunk.

The species of Feistmantelia will depend chiefly on the shape of the elevations. Those of Feistmantel's figure are decidedly fusiform, with the upper end of the spindle much larger. That form may therefore be called *Feistmantelia fusiformis*. His statement that they are "spirally disposed" is scarcely justified by the figure, but here, as in all other cases observed by me, they are alternately disposed, i. e., lying side by side, but each one beginning and ending at a different point from its neighbor, which is a characteristic feature of Cycadeomyelon, and strongly suggests a connection with the medullary rays. The Cockpit Point specimens have some of the half-reliefs somewhat fusiform, but often simply oblong, i. e., half cylinders abruptly rounded at the ends. This latter is almost the only form preserved by the Hay Creek specimens, and on this account I have preferred the specific name *oblonga*.

This plant affords a good example of the geological value of certain kinds of objects which appear to have very little value for biology. Many paleobotanists look with contempt upon anything whose systematic position is in doubt and declare that it does more harm than good to list forms which can not be referred with practical certainty to some definite family or genus. They argue, correctly enough, that the attempt to draw conclusions from such material as to the history of plants is wholly misleading and vitiates all reasoning from fossil plants. They forget, or never seem to have thought, that a form may have a geological value quite independent of all such conclusions. Such reasoning is really biological after all, i. e., it is an attempt to work out the genealogy of certain groups of vegetation. The forms, such as this one, are worthless for this purpose and any attempt to employ them in this manner can not be too strongly condemned. The value they have is what is called *geognostic*. If, as in the present case, the objects are clear and definite, so as to be readily recognizable whenever found, and especially if, as also in this case, they are confined to certain geological horizons, they become useful indices and characteristic marks of geological formations, and, wisely employed, become valuable aids to geology. If these peculiar markings had only been seen once, they might be regarded as mere *lusus naturæ* and neglected; but when we find them under practically the same conditions at about the same horizon and all exactly alike in widely different parts of the country, we begin to see that they represent similar beds and add important testimony to the similarity in age.

All the American forms have occurred in the Lower Cretaceous, and their range, so far as now known, is from near the base of the Cretaceous to near the top of the beds that lie below the Dakota group or Cenomanian of Europe, i. e., from the Neocomian to the Gault or Albian of Old World nomenclature. If the specimens from India are the same as ours, this carries the genus down to the Lias, provided the beds of Kach have been correctly correlated. When the Jurassic of America is better known we may expect to find representatives of this plant in them, but there is reason to believe that the species will differ in the same way that they do in other better-understood genera. It will be further observed that this range is about the same as that of the fossil cycads in general, which may or may not be taken as an argument for the cycadaceous nature of Feistmantelia.—L. F. W.

LOCALITIES AT WHICH COLLECTIONS SHOULD BE MADE.

The preceding descriptions include all the fossil plants obtained thus far from the Lower Cretaceous strata of the Hay Creek region that are sufficiently well characterized to be worthy of mention. Incidentally, in the descriptions of the plants, attention has been called to some of the localities which seem worthy of having additional collections made from them. There are some other localities equally worthy of further attention, which may be noticed here.

The shale in the cliff on the north side of the valley of the South Fork of Hay Creek, lying 150 feet above the Jurassic, is one that should have additional collections made from it. It has yielded a large number of good fossils from a small amount of material, but there are indications that a careful and prolonged examination would discover many more, probably new ones. The shale is fine-grained and fissile, having a light brown color. It preserves the plants beautifully and they are easily worked out of it. It has fragments of plants which with the material in hand are not capable of determination, but which hint at the existence of forms different from those described. A number of plants found here have not been discovered elsewhere. They occur on an important horizon and seem to be very rich in fossils.

Material occurring at the cliff in the east bank of Oak Creek, 2 miles below Robbin's Ranch, is found in a fine-grained, thinly laminated argillaceous sandstone that is interstratified with thin layers of a very fine-grained shale. These shale partings preserve plants finely and have yielded some very distinct and large imprints. Only a small amount of material has been obtained from this place. It well deserves further examination. It occurs on a critical horizon and the plants found here do not seem to have suffered so much from drifting as they have at most of the other localities.

The bed of shales at the contact of the Jurassic with the Cretaceous, at Lon Cottle's Ranch, is another critical horizon, and eminently deserves further and careful examination. This shale is light chocolate in color, very fine grained and fissile, enabling one to work out the plants easily. It preserves them finely. It is full of fragments of plants, and as the amount of material obtained from it is very small; there is little doubt that careful search would disclose many new species. This shale contains among others the seeds and cone scales of *Araucarites wyomingensis*, and the fossils found here do not occur elsewhere.

THE FOSSILS OF THE DIFFERENT HORIZONS.

Before going into the consideration of the age of the Hay Creek beds that lie beneath the typical Dakota sandstone it will be useful to present lists of the plants that occur on the several horizons. I will begin with the lowest.

Plants occurring at the contact of the Cretaceous with the Jurassic, Division No. 4.

1. Thyrsopteris elliptica Font.?
2. Araucarites wyomingensis n. sp.
3. Carpolithus fœnarius Ward n. sp.

Plants occurring from 50 to 75 feet above the Jurassic, Division No. 4.

1. Thyrsopteris dentifolia n. sp.
2. Thyrsopteris brevifolia Font.
3. Thyrsopteris pecopteroides Font.
4. Zamites borealis Heer.
5. Pinus susquaensis Dn.
6. Czekanowskia nervosa Heer.

Plants occurring on the horizon 150 feet above the Jurassic, Division No. 3.

1. Equisetum virginicum Font.?
2. Cladophlebis parva Font.?
3. Sphenopteris plurinervia Heer?
4. Thyrsopteris pinnatifida Font.?
5. Thyrsopteris crassinervis Font.?
6. Thyrsopteris elliptica Font.
7. Thyrsopteris brevipennis Font.?
8. Scleropteris distantifolia n. sp.
9. Scleropteris rotundifolia n. sp.
10. Zamites brevipennis Heer.
11. Zamites borealis Heer.
12. Williamsonia? phœnicopsoides Ward n. sp.
13. Araucarites wyomingensis n. sp.
14. Araucarites? cuneatus Ward n. sp.
15. Pinus susquaensis Dn.
16. Sequoia sp. Font. Immature cone.
17. Nageiopsis longifolia Font.
18. Nageiopsis angustifolia Font.
19. Baieropsis adiantifolia Font.
20. Czekanowskia nervosa Heer.
21. Cephalotaxopsis magnifolia Font.
22. Male ament of a conifer.
23. Male ament of a dicotyledon?
24. Carpolithus fasciculatus Font.
25. Carpolithus montium-nigrorum Ward n. sp.
26. Carpolithus barrensis Ward n. sp.

Plants occurring on the horizon 100 feet below the Dakota sandstone, Division No. 2.

1. Equisetum virginicum Font.
2. Weichselia reticulata (Stokes and Webb) Ward.
3. Matonidium Althausii (Dunk.) Ward.
4. Pecopteris Geyleriana Nath.
5. Zamites species?
6. Cycadeospermum rotundatum Font.
7. Pinus susquaensis Dn.?
8. Leptostrobus longifolius Font.
9. Leptostrobus? alatus Ward n. sp.
10. Athrotaxopsis tenuicaulis Font.
11. Sequoia Reichenbachi (Gein.) Heer.
12. Sequoia gracilis Heer.
13. Geinitzia Jenneyi n. sp.
14. Sphenolepidium Kurrianum (Dunk.) Heer.
15. Sphenolepidium parceramosum Font.
16. Glyptostrobus brookensis (Font.) Ward.
17. Baieropsis pluripartita Font.?
18. Cephalotaxopsis magnifolia Font.
19. Quercophyllum wyomingense n. sp.
20. Ulmiphyllum densinerve n. sp.
21. Sapindopsis variabilis Font.
22. Carpolithus virginiensis Font.
23. Feistmantelia oblonga Ward n. sp.

Plants occurring on the horizon 50 to 60 feet below the Dakota sandstone, Division No. 2.

1. Weichselia reticulata (Stokes and Webb) Ward.
2. Pecopteris Geyleriana Nath.
3. Pecopteris borealis Brongn.
4. Cladophlebis wyomingensis n sp.
5. Pinus susquaensis Dn.
6. Abietites angusticarpus Font.
7. Leptostrobus longifolius Font.
8. Athrotaxopsis tenuicaulis Font.
9. Sequoia Reichenbachi (Gein.) Heer.
10. Geinitzia Jenneyi n. sp.
11. Sphenolepidium Kurrianum (Dunk.) Heer.
12. Sphenolepidium parceramosum Font.
13. Glyptostrobus brookensis (Font.) Ward.
14. Ficophyllum serratum Font.
15. Sapindopsis variabilis Font.

CONCLUSIONS AS TO THE DISTRIBUTION OF THE PLANTS.

From these lists it will be seen that the flora of the horizon 100 feet below the Dakota sandstone and that of the horizon 60 feet below it are essentially the same. The resemblance is not fully disclosed by the lists alone. The same plants that are abundant on the one horizon are also abundant on the other, and they show very much the same state of preservation. It is noteworthy that on both of these horizons, from some cause, the plants are more distinctly characterized than they are on the lower horizons. They also occur in larger and more complete specimens, and the leaves are more often attached to stems. The plants indicate that there is no break between the two horizons named, both of which occur in Professor Jenney's division No. 2. The horizon 60 feet below the Dakota sandstone is shown by the plants to be somewhat higher than that 100 feet below it, in the disappearance of some of the survivors from lower horizons, which had struggled on to the latter. *Thyrsopteris elliptica* Font. comes up into the horizon 100 feet below the Dakota sandstone, showing one or two doubtful specimens. It does not appear at all on the higher horizon. *Cephalotaxopsis magnifolia* Font., surviving feebly on the lower horizon in division No. 2, does not pass up into the higher. *Pinus susquaensis* Dn. is the only plant belonging to the lower horizons that is found on the highest horizon of division No. 2. It should be stated, however, that the specimens supposed to be this Pinus, that are found on the two horizons of division No. 2, are few and not well characterized, so that the identification of them with *P. susquaensis* is not entirely free from doubt.

If we compare the list of plants found on the lowest horizon in division No. 2, or that 100 feet below the Dakota sandstone, with that yielded by the horizon 150 feet above the Jurassic and occurring in division No. 3, we find a decided change. No dicotyledons occur below division No. 2. The plants that are most abundant on the lower horizon in division No. 2, and most characteristic of it, do not occur at all below it. Those that come up to it from lower horizons appear as survivors and not as well-established plants. They occur in some cases as doubtful forms, and in all cases are rare. Many of the most characteristic plants of the lower horizons, such as *Czekanowskia nervosa* Heer, *Zamites borealis* Heer, *Zamites brevipennis* Heer, do not pass up into the horizon 100 feet below the Dakota sandstone. These and other evidences derived from a study of the plants indicate a time-break between Jenney's divisions No. 3 and No. 2. On the other hand, no change in the flora of the strata from the junction of the Jurassic with the Cretaceous up to the base of division No. 2 indicates a want of conformity in them. Divisions No. 3 and No. 4, so far as the evidence of the plants goes, make one group. It is true that there are changes in the species occurring on the lower horizons varying from the contact of the Jurassic with the Cretaceous up to and including the horizon

150 feet above the Jurassic, but the general character of the flora as a whole is the same. It is much more Jurassic in type than that of the beds higher up. Thyrsopteris, Zamites (of the type of *Z. borealis* Heer), conifers with flabellate leaves like Czekanowskia and Baieropsis, Araucarites and Scleropterids with small pinnules are the most characteristic plants. It must not be forgotten, however, that the collections of plants from these lower beds, especially those of division No. 4, are very scanty, and far inferior in the number of specimens to those obtained from division No. 2. A more thorough search of these strata may furnish numerous plants that would materially modify the conclusions drawn from the material now in hand.

GEOLOGICAL AGE OF THE HAY CREEK STRATA LYING BETWEEN THE TYPICAL DAKOTA SANDSTONE AND THE JURASSIC.

As stated in the beginning of this paper, the strata yielding the plants described in it were assumed by Newton to be of the same age as the true Dakota, a system of beds in which dicotyledons form nearly all the plants, they being of comparatively modern type. The plants found even on the highest horizon of division No. 2 differ totally from those of the true Dakota beds, and indicate a distinctly older series. The plants from the two horizons in division No. 2 are essentially the same and indicate that there is no unconformity in this division. We may leave out of consideration the fusiform markings (*Feistmantelia oblonga* Ward n. sp.), the questionable species of Zamites, *Baieropsis pluripartita* Font., and the possible seeds of Leptostrobus, that occur on the horizon 100 feet below the Dakota sandstone, for they are too poorly characterized to help in determining age. We have then 24 species from the two horizons of division No. 2. Of these, 4 are new, and for that reason can not be used in fixing the geological age. Of the 20 species remaining no fewer than 14 occur in the Lower Potomac of Virginia. The dicotyledons found in this division are of a more modern type than those which occur in the Lower Potomac beneath the Brooke or upper portion of that group of beds, and *Sapindopsis variabilis* Font., the most abundant dicotyledon in the Brooke strata, is by far the most abundant one in division No. 2. Besides, such plants as *Sphenolepidium Kurrianum* (Dunk.) Heer, *Sphenolepidium parceramosum* Font., *Glyptostrobus brookensis* (Font.) Ward, and *Leptostrobus longifolius* Font., that are common on the Brooke horizon, are common here also.

Of the 20 significant species occurring in division No. 2, and not found in the Lower Potomac, 6 have been previously described as coming from other formations. *Pinus susquaensis* Dn., according to Sir William Dawson, occurs in the Kootanie formation; *Sequoia gracilis* Heer, according to Heer, is found in the Kome beds of Greenland; *Matonidium Althausii* (Dunk.) Ward, according to Schenk and Heer, occurs in the Wealden of Europe; *Pecopteris Geyleriana* Nath., as stated by M. Yokoyama, is found in the Neocomian of Japan; *Weichselia reticulata* (Stokes and Webb) Ward, Schenk gives as occurring in the Urgonian Wernsdorf beds of Europe; Heer gives *Pecopteris borealis* Brongn. as found in the Kome beds of Greenland, which he regards as Urgonian in age. The Lower Potomac is, according to the plants, Neocomian in age. The Wealden being equivalent in age to Lower Neocomian, and the Urgonian being a formation of the Upper Neocomian, and the Kootanie being also Neocomian in age, it follows that all the fossil plants found in division No. 2 that are sufficiently well characterized to throw light on its age are Neocomian species. Of the new species, we may omit *Ulmiphyllum densinerve* and *Quercophyllum wyomingensis* as being too undetermined to be significant. The two remaining ones, *Geinitzia Jenneyi* and *Cladophlebis wyomingensis*, are closely allied to Neocomian fossils.

We may then conclude without hesitation that Jenney's division No. 2 is certainly older than the typical Dakota group with predominant dicotyledons, and that its age is Neocomian. We may also hold that of the various more or less local groups of beds of Neocomian age, it is nearest to the Lower Potomac, as exposed in Virginia. We may go further and determine with great probability that the age of division No. 2 corresponds with that of the Brooke group, an upper member of the Lower Potomac.

Coming now to divisions No. 3 and No. 4, we will not be able to make so satisfactory an analysis, for the fossils are not nearly so well preserved and the specimens are not so large as those of the upper division. In addition the collections from these members of the Hay Creek series are much more scanty, so that conclusions based on the absence of types are more risky than they are in division No. 2.

In the two lower divisions 32 different species of plants have been found whose characters have been more or less fully determined. Fourteen of these are new species, 5 have been found from formations other than Potomac, whose age is known, and 13 are Potomac species.

Most of the new species are so regarded because their character has been very imperfectly determined, and not enough is known of them to permit their identification with known species. In a number of cases there is nothing shown that would prevent more complete specimens from exhibiting features that would identify them with plants previously described. Indeed it is quite probable that such forms as *Carpolithus fœnarius* Ward, *Carpolithus barrensis* Ward, *Zamites?* species, *Williamsonia? phœnicopsoides* Ward, the aments supposed to belong to some conifer and some dicotyledons, and the immature cone of Sequoia, are not really new species. The apparently large proportion of new species has then no significance. The new species that have been determined with some definiteness, such as *Araucarites wyomingensis*, *Scleropteris rotundifolia*, and *Scleropteris distantifolia*, so far as their generic character goes, indicate survivors from the

Jurassic. Thirteen species have been determined, many of them doubtfully, as identical with Lower Potomac forms. They indicate that the beds containing them correspond in age with the lower portion of the Lower Potomac. A number of them are Jurassic in type, being probably survivors of a flora of that age. The large proportion of Potomac species confirms the conclusion deduced from the plants of division No. 2, viz, that the flora of the Hay Creek beds is, among the local Lower Cretaceous floras, nearest to that of the Lower Potomac. Five of the 32 species found in the beds now in question have been previously described as coming from Lower Cretaceous groups other than Lower Potomac. *Zamites borealis* Heer, and *Zamites brevipennis* Heer, were described by Heer from the Kome beds of Greenland, and *Sphenopteris plurinervia* Heer from the Wealden of Portugal. From the latter formation Heer also describes *Czekanowskia nervosa* Heer. *Pinus susquaensis* Dn., before mentioned, seems more at home in these beds, but survives into division No. 2. Eighteen out of the 32 species are then more or less certainly Neocomian species, and they include all the plants from these lower strata that are identical with forms previously described.

We find from this review of the plants that all the species of the third and fourth divisions of the Hay Creek beds that lie under the Dakota sandstone which can be identified with previously described plants are Neocomian in age, and this is a remarkably close agreement between the flora of the strata now in question and that of the Neocomian. The fact that the Hay Creek flora shows a much greater resemblance to that of the Lower Potomac than to the Kootanie floras of British America and of Great Falls, Montana, which occur much nearer to the Hay Creek region than does the Potomac of Virginia, is another surprising feature.[1]

4. FLORA OF THE DAKOTA GROUP PROPER.

It remains only to consider the forms of plant life that have been obtained from the highest member of the Dakota group of Newton, which, there is no reason to doubt, represents some horizon of the true Dakota No. 1 of Meek and Hayden, although, in the imperfect state of our knowledge of that formation, it is impossible to fix its position with exactness. The rock or matrix in which the plants are embedded is wholly different from that of the plains of Kansas where the greater part of the plants have been found. No signs of the dark-brown ferruginous sandstones and clay ironstones so characteristic of the latter were seen by me, and Professor Jenney describes none in the Hay Creek region. But it is known that the Dakota group is not wholly made up of these, and quite recently heavy beds of different material have been found in southern Kansas underlying the typical plant-bearing Dakota

[1] This and a number of similar questions are discussed by Professor Jenney in his notes (see supra, pp. 568-593).

and overlying equally typical Kiowa shales belonging to the Comanche series.[1]

Although there is believed to be unconformity between the true Dakota sandstone of the Black Hills and the Lower Cretaceous beds beneath them, still it is not probable that the time interval was very great, and therefore it is reasonable to suppose that the Dakota sandstones here represented lie near the base of that formation and correspond rather to some of the "transition beds" of Kansas than to the plant-bearing horizons of the plains; and it seems a fair presumption that the latter are wanting in this region. We should not, therefore, expect that the flora of these beds would be precisely the same as that which is now so well known as the flora of the Dakota group—that is, we should expect it to contain some of the elements of that flora along with some of those of the underlying older floras. This, in fact, is just what the small collection made by Professor Jenney and myself, in the vicinity of Evans quarry in September, 1893, reveals, and this constitutes all that we thus far know of the plants of the Dakota group in the Black Hills, Professor Jenney not having included any of these in his collection from the Hay Creek region for reasons that he gives. We may therefore proceed at once to the examination of these plants.

The study that was made of this collection after my return, by Dr. Knowlton and myself, although characterized as "careful,"[2] was not as thorough as it might have been, and I am obliged to admit several mistakes in the determinations. No figures had been prepared at that time, and it was only in the cases where the nervation was clear that we could be certain of its nature. In very obscure and indistinct specimens there is always the liability to mistake meaningless markings on the rock for nerves. However it may be with other fossil remains, in the case of plants, and especially of dicotyledonous leaves with obscure nervation, but upon which almost everything depends, it is wholly unsafe to attempt to determine a collection without drawings, or at least pencil sketches, made with the aid of special appliances for finding the nerves and following them out to the margins of the leaves. Such drawings have now been made, and with their aid a reexamination of the specimens has resulted in the following determinations, which are probably as correct as they can be made from the material in hand.

[1] The results of the observations made by me in company with Mr. C. N. Gould were presented in brief to the Geological Society of Washington on November 10, 1897, and an abstract prepared by myself was published in Science, N. S. Vol. VI, No. 152, for November 26, 1897, pp. 814–815. A more extended paper by Mr. Gould, entitled "On a series of transition beds from the Comanche to the Dakota Cretaceous in southwest Kansas," by Charles Newton Gould, in the American Journal of Science, 4th series, Vol. V, March, 1898, pp. 169–175, sums up more fully our joint observations.

[2] Jour. Geol., Vol. II, No. 3, April-May, 1894, p. 261.

DESCRIPTION OF THE SPECIES.

Subkingdom PTERIDOPHYTA.

Class FILICALES (Ferns).

Genus ASPLENIUM Linnæus.

ASPLENIUM DICKSONIANUM Heer.

Pl. CLXX, Fig. 1.

1874. *Asplenium Dicksonianum* Heer: Die Kreide-Flora der arctischen Zone, K. Svensk. Vet.-Akad. Handl., Vol. XII, No. 6 (Fl. Foss. Arct., Vol. III, Abth. II), p. 31, pl. i, figs. 1 (excl. b. c.), 1aa, 2, 3, 3b, 4, 5 (excl. a, b).

Several fine specimens of this fern, of which the one figured is a fair sample, were obtained from the carbonaceous shales overlying the hard sandstone at the falls of the Minnekahta Creek or Fall River on the right bank.

This plant was first described by Heer from the Kome beds of Greenland (Gault or Urgonian), but it also occurs in the Atane beds, which are correlated with the Cenomanian, and have been supposed to be nearly equivalent to the Dakota group. It has been found in the Kootanie deposits of British America, in a supposed Neocomian deposit at Cape Lisburn, Alaska, and in the Amboy Clays at Woodbridge, New Jersey. It is also one of the few ferns that have been found in the Dakota group, where, however, it is rare. Its evidence, therefore, considered by itself, would be to put even this uppermost deposit in the Lower Cretaceous, but this is overcome by that of the remaining forms. The specimens are the best in the collection, good and characteristic, leaving no doubt on the score of identity. They present a strong contrast with the few very small and doubtful forms found by us on the slope of Red Cañon and figured on Pl. CLXII, Figs. 6, 7, 8 (see supra, p. 664).

Subkingdom SPERMATOPHYTA (Phanerogams).

Subdivision ANGIOSPERMAE.

Class DICOTYLEDONEÆ.

Family FAGACEÆ (Beech and Oak family).

Genus QUERCUS Linnæus.

QUERCUS WARDIANA Lesquereux?

Pl. CLXX, Figs. 2, 3.

1892. *Quercus Wardiana* Lx.: Flora of the Dakota Group, Mon. U. S. Geol. Survey, Vol. XVII, p. 53, pl. vii, fig. 1.

These two specimens were collected from the coarse sandstone of bed No. 7 of my section, on page 258 of the Journal of Geology for April–

May, 1894, Vol. II, No. 3, reproduced in this paper (supra, p. 560). The one represented by Fig. 2 of Pl. CLXX was found in place over Evans quarry, and the one by Fig. 3 in the loose material thrown down in uncovering the workable stone, but from the character of the rock it undoubtedly came from the same stratum. The rock is too coarse to show the finer nervation, and neither specimen shows base, summit, or margin. The determination, therefore, as stated on page 262 of that memoir, must remain uncertain. Still, the midrib and secondary nerves are very distinct, and agree well with both description and figure as given by Lesquereux, while nothing else can be found into which they will fit. The general aspect is that of an oak of the type of *Q. Prinus* L.

Family LAURACEÆ (Laurel and Sassafras family).

Genus SASSAFRAS Nees and Eberm.

SASSAFRAS MUDGII Lesquereux.

Pl. CLXX, Figs. 4. 5; Pl. CLXXI, Fig. 1.

1868. *Sassafras Mudgii* Lx.: Am. Jour. Sci., 2d ser., Vol. XLVI, p. 99.
1874. *Sassafras Mudgei* Lx.: Cretaceous Flora, Contr. Foss. Fl. West. Terr. (Hayden), Vol. VI, p. 78, pl. xiv, figs. 3, 4; pl. xxx, fig. 7.

The specimens are all without doubt from bed No. 7 over the quarry sandstone at Evans quarry, but those represented by Fig. 4 of Pl. CLXX and Fig. 1 of Pl. CLXXI were found in the débris thrown down in uncovering the quarry. These are in coarse, thinly laminated sandstone shale, while the other specimen, represented by Fig. 5 of Pl. CLXX, came from a clay shale bed in place, which is much finer and shows the impression very clearly. The agreement with Lesquereux's figures is very close, and I have compared it with the original specimens. Our Fig. 4 of Pl. CLXX may be compared with Lesquereux's fig. 7 of pl. xxx, and our Fig. 5 comes nearest to his fig. 4 of pl. xiv. Both of the original specimens unfortunately bear the same number (649) of the U. S. National Museum collection, but they also bear Professor Lesquereux's original numbers, and the former is his No. 1349, while the latter is No. 682. They were collected by Mr. Charles Sternberg at Salina, Kansas, in typical Dakota sandstone.

When I studied these specimens for my paper on the Cretaceous Rim of the Black Hills (Jour. Geol., Vol. II, p. 262), I did not make out the nervation on the coarse sandstone of the two specimens now shown in Fig. 4 of Pl. CLXX and Fig. 1 of Pl. CLXXI, and from the general form I identified them with *Lindera venusta* of Lesquereux. This is now seen to have been an error. I also wrongly supposed that the specimen Fig. 5 of Pl. CLXX was the same as the others that I had referred to *Aralia Towneri* Lx., and so placed it. On careful comparison of the figures and specimens it is obvious that none of them represent that species, and that they differ generically from one another.

Family PLATANACEÆ (Plane-tree family).

Genus PLATANUS Linnæus.

PLATANUS CISSOIDES Lesquereux?

Pl. CLXXI, Fig. 2.

1892. *Platanus cissoides* Lx.: Flora of the Dakota Group, Mon. U. S. Geol. Survey, Vol. XVII, p. 75, pl. lxi, fig. 3.

This is only a fragment, but so far as it goes it agrees with the specimen figured by Lesquereux. It is in a fine-grained clay shale, which shows the nervation clearly. I referred it doubtfully to this species in my early paper, and now, after a drawing has been made and the matter has been subjected to a reexamination, I find myself unable to suggest another reference. It is a question of letting it stand or rejecting it entirely, and as it is clearly different from anything else obtained, I incline to the former course. It was found in place over the quarry sandstone at Evans quarry.

Family CELASTRACEÆ (Staff-tree family).

Genus CELASTROPHYLLUM Göppert.

CELASTROPHYLLUM PULCHRUM n. sp.

Pl. CLXXI, Figs. 3, 4.

Leaves elliptical in outline, 4 to 6 cm. long, about 3 cm. wide, crenate-dentate with rounded teeth to near the base, petioled, oblique at base, the lamina extending lower on one side, rounded at the summit; midrib strong, more or less curved; secondary nerves about 6 on a side, rather distant, irregularly placed, leaving the midrib at an angle of about 45°, curving upward, the lower more than the upper, so as to converge in crossing the blade, slightly undulating or irregular in their course, giving off a few tertiary nerves or nervilles from both sides, which sometimes join some distance from the margin and form an angular arch or loop, from the outer part of which small nerves proceed into the teeth, sometimes forking or dividing, the branches entering the teeth.

Fig. 3 of Pl. CLXXI represents a specimen from the clay shales above Evans quarry, consisting of the lower part of two leaves lying side by side, with petioles complete. Considerably more than half of one of them is preserved and one side of the other, showing the nervation clearly. In searching for the equivalent of this form I have been unable to find it in the Dakota group, and, indeed, I have thus far failed to find anything similar in any published illustrations. That it represents a Celastrophyllum is clear both from the characteristic nervation and from the general facies, and a large number of species of that genus have been described from different formations ranging from the older Potomac to the Miocene. In the Potomac formation, as I have previously shown,[1] it constitutes one of the most complete series that we have, rising with slight modifications from one horizon to another, from the lowest to the highest beds. Many of these forms have been described and figured, but others remain unpublished. I have studied them all more or less, and I remembered one species in particular obtained by me from the Aquia Creek series at Fort Foote, Maryland, in a bluff on the bank of the Potomac, to which I had given special attention, and of which pencil sketches had been made to enable me to make out the exact nervation. This I knew must be close to the form in question, and when I compared it I found them substantially identical. I had gone so far as to name the Potomac form *Celastrophyllum pulchrum* on the labels without having as yet written the description. The agreement is so close that there seems no course left but to consider the Black Hills plant as the same as the Maryland one, and I here introduce one of the figures already prepared (Fig 4. of Pl. CLXXI) for comparison. The difference in the horizon points, along with other facts, to a low position in the Dakota series for the beds in question.

Family VITACEÆ (Vine family).

Genus CISSITES Heer.

CISSITES SALISBURIÆFOLIUS Lesquereux.

Pl. CLXXI, Fig. 5.

1868. *Populites salisburiæfolia* Lx.: Am. Jour. Sci., 2d ser., Vol. XLVI, p. 94.
1872. *Sassafras obtusus* Lx.: Fifth Ann. Rept. U. S. Geol. Surv. Terr. (Hayden) for 1871, p. 303.
1873. *Sassafras obtusus* Lx.: Sixth Ann. Rept. U. S Geol. Surv. Terr. (Hayden) for 1872, p. 424.
1874. *Sassafras obtusum* Lx.: Cretaceous Flora, Contr. Foss. Fl. West. Terr., Pt. I, Rept. U. S. Geol. Surv. Terr. (Hayden), Vol. VI, p. 81, pl. xiii, figs. 2–4.
1876. *Cissites obtusum* Lx.: Eighth Ann. Rept. U. S. Geol. Surv. Terr. (Hayden) for 1874, p. 354.
1883. *Cissites salisburiæfolius* Lx.: Cretaceous and Tertiary Flora, Contr. Foss. Fl. West. Terr., Pt. III, Rept. U. S. Geol. Surv. Terr. (Hayden), Vol. VIII, p. 66.

This fine specimen was found at the falls on the right bank of Minnekahta Creek or Fall River, below Evans quarry, in the shales overlying the hard sandstone, associated with *Asplenium Dicksonianum* Heer, already recorded. The shales were so thin that they broke into a number of pieces, which were carefully preserved, so that on examining the material it was possible to find an almost complete leaf, and for a large part of this both surfaces (counterparts) are present. It proves

[1] Fifteenth Ann. Rept. U. S. Geol. Survey, p. 367.

to be one of the most beautiful specimens that have thus far been found of this species.

In studying the broken pieces before they had been put together and a complete figure made, I was led to compare it with *Aralia Towneri* of Lesquereux, to which it bears some resemblance, but upon a reinvestigation I am satisfied that it is not that plant, which does not occur in the collection.

Our form has the very rounded lobes of those represented in the Cretaceous Flora, pl. xiii, and though considerably larger, most closely approaches figs. 2 and 3 of that plate. There is the same tendency of one of the lateral primaries to curve outward more than the other that is seen in fig. 3, only this is still more marked.

The general question as to whether plants of this type from the American Cretaceous are really the ancestors of the exclusively American genus Sassafras, or should be referred to the vine or the plane trees, need not be discussed here. It will suffice to refer to two of my early papers on the subject published in 1888 and 1890, respectively.[1]

CISSITES INGENS Lesquereux.

Pl. CLXXII, Figs. 1, 2.

1892. *Cissites ingens* Lx.: Flora of the Dakota Group, Mon. U. S. Geol. Survey, Vol. XVII, p. 159, pl. xix, figs, 2, 2a.

The specimen represented by Fig. 1 of Pl. CLXXII was collected at the falls on the right bank of Minnekahta Creek or Fall River in thin shale, which was rather coarse and had very uneven partings, rendering the collection of specimens unsatisfactory. The nervation is obscure. The other specimen, Fig. 2, is one that was picked up in the débris at the foot of the cliff below Evans quarry and must have come from bed No. 7. It is somewhat more clear in its nervation, but the upper part of the leaf is wanting and none of the lobes or sinuses remain. I had labeled it *Aralia Towneri*, and it is possible that it may represent *Sassafras Mudgii*, but I seem to see a difference in its general aspect from the other specimens so referred. Both these specimens, so far as they go, agree almost perfectly with *Cissites ingens* Lx., as shown by the perfect specimen figured on pl. xix, fig. 2, of the flora of the Dakota group. This conformity extends in both cases so far as to include the rather unusual feature seen in the opposite secondary nerves of the midrib or middle primary. I think there is good reason to believe that both these leaves belong to the same species as those figured by Lesquereux from the Dakota group of Ellsworth County, Kansas, but whether they are ancestors of the vine or of the plane tree is a much more difficult question.

[1] Proc. U. S. Nat. Mus., Vol. XI, pp. 39-42, pl. xvii-xxii, 1888; American Naturalist, Vol. XXIV, September, 1890, pp. 797-810, pl. xxviii.

Family CAPRIFOLIACEÆ (Honeysuckle and Arrow-wood family).

Genus VIBURNITES Lesquereux.

VIBURNITES EVANSANUS Ward.

Pl. CLXXII, Figs. 3, 4.

1894. *Viburnites Evansanus* Ward: Jour. Geol., Vol. II, p. 261, 262.

Leaves coriaceous, oblong, rounded at the summit, subcordate or truncate at the base, entire or slightly denticulate, pinnately nerved; midrib strong, straight or slightly curved; secondaries thick, rather near together, approximately parallel, straight or slightly curving upward, somewhat irregular in their course, closer on one side of the midrib than on the other and making a different angle with it, this angle varying from 30° near the summit, where they curve in toward the apex, to 60° near the base, some of them forking and others simple, the dichotomy sometimes taking place near the margin and sometimes near the middle of the nerve; nervilles distinct and numerous, many of them percurrent, but others joining and anastomosing to form triangular or rectangular meshes.

In my early paper I did not give the full character of this species, but only pointed out its relation to the only other two species of the genus. Professor Lesquereux, as appears from Dr. Knowlton's foot-note to page 124 of the Flora of the Dakota Group, recognized the resemblance of the forms for which the genus was established to Protophyllum, and had he not made the genus Viburnites I should have been obliged to refer these forms to Protophyllum. The difference is perhaps not generic, and it is an interesting question whether it points to a real relationship between the fossil Viburnums and Protophyllum. There is scarcely a doubt as to the correctness of the reference of many of our fossil leaves to Viburnum, and I have found seeds of Viburnum associated with such leaves.[1] The similar nervation of many species of Protophyllum, and especially the strong dichotomy of the secondary nerves, has always suggested to me an affinity between these genera. As the systematic position of Protophyllum has always been a matter of speculation, this possible connecting link in Viburnites has a special interest for the botanist.

Both the specimens were found in place in the shales above Evans quarry, bed No. 7 of my section.

I take pleasure in repeating the statement formerly made, that the specific name chosen for this plant was meant to give some slight expression of my appreciation of the favors extended to me and my party by Mr. Fred. Evans, of Hot Springs, the leading citizen of the town, proprietor of Evans's quarry, and a public spirited and generous man.

[1] Types of the Laramie Flora, Bull. U. S. Geol Survey, No. 37, 1887, p. 109, pl. li, figs. 4–8.

5. DISTRIBUTION OF THE FLORA.

Under the four preceding heads there have been described 87 distinct forms of plant life from the Cretaceous deposits of the Black Hills, viz, 22 in the condition of silicified cycadean trunks without foliage, 1 in the condition of silicified wood belonging to the Coniferæ, 57 in the condition of impressions upon the sandstones and shales of Lower Cretaceous rocks of stems, leaves, and fruits, and 8 in the same condition as the last occurring in rocks of the Dakota group proper, or Upper Cretaceous. One of these latter, *Asplenium Dicksonianum* Heer, occurs in both these beds, which accounts for the otherwise apparent increase in the number to 88 instead of 87.

Professor Fontaine has given, at the close of his treatment of the Hay Creek flora (supra, pp. 699-702), a fairly complete summary of the general results of a study of these plants, and as this constitutes the great bulk of the entire flora, there is little to add by way of correlation.

Professor Jenney has also discussed certain questions arising out of the geological and geographical distribution of the plant remains, having been furnished with a copy of Professor Fontaine's report in manuscript. It occurred to me, however, that a table showing the distribution of all the plants, not only within the Black Hills, but throughout the American beds, and also in other countries wherever species previously known have been identified in the Black Hills, would afford any who might be disposed to do so an opportunity to make general comparisons and to better understand the full meaning of the data presented.

It will be observed that the above table is divided into two principal parts, viz: First, that containing the distribution within the Black Hills; and, secondly, the outside distribution of the species that are not new. So far as the Hay Creek species are concerned, Professor Fontaine has sufficiently dwelt upon the remarkable features of the distribution, especially the great number that are common to those beds and the Potomac formation. He has also discussed the value from a paleontological point of view of Professor Jenney's stratigraphical subdivisions. I will only say on this last head that after a careful comparison of his sections with those that were made by us conjointly in 1893, I have decided that the plant bed which we discovered on the eastern slope of Red Canyon, a short distance west of the principal fossil forest, some 3 miles southwest of Minnekahta station, 50 to 75 feet above the Jurassic, and constituting No. 9 of our first section (Jour. Geol., Vol. II, p. 255), must come within his division No. 4, while the principal cycad bed, No. 12 of that section, which lies 175 to 200 feet above the Jurassic and about 60 to 100 feet below the base of the Dakota sandstone, which is eroded away in that region, probably comes within his division No. 2, and is so treated in the table. The position of the cycad bed in the Blackhawk region has also been carefully studied, and is found to occupy the same relation to the underlying and overlying strata as that of Minnekahta. I have therefore assumed that all the cycads come from No. 2, a conclusion which is subject to future correction.

Other forms of cycadaceous vegetation are very scarce, only three undoubted species of that type occurring in the collection. Two of these, *Zamites brevipennis* Heer and *Z. borealis* Heer, are from the Hay Creek region, and, as Professor Jenney in one of his letters remarks, these were found in divisions No. 3 and No. 4. The *Glossozamites Fontaineanus* found by us in Red Canyon is also referable to No. 4. If these are the leaves of the plants whose trunks occur in such great abundance the two ought to be found at about the same horizon. Still, so meager is the present known flora that no conclusions drawn from its absence in certain beds can be considered valid. The further fact, also pointed out by Professor Jenney, that the principal cycad bed is nearly 100 miles south of the Hay Creek region may possess some significance for the vertical distribution.

A glance at the first part of the table serves chiefly to impress the mind with the defectiveness of the record, and the somewhat orderless grouping of the marks in certain parts of the pages can scarcely be said to furnish a basis for discussing the range of the species. As it stands, however, it may be said in general that while most of the ferns occur in divisions No. 3 and No. 4, most of the true conifers are found in division No. 2, and well up in that. The Taxaceæ and Ginkgoales occupy a somewhat intermediate position in No. 3.

The number of forms common to the Black Hills Lower Cretaceous and the Potomac formation greatly exceeds those common to it and the Kootanie; but it must be remembered that the present known Potomac flora is many times greater than the Kootanie flora as now known, and it is probable that this difference would be equalized were we in possession of all the data for comparison. A few species occur in the Amboy Clays, Tuscaloosa formation, and Island series, i. e., in the Newer Potomac, but these are not sufficient to warrant us in assuming that any of the plant-bearing beds of the Black Hills thus far found are the equivalent of these upper beds. On the other hand, as I have already pointed out (supra, p. 703), the small flora known from the Dakota sandstone above Evans quarry and at Minnekahta Falls indicates a very low place for these beds in the true Dakota group, and would not be wholly inconsistent with their reference to the horizon of the Cheyenne sandstone or lower Albirupean.

The distribution outside of America is principally confined to the Lower Cretaceous, especially the Wealden and Neocomian, which are probably for the most part parallel series, the name being dependent upon the character of the deposits, the Wealden being the estuarine or lacustrine equivalent of the marine Neocomian of various countries. It is further significant that all the species of wide lateral and vertical range, *Weichselia reticulata*, *Matonidium Althausii*, *Sequoia Reichenbachi*, and *Spehnolepidium Kurrianum*, which make up the bulk of the foreign distribution, are primarily Wealden or Neocomian species, and their range above and below is merely the result of the great abundance, exuberance, and persistence of these forms, or in part, perhaps, of errors in determination.

I have frequently alluded to these facts and have given the distribution of the same and other similar forms occurring in the Lower Cretaceous of America,[1] and my only excuse for repeating them here, in so far as they concern this paper, is that I desire to make the evidence as complete as possible, and omit nothing that in any important degree bears upon the age of the beds yielding the flora here recorded. To any one competent to weigh this evidence there should no longer remain a doubt on the general subject, and alike the original claim that all the sandstones of the Cretaceous rim of the Black Hills belong to the Dakota group proper, or No. 1 of Meek and Hayden, and the recent contention that the cycad and other plant-bearing beds form a part of the Jurassic may be regarded as definitively overthrown.

[1] See Am. Jour. Sci., 3d series, Vol. XXXVI, August, 1888, p. 127; Fifteenth Ann. Rept. U. S. Geol. Survey, pp. 388-392; Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, pp. 482-483.

Table of distribution of the fossil plants of the Cretaceous formation of the Black Hills.

Distribution within the Black Hills.

Systematic number.	Names of the species.	Division No. 4. Jurassic contact. Lon Cottle's ranch.	Division No. 4. 50 feet above the Jurassic. Webster's ranch.	Division No. 4. 50 feet above the Jurassic. Shales over coal 2 miles southeast of Barrett.	Division No. 4. 50-75 feet above the Jurassic. Larrabee's shaft.	Division No. 4. 50-75 feet above the Jurassic. Slope on left bank of Red Canyon, 3 miles southwest of Minnekahta station.	Division No. 3. 150 feet above the Jurassic. Shales under third sandstone at Barrett.	Division No. 3. 150 feet above the Jurassic. John Barr's tunnel.	Division No. 3. 150 feet above the Jurassic. Cliff on north side of valley of south fork of Hay Creek.	Division No. 2. 175-200 feet above the Jurassic. Cycad beds. Three miles southwest of Minnekahta station.	Division No. 2. Cycad beds. Two miles southeast of Minnekahta station.	Division No. 2. Cycad beds. Three or 4 miles southwest of Hot Springs.	Division No. 2. Cycad beds. Black's ranch, 2 miles north of Blackhawk.	Division No. 2. Cycad beds. Two and one-half or 3 miles west of Sturgis.	Division No. 2. 100 feet below the Dakota sandstone. Cliff on the north side of Pine Creek.	Division No. 2. 100 feet below the Dakota sandstone. Cliff on the south side of Pine Creek.	Division No. 2. 100 feet below the Dakota sandstone. Cliff on Oak Creek at Robbin's ranch.	Division No. 2. 100 feet below the Dakota sandstone. Rollin's tunnel.	Division No. 2. 60 feet below the Dakota sandstone. Cliff on east bank of Oak Creek, 2 miles below Robbin's ranch.	Division No. 2. 60 feet below the Dakota sandstone. Cliff on north side of Red Water Valley.	Division No. 1. Dakota group proper. Shales over hard sandstone at Minnekahta Falls.	Division No. 1. Dakota group proper. Shales over Evans quarry.
1	Equisetum virginicum Font								×						×							
2	Weichselia reticulata (Stokes and Webb) Ward															×	×	×	×	×		
3	Matonidium Althausii (Dunk.) Ward														×			×				
4	Pecopteris Geyleriana Nath														×		×	×	×			
5	borealis Brongn																		×			
6	Cladophlebis wyomingensis n. sp																		×			
7	parva Font								×													
8	Sphenopteris plurinervia Heer (?)								×													
9	Thyrsopteris pinnatifida Font (?)								×													
10	crassinervis Font								×													
11	elliptica Font	×					×		×													
12	dentifolia n. sp			×																		
13	brevifolia Font			×																		
14	pecopteroides Font			×																		
15	brevipennis Font								×													
16	Scleropteris distantifolia n. sp								×													
17	rotundifolia n. sp								×													
18	Asplenium Dicksonianum Heer					×															×	
19	Gleichenia Zippei Heer (?)					×																
20	Cycadeoidea dacotensis (McBride) Ward emend									×	×		×	×								
21	colossalis n. sp									×												
22	Wellsii n. sp									×												
23	minnekahtensis n. sp									×												
24	pulcherrima n. sp									×												
25	cicatricula n. sp												×									
26	turrita n. sp									×												
27	McBridei n. sp									×			×									
28	Marshiana n. sp									×												
29	furcata n. sp									×												
30	Colei n. sp									×												
31	Paynei n. sp									×												
32	aspera n. sp												×									
33	insolita n. sp									×												
34	occidentalis n. sp									×												
35	Jenneyana Ward									×			×									
36	ingens n. sp												×									
37	formosa n. sp												×									
38	Stillwelli n. sp									×			×									
39	excelsa n. sp											×										
40	nana n. sp									×												
41	Zamites brevipennis Heer							×														
42	borealis Heer		×		×			×														
43	(?) sp. Font																×					
44	Glossozamites Fontaineanus Ward n. sp					×																
45	Cycadeospermum rotundatum Font																×					
46	Williamsonia (?) phoenicopsoides Ward n. sp								×													
47	Araucarioxylon Hoppertonæ Kn. n. sp									×												
48	Araucarites wyomingensis n. sp	×							×													
49	(?) cuneatus Ward n. sp							×														
50	Pinus susquaensis Dn		×				×								×				×			
51	Abietites angusticarpus Font																		×			
52	Leptostrobus longifolius Font														×		×		×			
53	alatus Ward n. sp														×							
54	Athrotaxopsis tenuicaulis Font														×				×			
55	Sequoia Reichenbachi (Gein.) Heer														×				×			
56	gracilis Heer														×	×						
57	sp. Font. (immature cone)								×													
58	Geinitzia Jenneyi n. sp														×				×			
59	Sphenolepidium Kurrianum (Dunk.) Heer														×	×	×		×			
60	parceramosum Font														×				×			
61	Glyptostrobus brookensis (Font.) Ward														×				×			
62	Nageiopsis longifolia Font						×		×													
63	angustifolia Font. (?)						×															
64	Baieropsis adiantifolia Font						×		×													
65	pluripartita Font (?)						×								×							
66	Czekanowskia nervosa Heer		×				×															
67	Cephalotaxopsis magnifolia Font						×		×						×							
68	Male ament of a conifer								×													
69	Quercophyllum wyomingense n. sp														×							
70	Quercus Wardiana Lx. (?)																					×
71	Ulmiphyllum densinerve n. sp																	×				
72	Ficophyllum serratum Font																		×			
73	Sassafras Mudgii Lx																					×
74	Platanus cissoides Lx. (?)																					×
75	Celastrophyllum pulchrum Ward n. sp																					×
76	Sapindopsis variabilis Font																×		×			
77	Cissites salisburiæfolius Lx																				×	
78	ingens Lx																				×	×
79	Viburnites Evansanus Ward																					×
80	Male ament of a dicotyledon								×													
81	Carpolithus fasciculatus Font								×													
82	montium-nigrorum Ward n. sp								×													
83	barrensis Ward n. sp							×														
84	virginiensis Font														×							
85	fœnarius Ward n. sp	×																				
86	Feistmantelia oblonga Ward n. gen. n. sp														×							

American distribution outside of the Black Hills.

Systematic number.	Lower Cretaceous. Trinity of Texas.	Lower Cretaceous. Kootanie of Great Falls, Montana.	Lower Cretaceous. Kootanie of British America.	Lower Cretaceous. Cape Lisburn, Alaska.	Lower Cretaceous. Shasta group, California.	Lower Cretaceous. James River, Virginia.	Lower Cretaceous. Rappahannock series, Virginia.	Lower Cretaceous. Mount Vernon series, Virginia.	Lower Cretaceous. Aquia Creek series, Virginia and Maryland.	Lower Cretaceous. Tuscaloosa formation, Alabama.	Lower Cretaceous. Amboy clays, New Jersey.	Lower Cretaceous. Cheyenne sandstone, Kansas.	Lower Cretaceous. Island series.	Upper Cretaceous. Cliffwood, New Jersey, Matawan formation.	Upper Cretaceous. Morrison, Colorado.	Upper Cretaceous. Dakota group of Kansas and Nebraska.	Upper Cretaceous. Kanab Valley, Utah.	Upper Cretaceous. Vancouver Island.	Upper Cretaceous. Peace and Pine rivers, British America.	Upper Cretaceous. Belly River, British America.	Upper Cretaceous. Rock Creek, Wyoming.	Upper Cretaceous. Livingston, Montana.	Upper Cretaceous. Spring Canyon, Montana.
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Foreign distribution.

Systematic number.	Jurassic. Bavaria (Rhetic).	Jurassic. Italy (Lias).	Jurassic. Kach, India (Lias).	Jurassic. Yorkshire (Oolite).	Jurassic. Cracow (Oolite).	Jurassic. Portugal (Jurassic).	Jurassic. Purbeck beds (England).	Wealden. England.	Wealden. France.	Wealden. Germany.	Neocomian. Belgium.	Neocomian. Portugal.	Neocomian. Westphalia.	Neocomian. Russia.	Neocomian. Spitzbergen.	Neocomian. Japan.	Urgonian. Austrian Silesia.	Urgonian. Portugal.	Urgonian. Greenland (Kome beds).	Aptian. Portugal.	Gault. Portugal.	Gault. Switzerland.	Gault. Westphalia.	Cenomanian. Greenland (Atane beds).	Cenomanian. Portugal.	Cenomanian. Saxony.	Cenomanian. Bohemia.	Cenomanian. Moravia.	Turonian. Saxony.	Senonian. France.	Senonian. Westphalia.	Senonian. Aachen.	Senonian. Silesia.	Senonian. Quedlinburg.	Senonian. Bohemia (Gosau).	Senonian. Greenland (Patoot beds).	Systematic number.
1																																					1
2							×	×	×	×	×		×	×		×	×			×			×											×			2
3	×			×	×		×			×	×	×		×																				×			3
4																×																					4
5																			×					×													5
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PLATES.

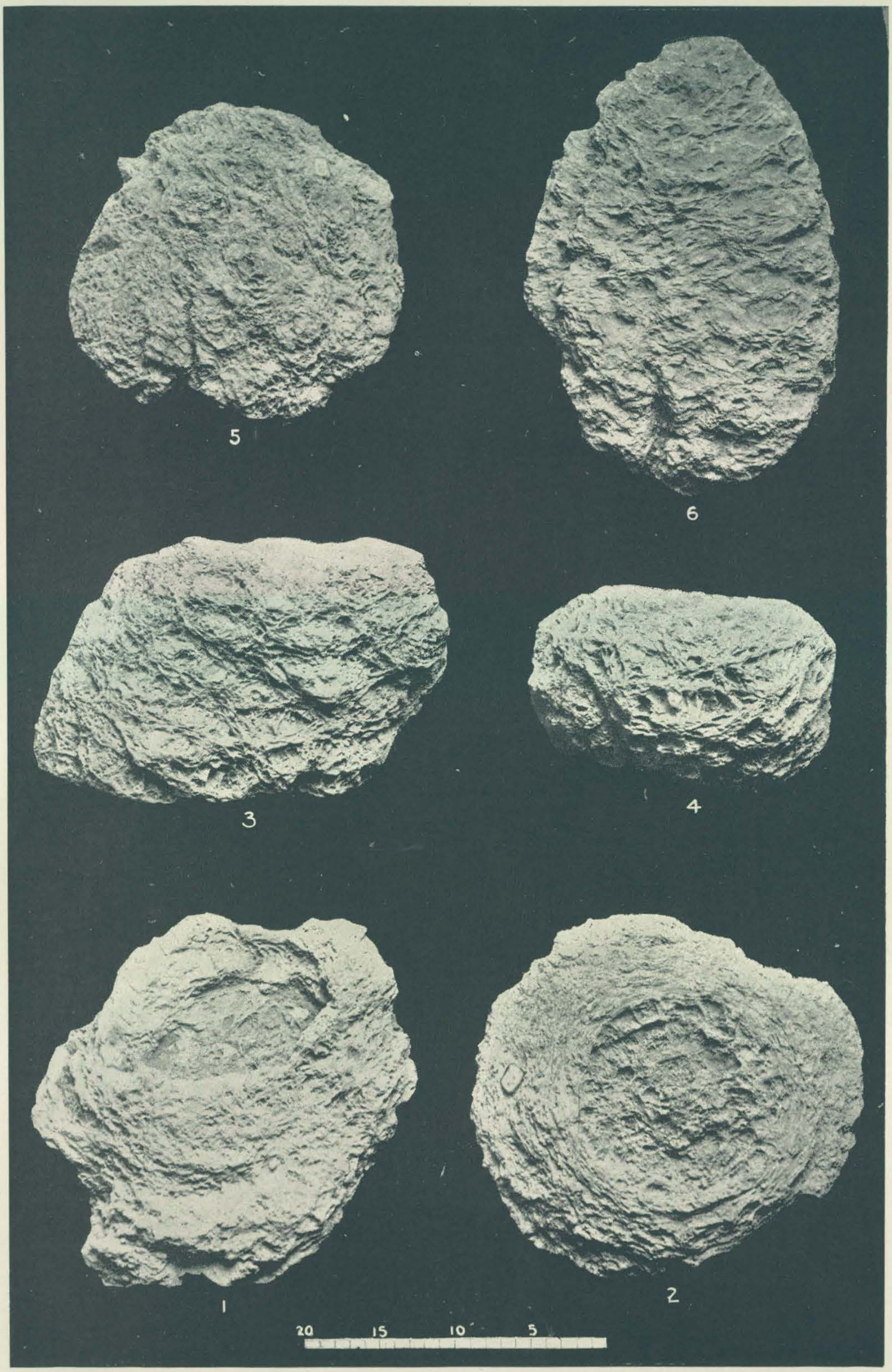
PLATE LVII.

PLATE LVII.

CYCADEAN TRUNKS FROM THE PURBECK BEDS OF THE ISLE OF PORTLAND, ENGLAND, BELONGING TO THE U. S. NATIONAL MUSEUM COLLECTION.

		Page.
FIGS. 1, 2.	CYCADEOIDEA MEGALOPHYLLA Buckl	601
FIGS. 3, 4.	CYCADEOIDEA MICROPHYLLA Buckl	601
FIGS. 5, 6.	CYCADEOIDEA PORTLANDICA Carr	601

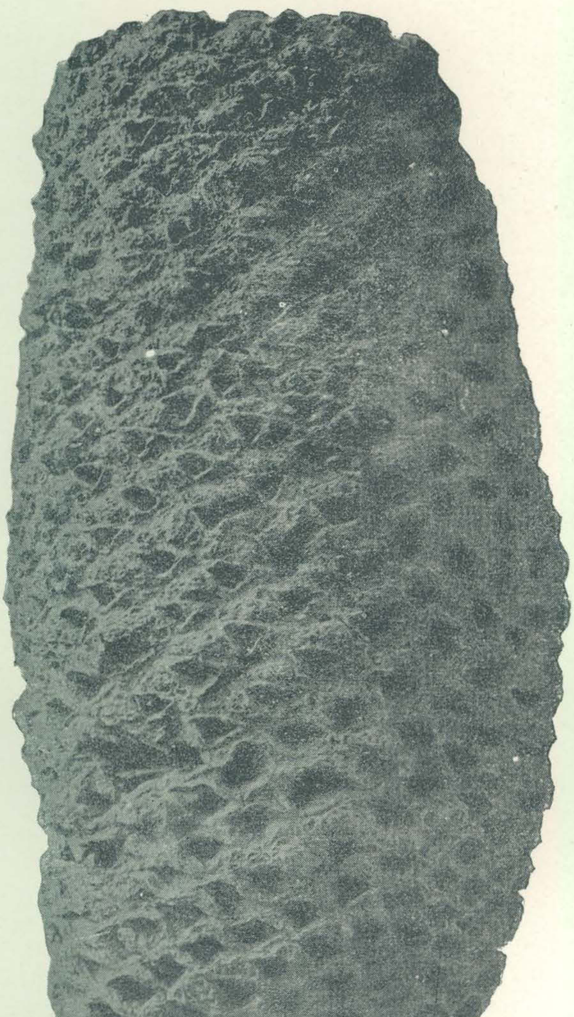
Scale, 20 cm.



GROUP OF CYCADEAN TRUNKS FROM THE PURBECK BEDS OF THE ISLE OF PORTLAND, ENGLAND.

PLATE LVIII.

PLATE LVIII.



CYCADEAN TRUNK (CYCADEOIDEA MASSEIANA) FROM THE SCALY CLAYS OF ITALY.

PLATE LIX.

PLATE LIX.

Page.

CYCADEOIDEA REICHENBACHIANA (Göpp.) Cap. and Solms 601

From a photograph of the specimen as mounted in the Royal Geological Museum at Dresden, furnished by Prof. Dr. Hans Bruno Geinitz.

CYCADEAN TRUNK (CYCADEOIDEA REICHENBACHIANA) FROM GALICIA.

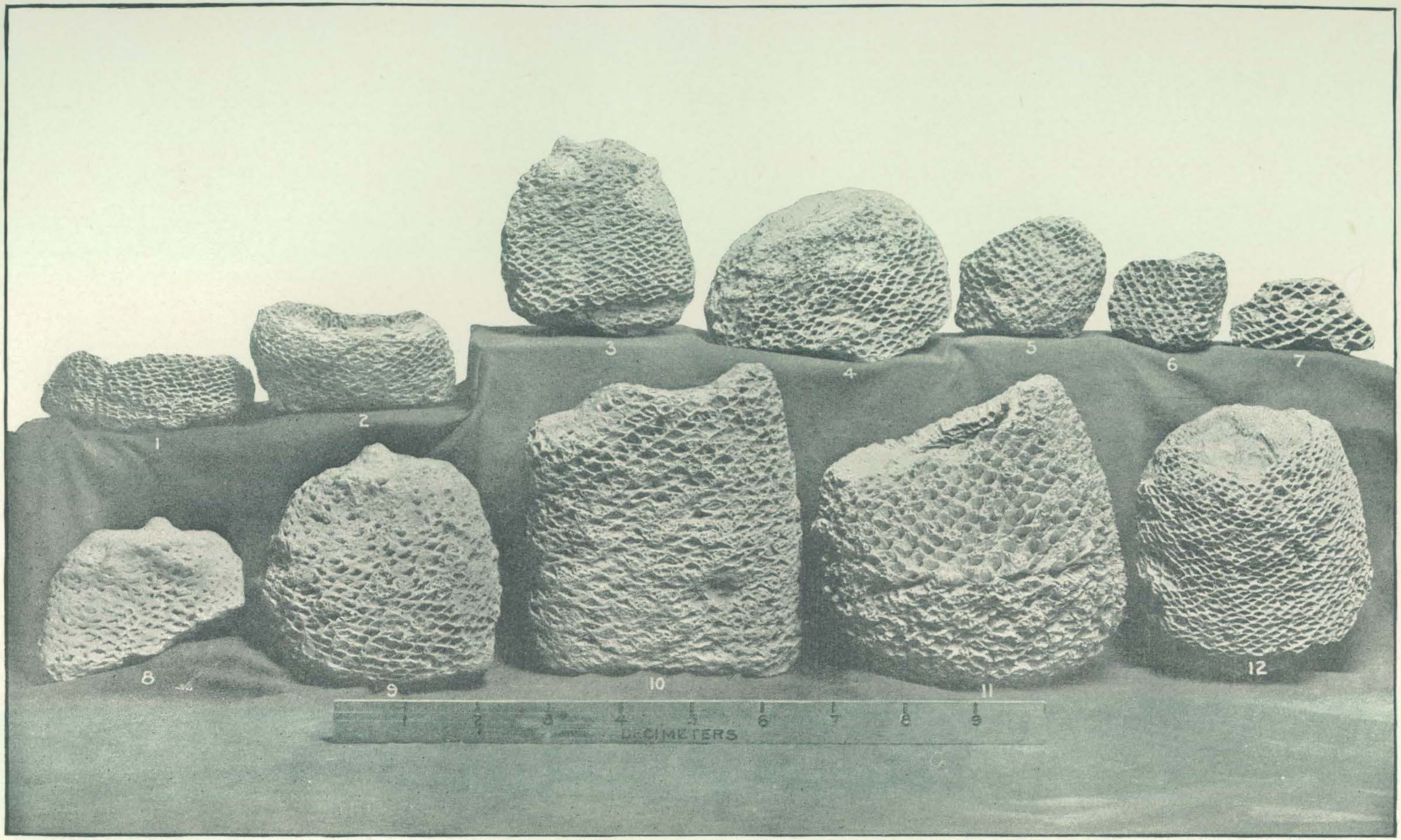
PLATE LX.

PLATE LX.

GROUP OF FOSSIL CYCADEAN TRUNKS FROM THE POTOMAC FORMATION OF MARYLAND, BELONGING TO THE WOMAN'S COLLEGE OF BALTIMORE, COLLECTED BY MR. ARTHUR BIBBINS.

Scale, 1 meter.

In photographing the trunk represented by Fig. 10 it was accidentally inverted



GROUP OF CYCADEAN TRUNKS FROM THE POTOMAC FORMATION OF MARYLAND.

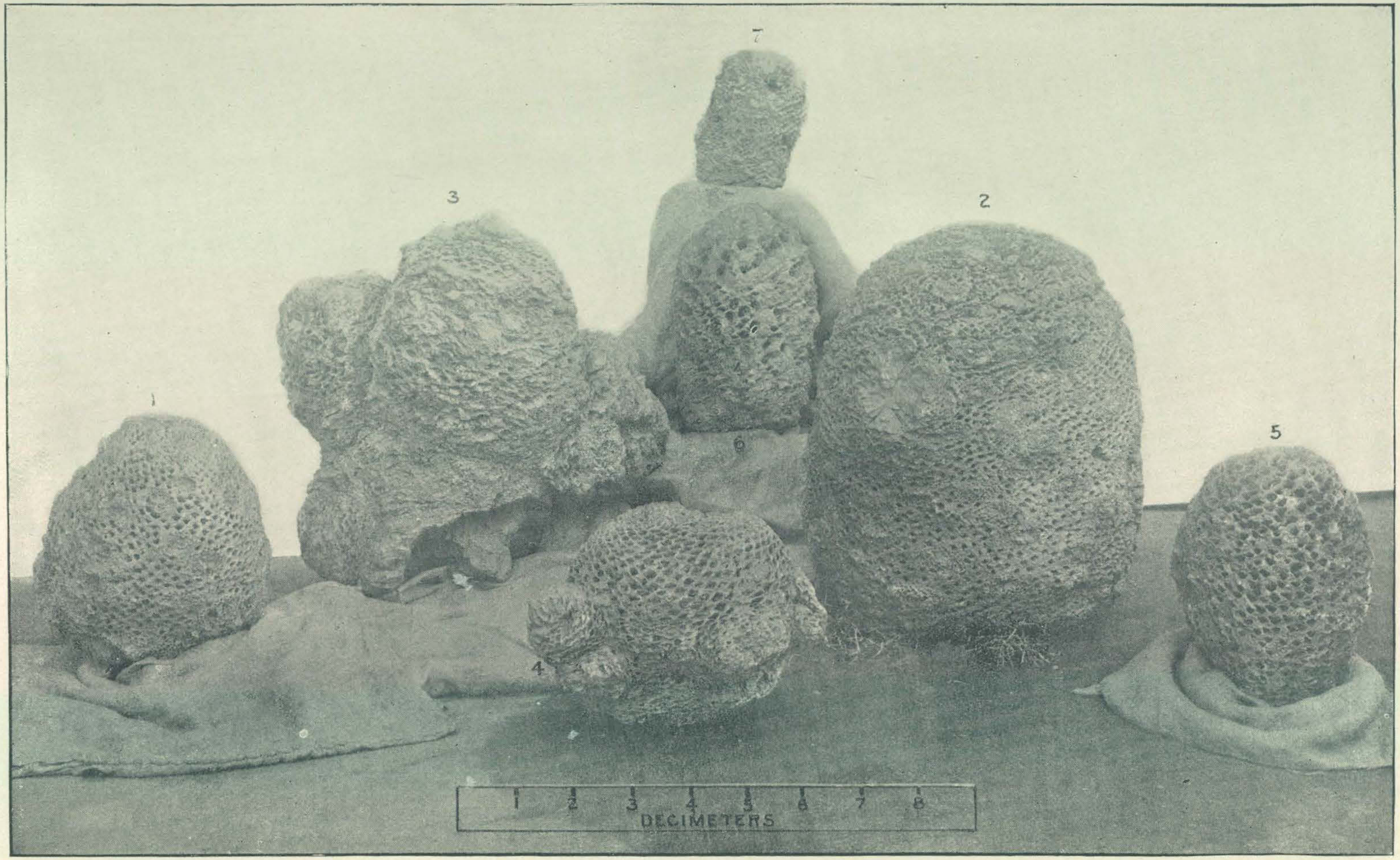
PLATE LXI.

PLATE LXI.

GROUP OF FOSSIL CYCADEAN TRUNKS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

		Page.
FIG. 1.	CYCADEOIDEA DACOTENSIS (McBride) Ward emend	602
FIG. 2.	CYCADEOIDEA COLOSSALIS n. sp	602
FIG. 3.	CYCADEOIDEA MINNEKAHTENSIS n. sp	602
FIG. 4.	CYCADEOIDEA PULCHERRIMA n. sp	602
FIG. 5.	CYCADEOIDEA COLEI n. sp	602
FIG. 6, 7.	CYCADEOIDEA PAYNEI n. sp	602

Scale, 1 meter.



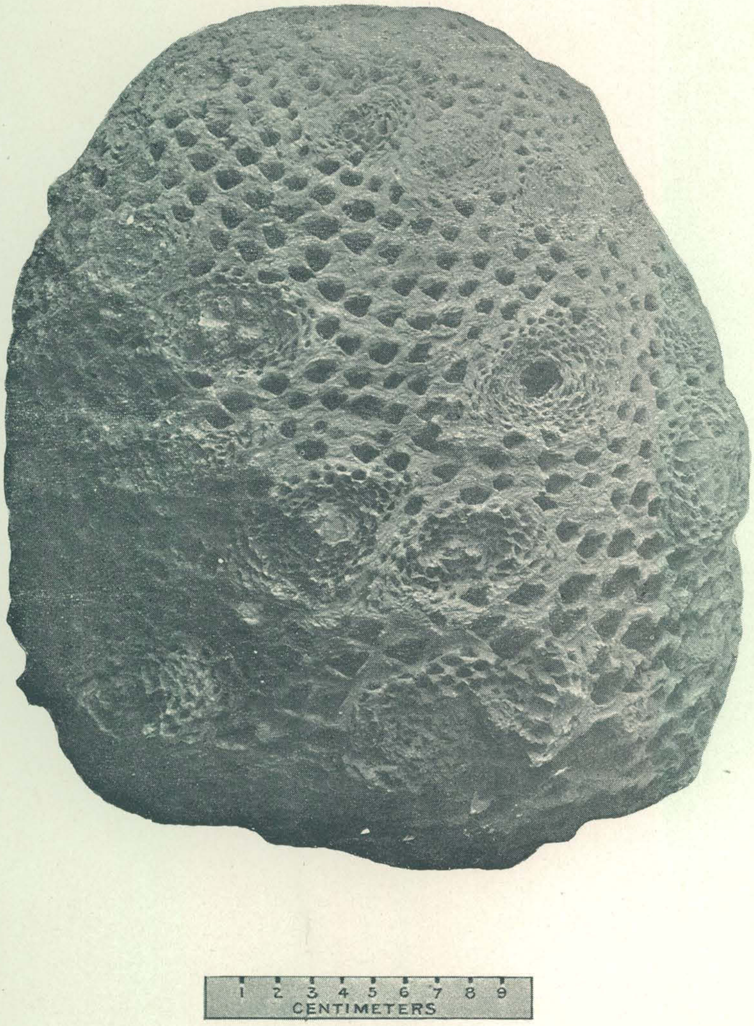
GROUP OF CYCADEAN TRUNKS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE LXII.

PLATE LXII.

Side view of trunk No. 1, U. S. National Museum collection.

Scale, 10 cm.



CYCADEOIDEA DACOTENSIS.

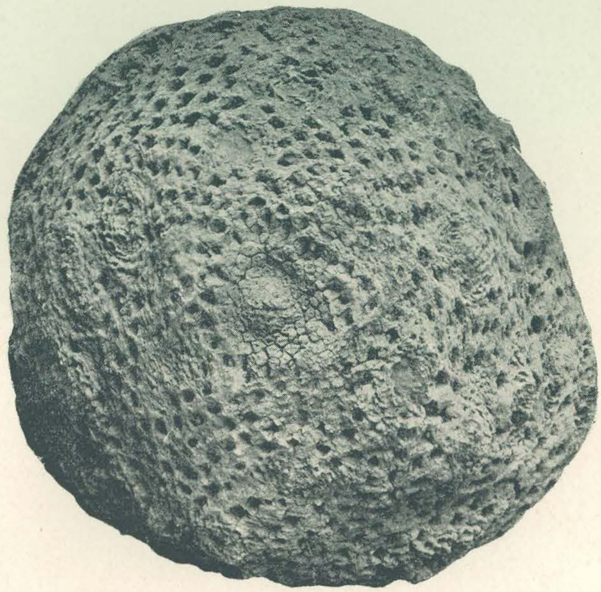
PLATE LXIII.

PLATE LXIII.

FIG. 1. View of the apex, showing arrangement of scars in the terminal bud.

FIG. 2. View of the base.

Scale, 10 cm.



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2

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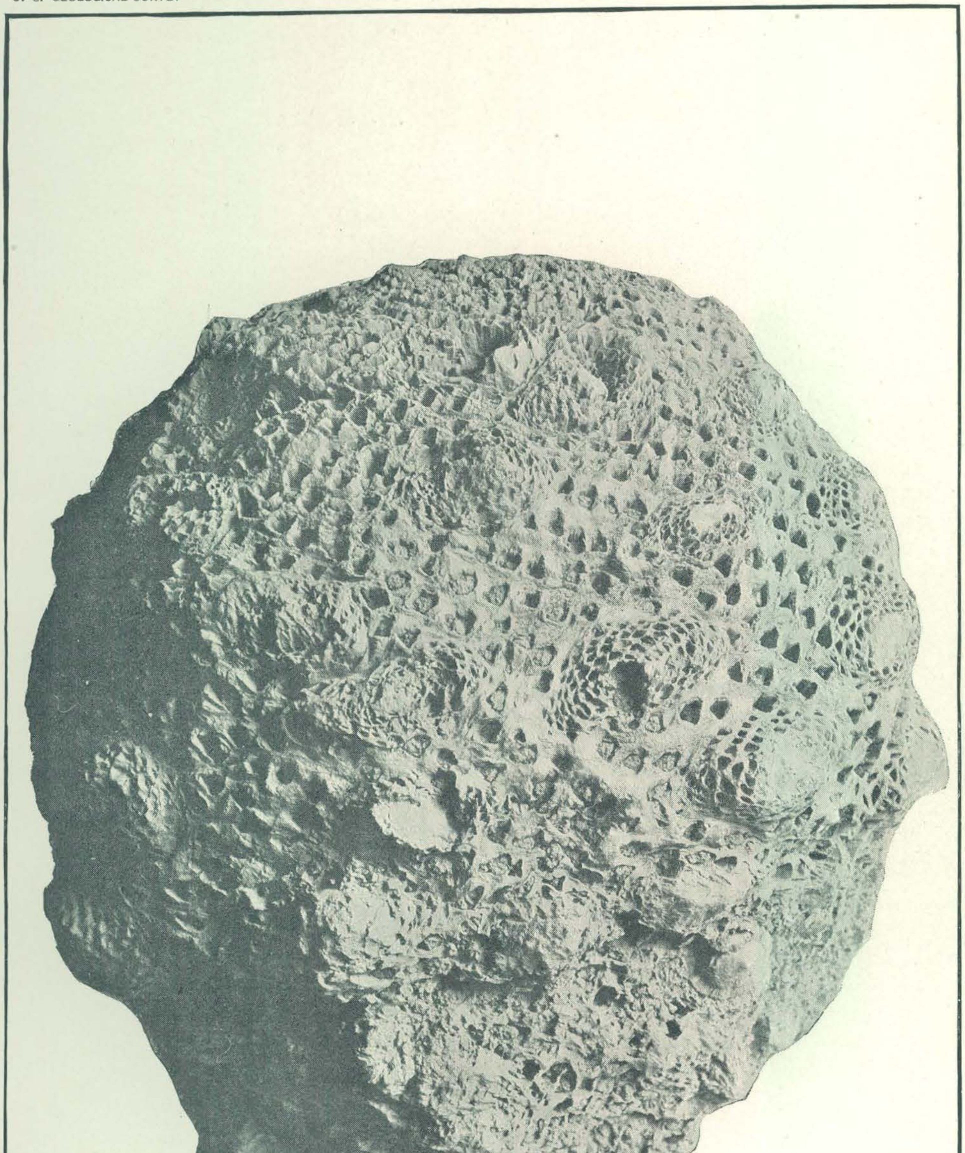
CENTIMETERS

CYCADEOIDEA DACOTENSIS.

PLATE LXIV.

PLATE LXIV.



CYCADEOIDEA DACOTENSIS.

PLATE LXV.

PLATE LXV.

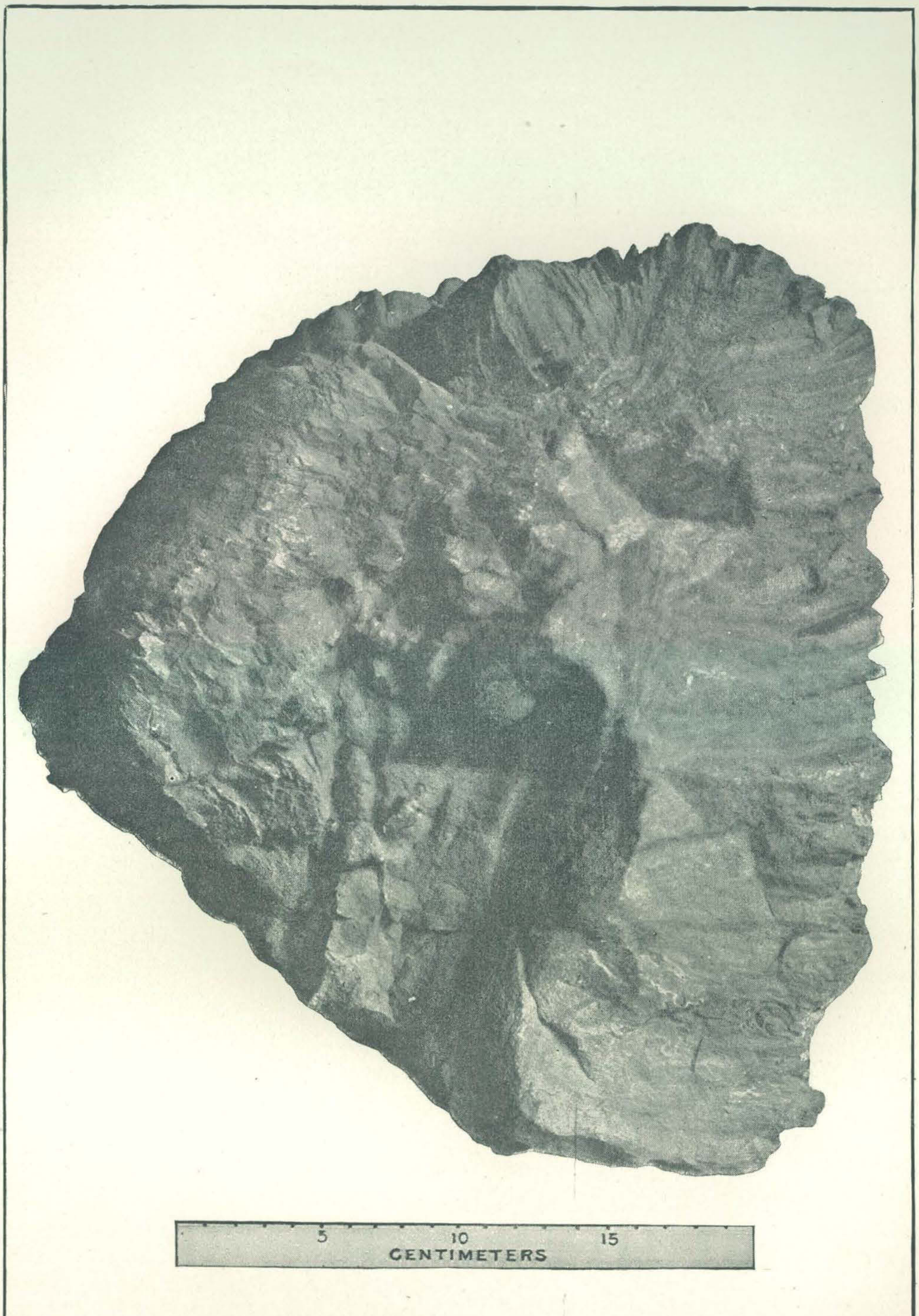
View of the apex of trunk No. 54 of the Yale collection, showing helicoid arrangement of scars in the terminal bud.

Scale, 20 cm.

CYCADEOIDEA DACOTENSIS.

PLATE LXVI.

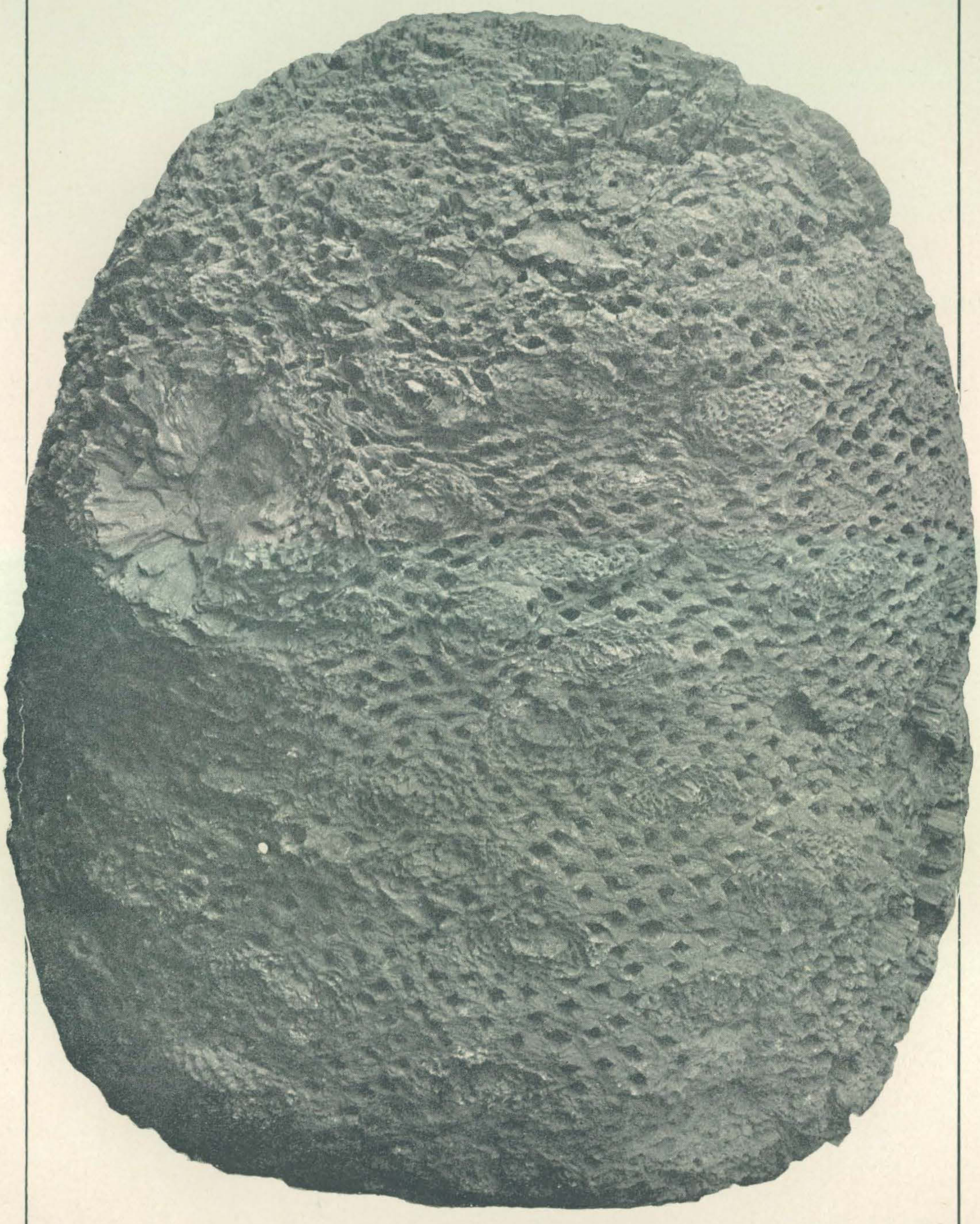
PLATE LXVI.



CYCADEOIDEA DACOTENSIS.

PLATE LXVII.

PLATE LXVII.



CYCADEOIDEA COLOSSALIS.

PLATE LXVIII.

PLATE LXVIII.

CYCADEOIDEA COLOSSALIS.

PLATE LXIX.

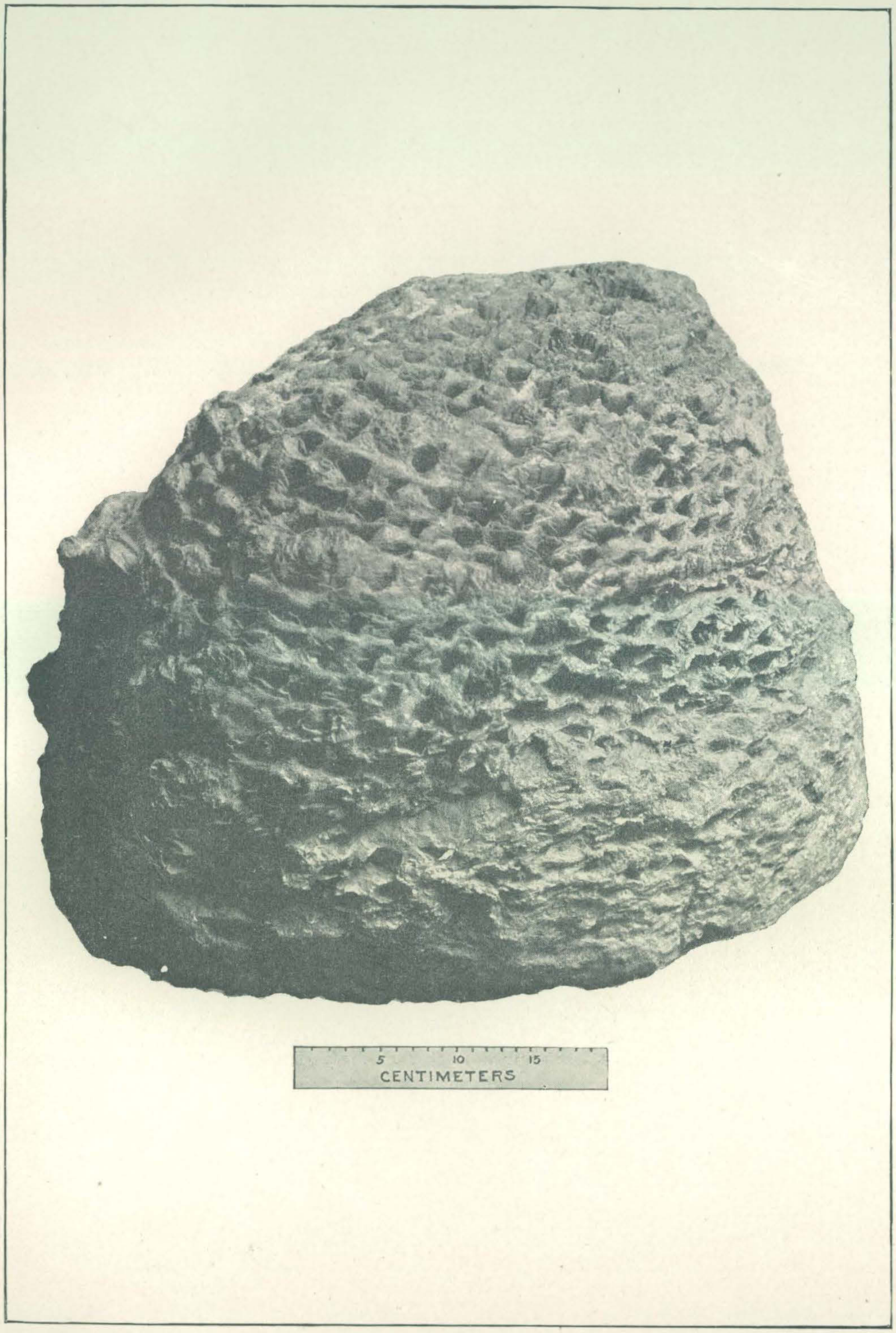
PLATE LXIX.

Page.

CYCADEOIDEA COLOSSALIS n. sp. 603

Side view of trunk No. 10 of the Yale collection.

Scale, 20 cm.



CYCADEOIDEA COLOSSALIS

PLATE LXX.

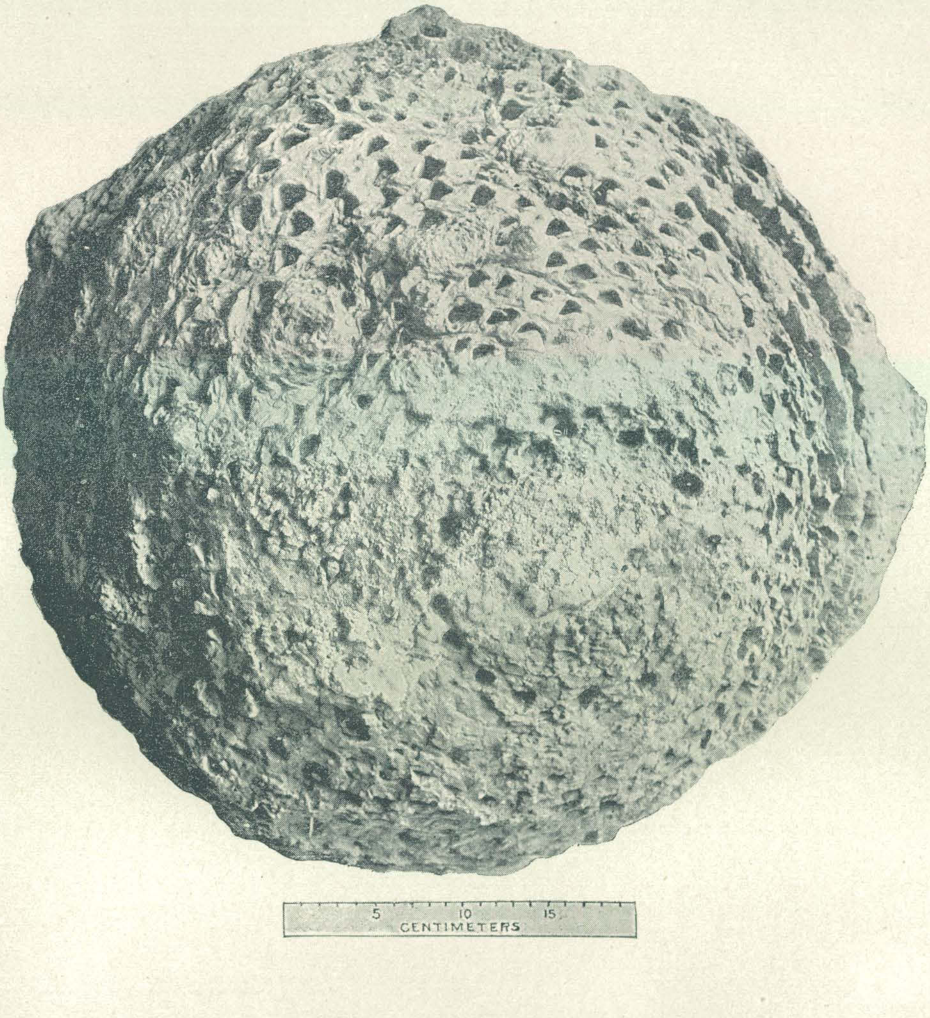
PLATE LXX.

Page.

CYCADEOIDEA COLOSSALIS n. sp. 603

View of the apex of trunk No. 2 of the Yale collection.

Scale, 20 cm.



CYCADEOIDEA COLOSSALIS.

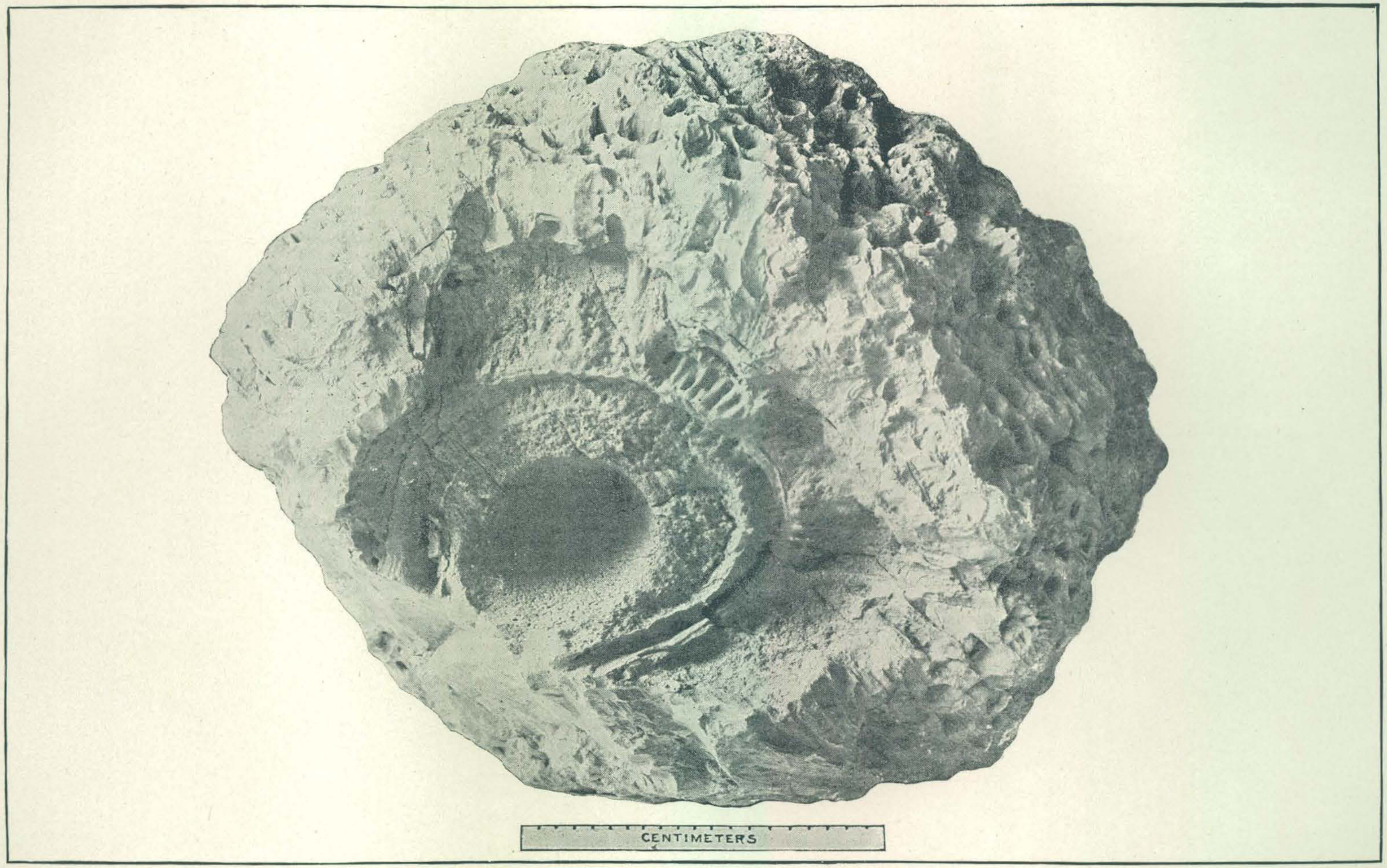
PLATE LXXI.

PLATE LXXI.

CYCADEOIDEA COLOSSALIS.

PLATE LXXII.

PLATE LXXII.



CYCADEOIDEA COLOSSALIS.

PLATE LXXIII.

PLATE LXXIII.

CYCADEOIDEA WELLSII.

PLATE LXXIV.

PLATE LXXIV.

750

CYCADEOIDEA WELLSII.

PLATE LXXV.

PLATE LXXV.

CYCADEOIDEA WELLSII.

PLATE LXXVI.

PLATE LXXVI.

Side view of trunk No. 7 of the U. S. National Museum collection.

Scale, 20 cm.

CYCADEOIDEA MINNEKAHTENSIS.

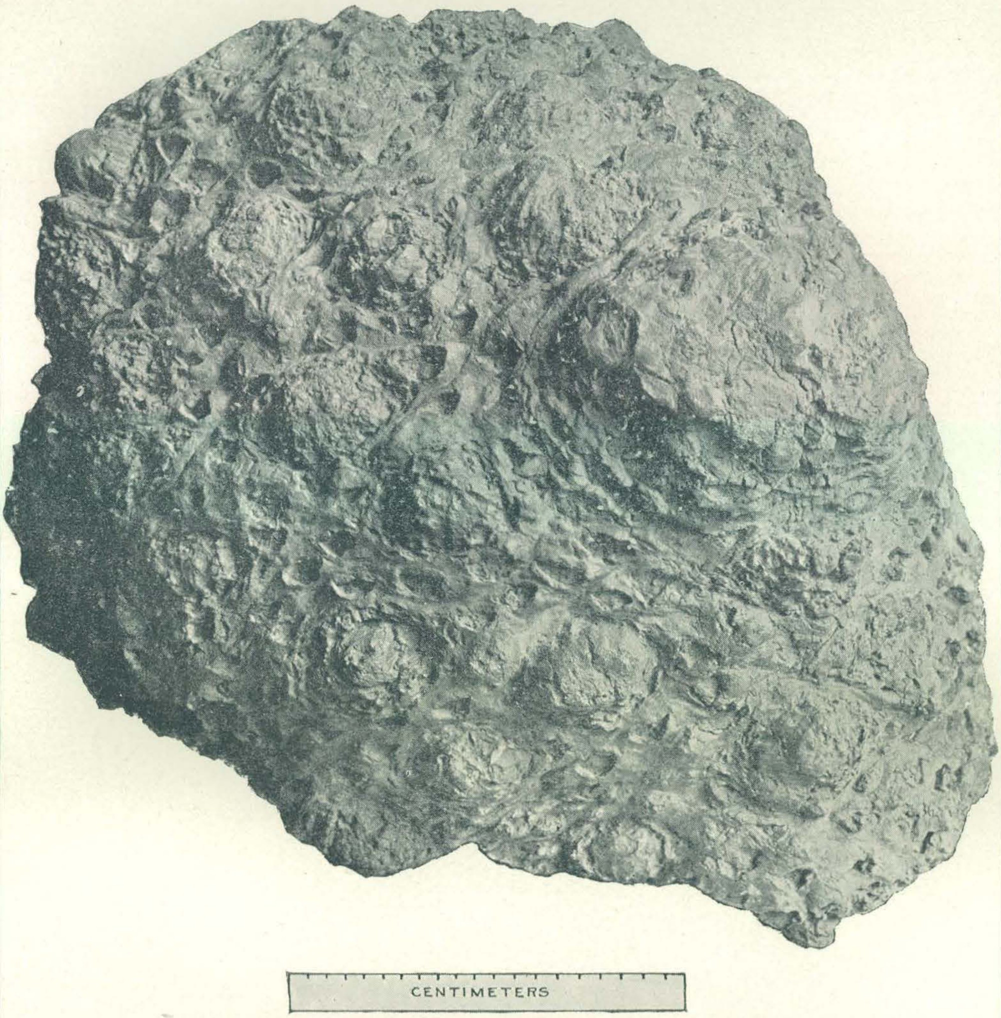
PLATE LXXVII.

PLATE LXXVII.

CYCADEOIDEA MINNEKAHTENSIS.

PLATE LXXVIII.

PLATE LXXVIII.



CYCADEOIDEA MINNEKAHTENSIS.

PLATE LXXIX.

PLATE LXXIX.

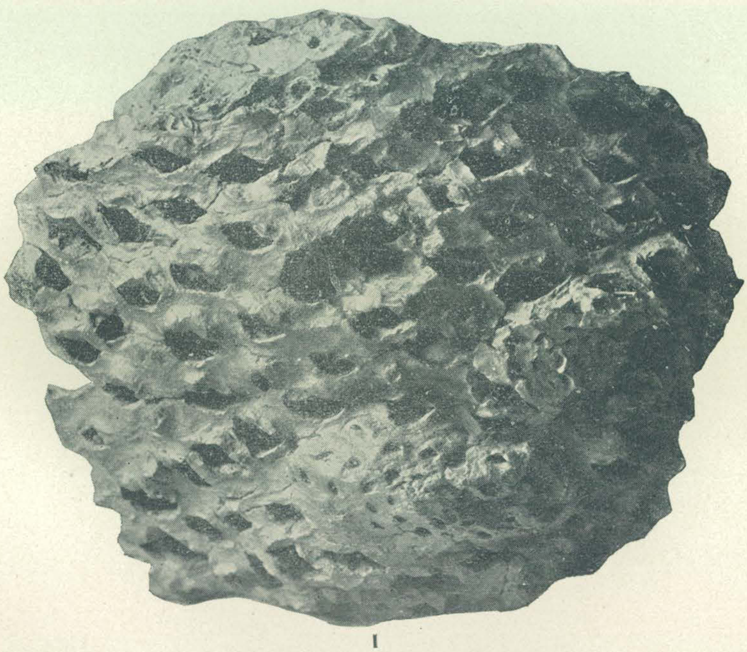
Page.

Fig. 1. View of the exterior of one of the fragments of No. 83 of the Yale collection.

Fig. 2. View of the fractured surface of fragment No. 86 of the Yale collection, showing also the terminal bud.

Scale, 10 cm.

2



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CENTIMETERS

CYCADEOIDEA MINNEKAHTENSIS.

PLATE LXXX.

PLATE LXXX.

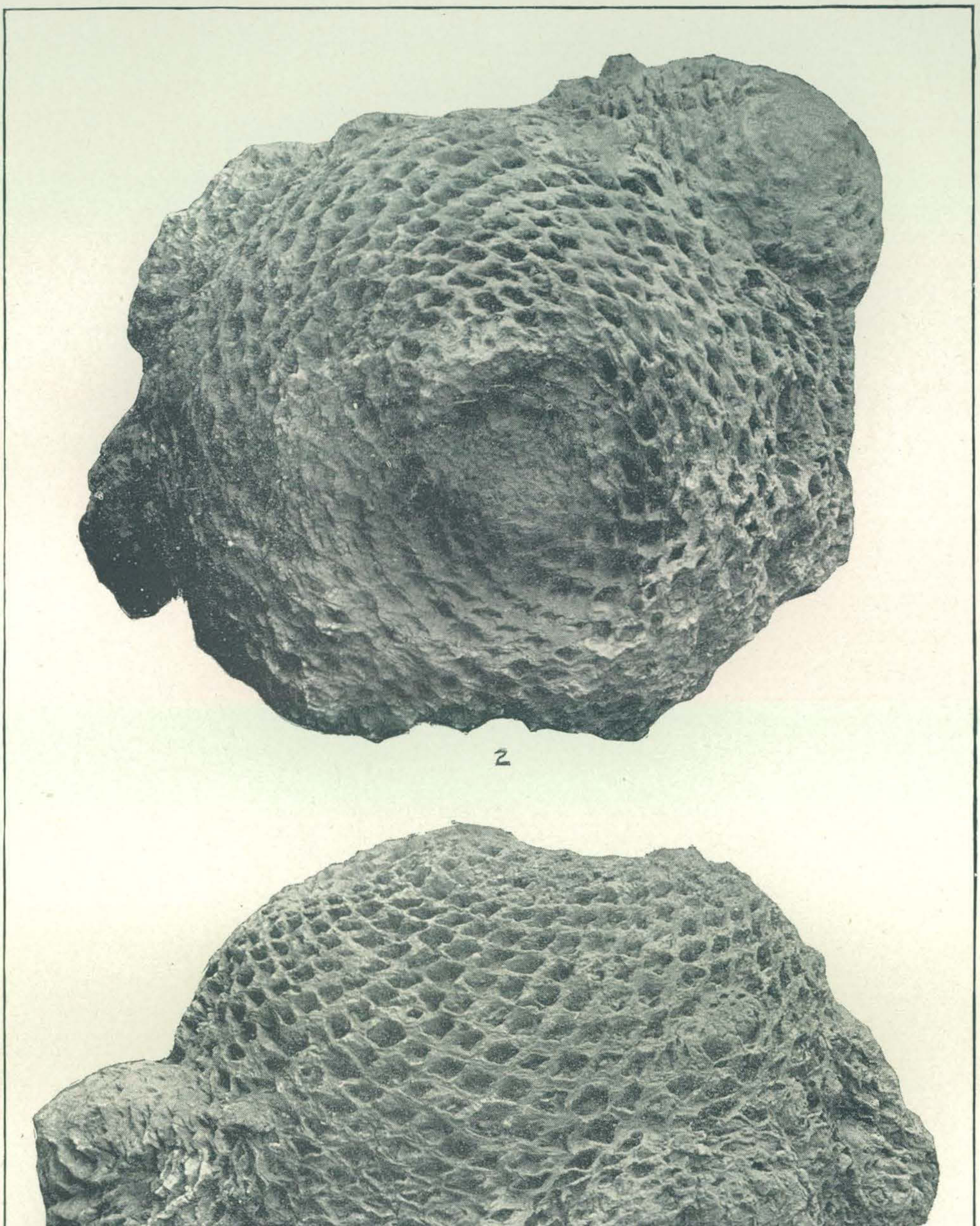
Page

CYCADEOIDEA PULCHERRIMA n. sp 608

FIG. 1. View of the perfect side of trunk No. 3 of the U. S. National Museum collection.

FIG. 2. View of the apex of the same.

Scale, 20 cm.



CYCADEOIDEA PULCHERRIMA.

PLATE LXXXI.

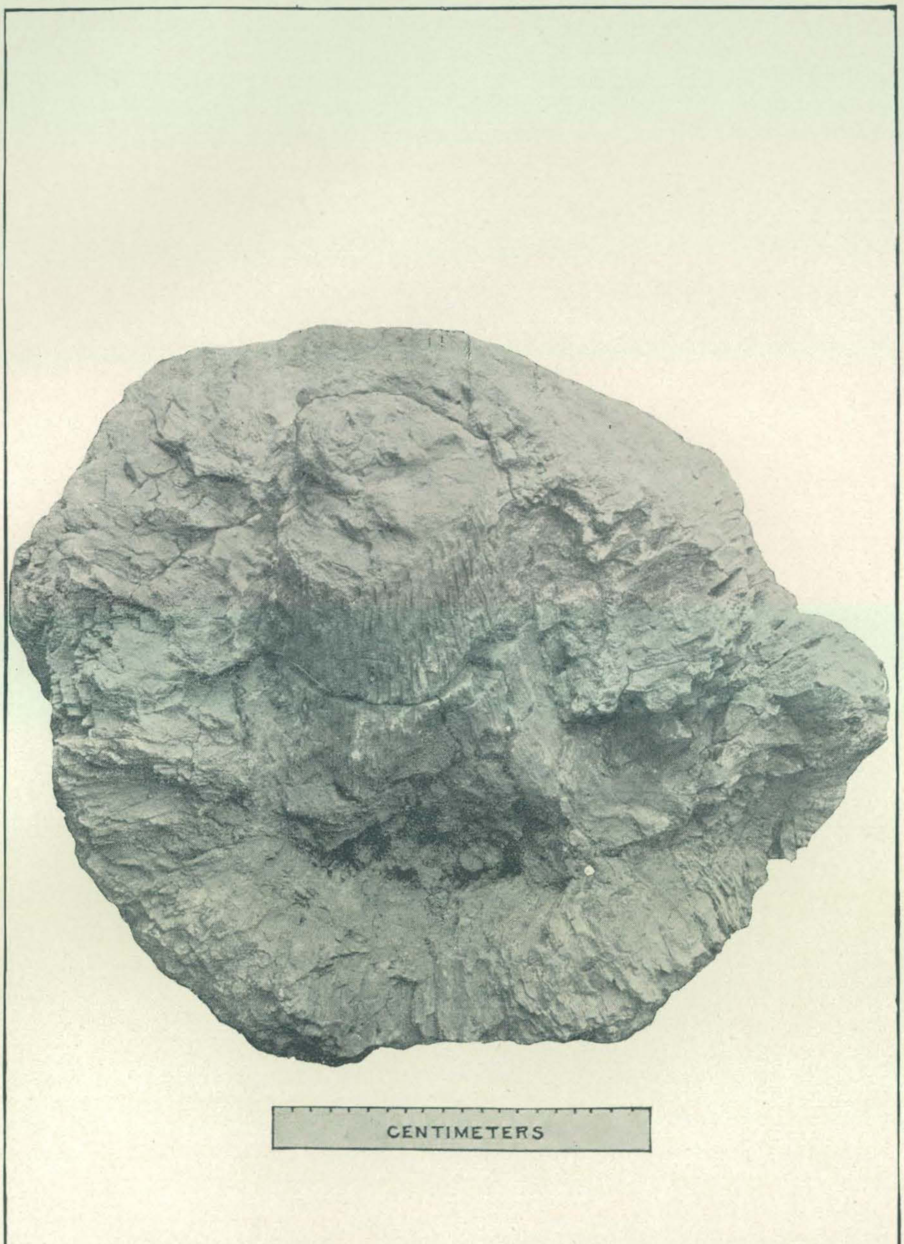
PLATE LXXXI.

Page.

CYCADEOIDEA PULCHERRIMA n. sp 608

View of the decayed side of trunk No. 3 of the U. S. National Museum collection, intentionally inverted better to show the exposed internal structure.

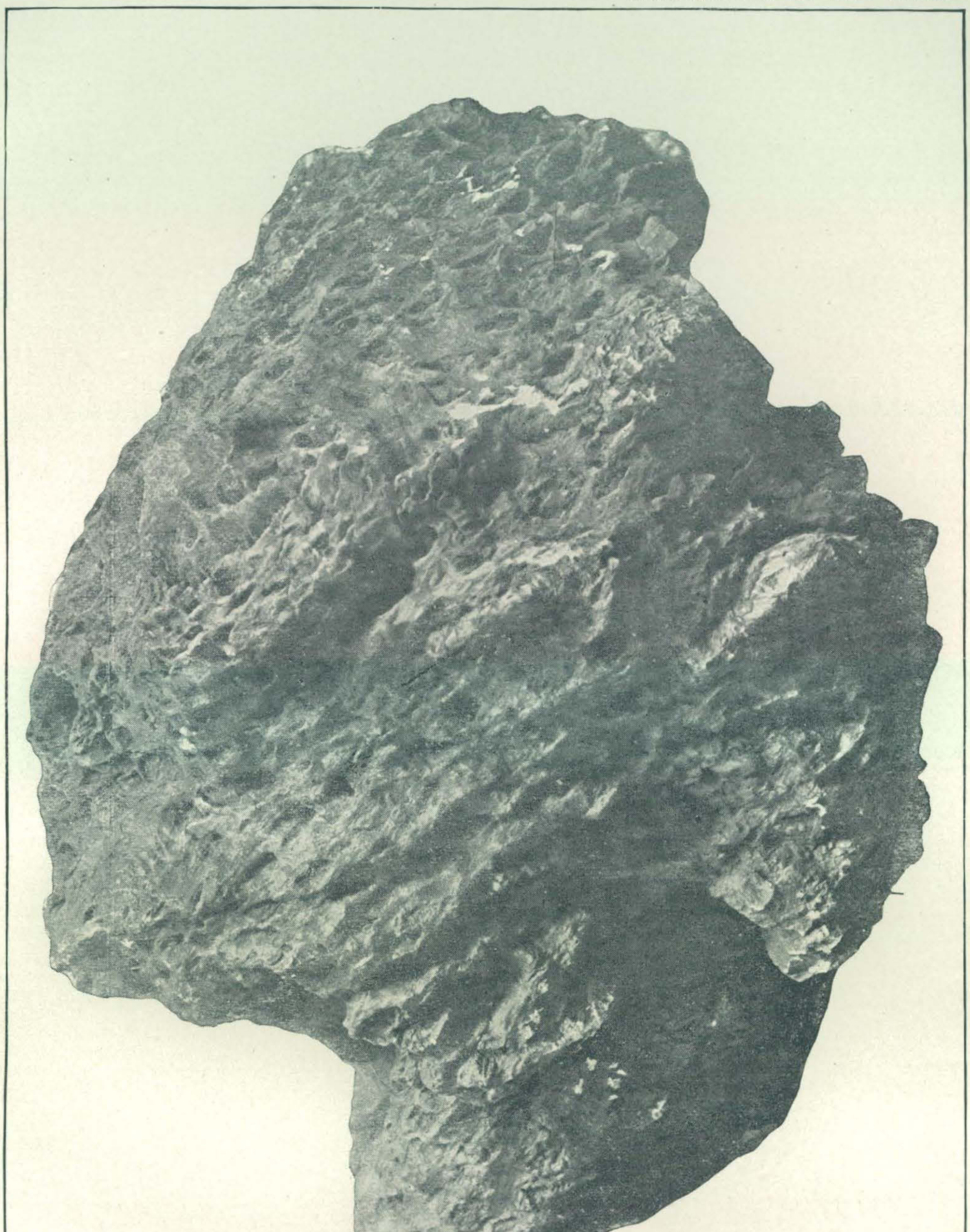
Scale, 20 cm



CYCADEOIDEA PULCHERRIMA.

PLATE LXXXII.

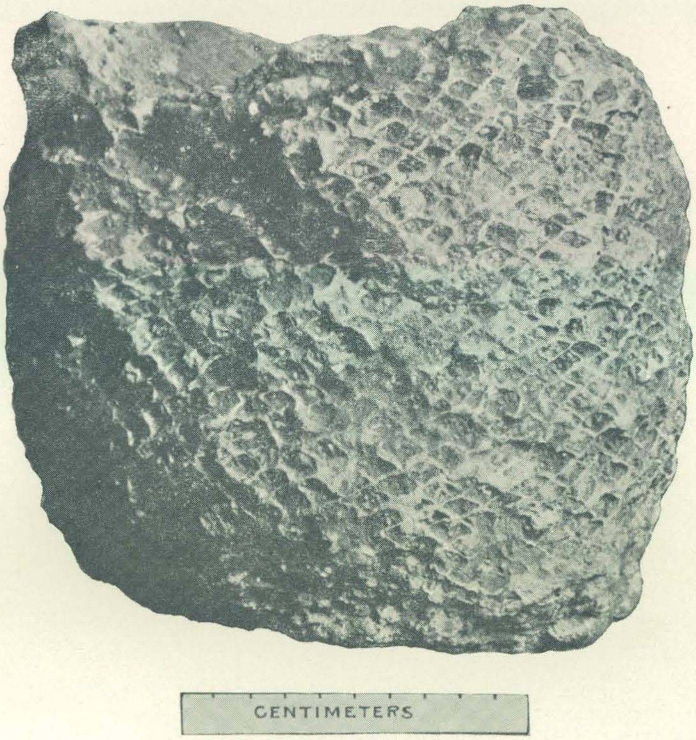
PLATE LXXXII.



CYCADEOIDEA PULCHERRIMA.

PLATE LXXXIII.

PLATE LXXXIII.



CYCADEOIDEA CICATRICULA.

PLATE LXXXIV.

PLATE LXXXIV.

Page.

CYCADEOIDEA CICATRICULA n. sp 609

Trunk No. 118 of the Yale collection.

FIG. 1. View of the base.

FIG. 2. View of the apex.

Scale, 10 cm.

2

1

CYCADEOIDEA CICATRICULA.

PLATE LXXXV.

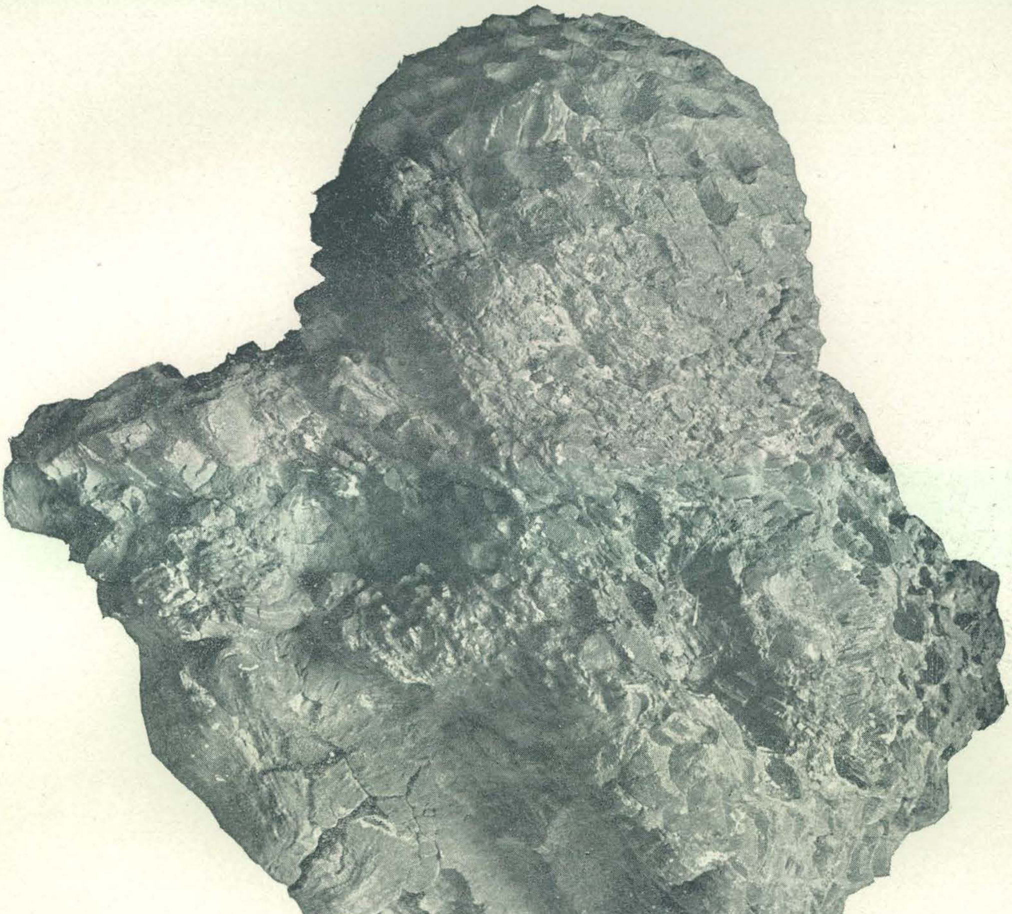
PLATE LXXXV.

No. 82 of the Yale collection.
Scale, 10 cm.

CYCADEOIDEA TURRITA.

PLATE LXXXVI.

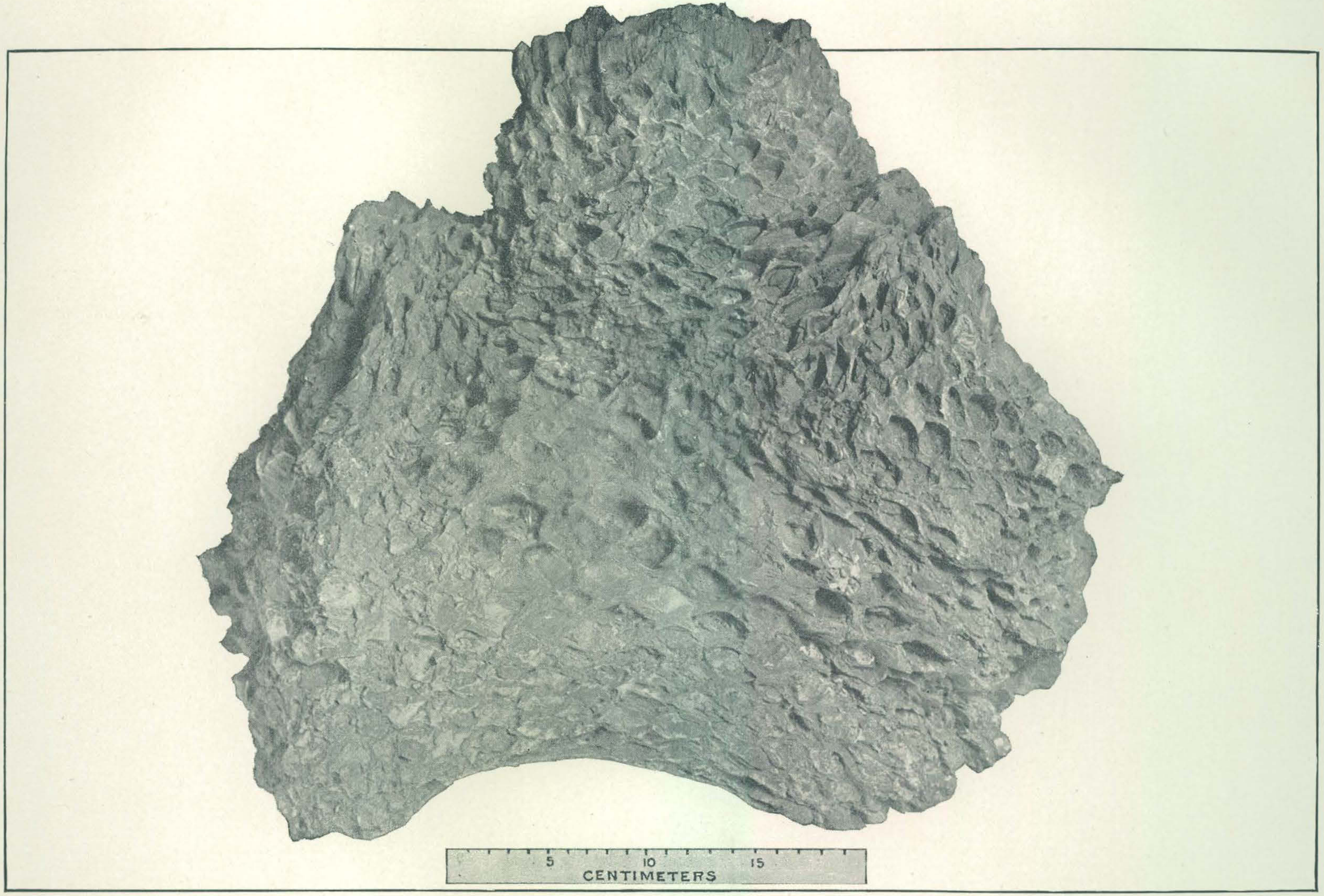
PLATE LXXXVI.



CYCADEOIDEA TURRITA.

PLATE LXXXVII.

PLATE LXXXVII.



CYCADEOIDEA TURRITA.

PLATE LXXXVIII.

PLATE LXXXVIII.

CYCADEOIDEA TURRITA.

PLATE LXXXIX.

PLATE LXXXIX.

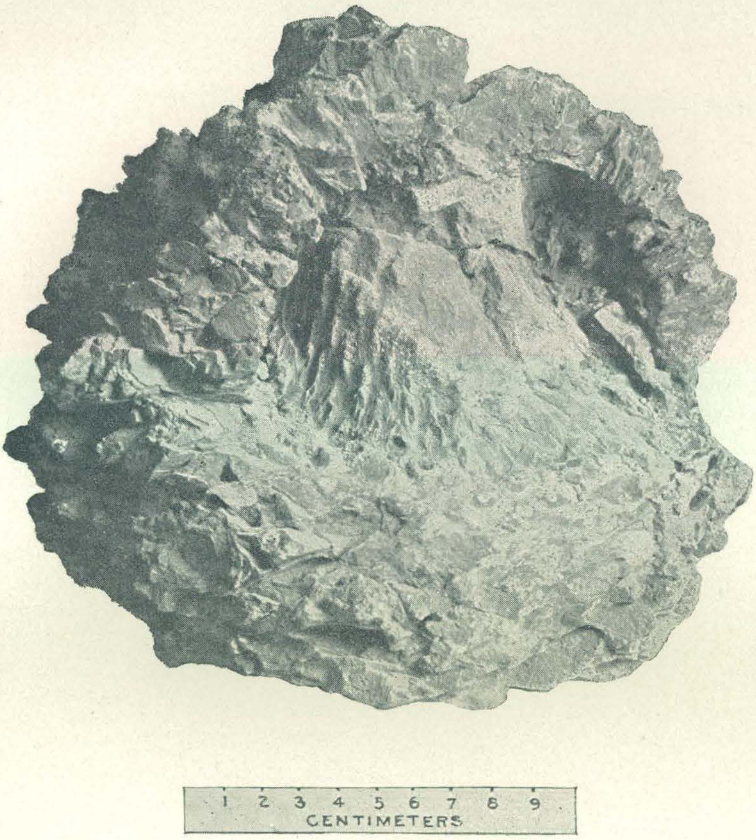
CYCADEOIDEA TURRITA.

PLATE XC.

PLATE XC.

View of the fractured side of fragment No. 15 of the Yale collection, showing internal structure.

Scale, 10 cm.



CYCADEOIDEA TURRITA.

PLATE XCI.

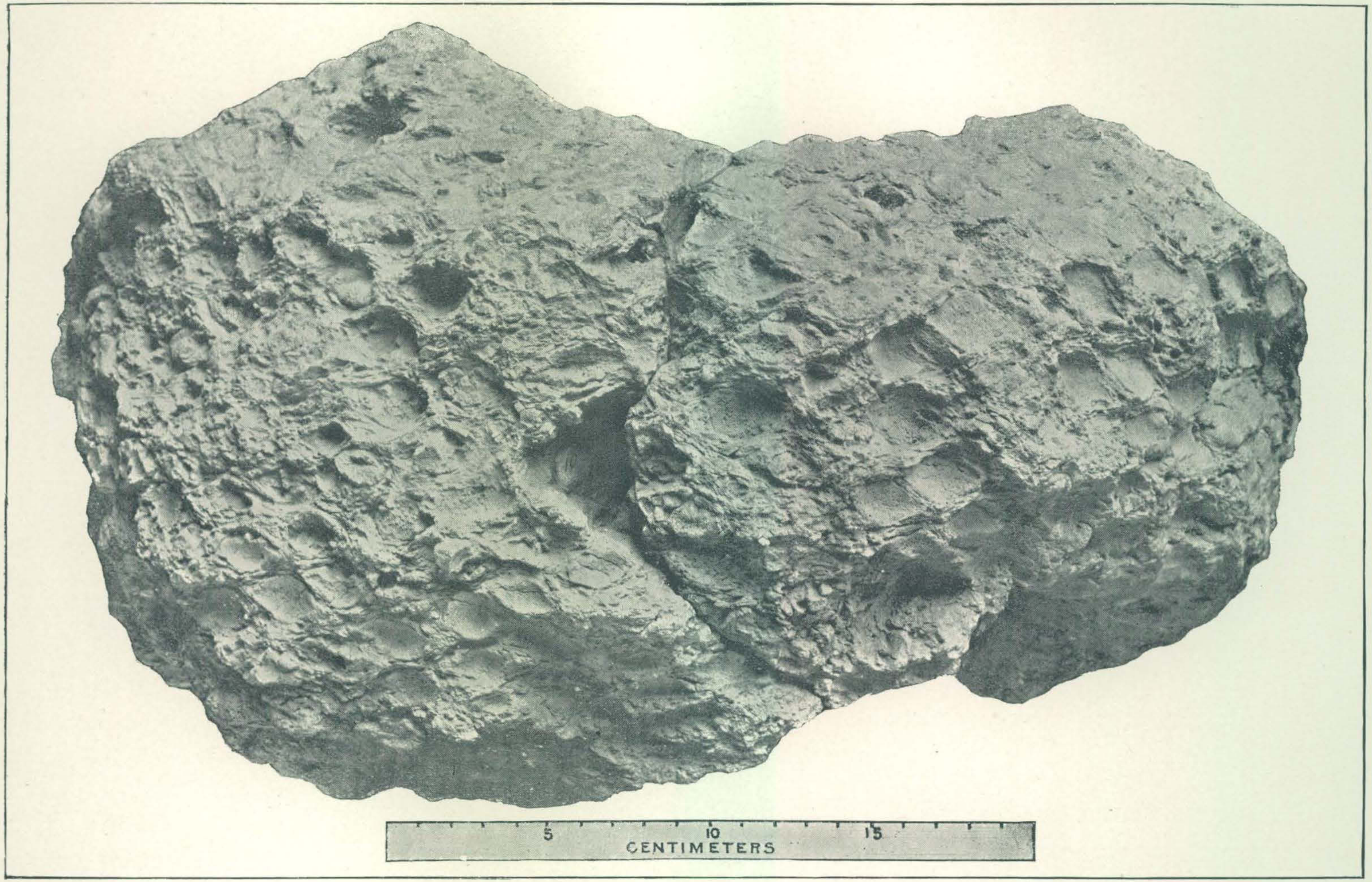
PLATE XCI.

Page

CYCADEOIDEA MCBRIDEI n. sp. 612

Side view of the nearly perfect trunk, consisting of fragments Nos. 10 and 14 of the U. S. National Museum collection.

Scale, 20 cm.



CYCADEOIDEA McBRIDEI.

PLATE XCII.

PLATE XCII.

CYCADEOIDEA McBRIDEI.

PLATE XCIII.

PLATE XCIII.

Page.

Cycadeoidea McBridei n. sp. 612

View of the exposed, inner wall of the libro-cambium layer of fragment No. 16 of the U. S. National Museum collection, showing scars of the vascular bundles.

Natural size.

CYCADEOIDEA McBRIDEI.

PLATE XCIV.

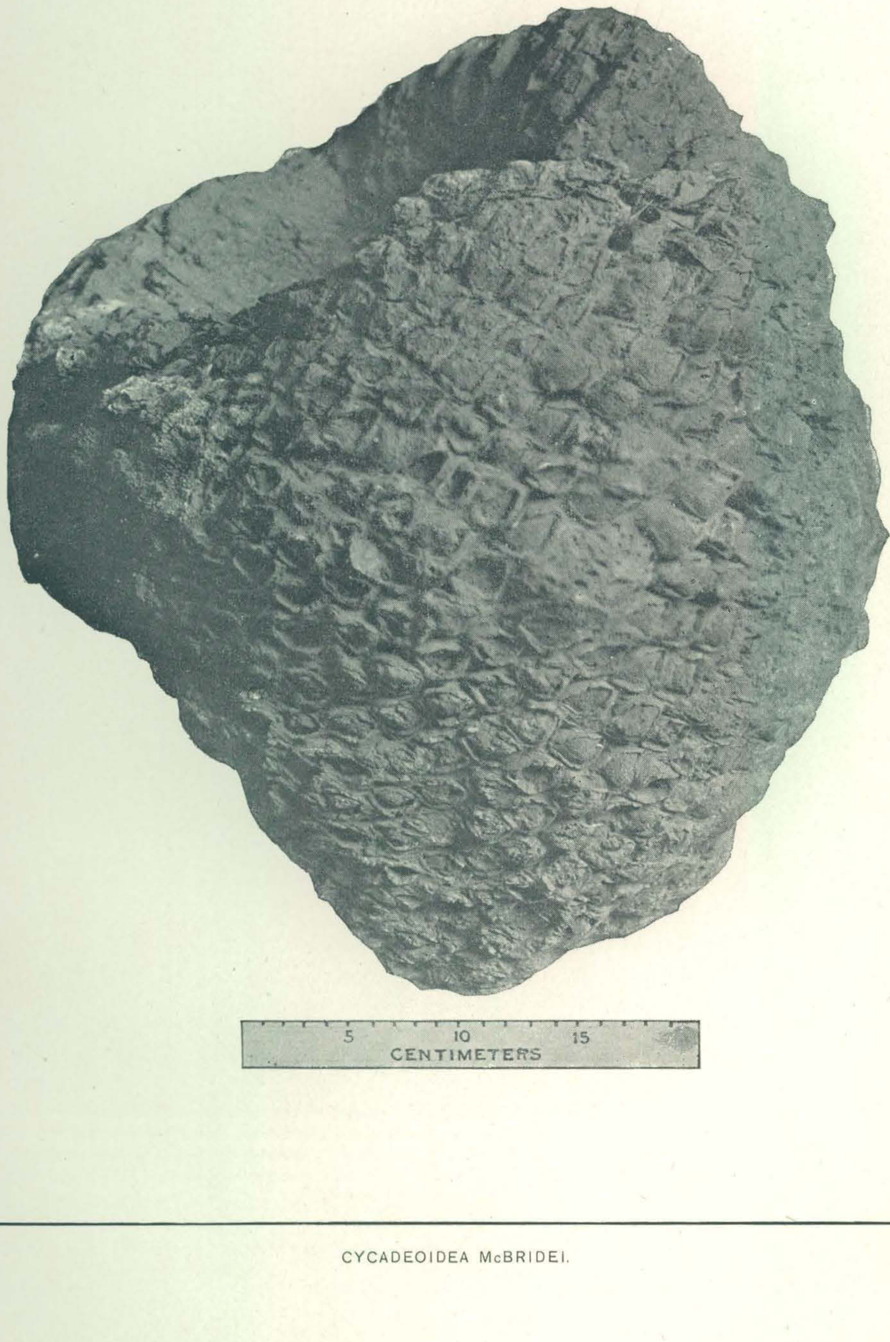
PLATE XCIV.

Page.

CYCADEOIDEA MCBRIDEI n. sp 612

Side view of trunk No. 23 of the Yale collection.

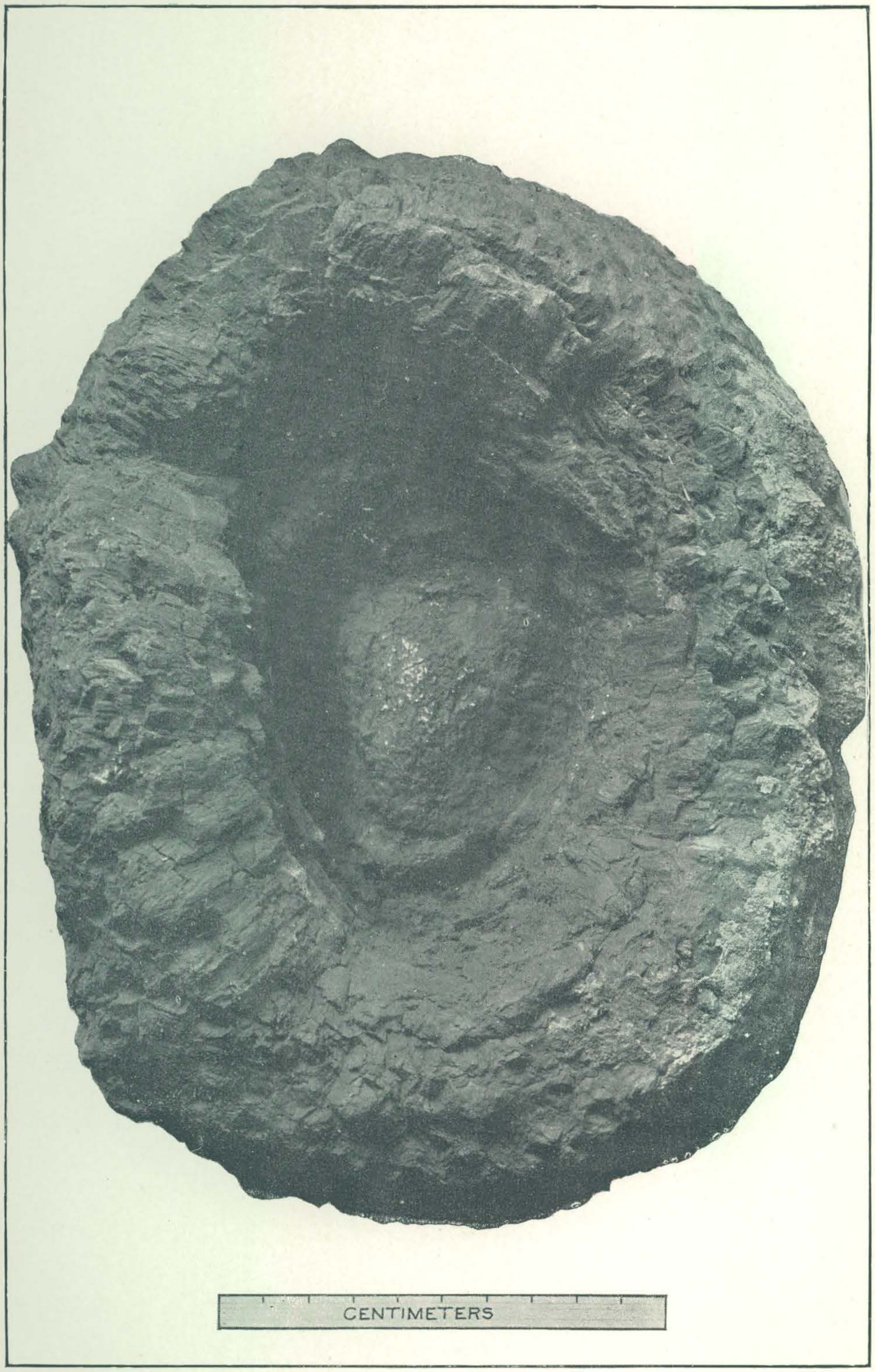
Scale, 20 cm.



CYCADEOIDEA McBRIDEI.

PLATE XCV.

PLATE XCV.



CYCADEOIDEA McBRIDEI.

PLATE XCVI.

PLATE XCVI.

CYCADEOIDEA McBRIDEI.

PLATE XCVII.

PLATE XCVII.

View of the inner surface of the armor as exposed in the fragment No. 27 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA McBRIDEI.

PLATE XCVIII.

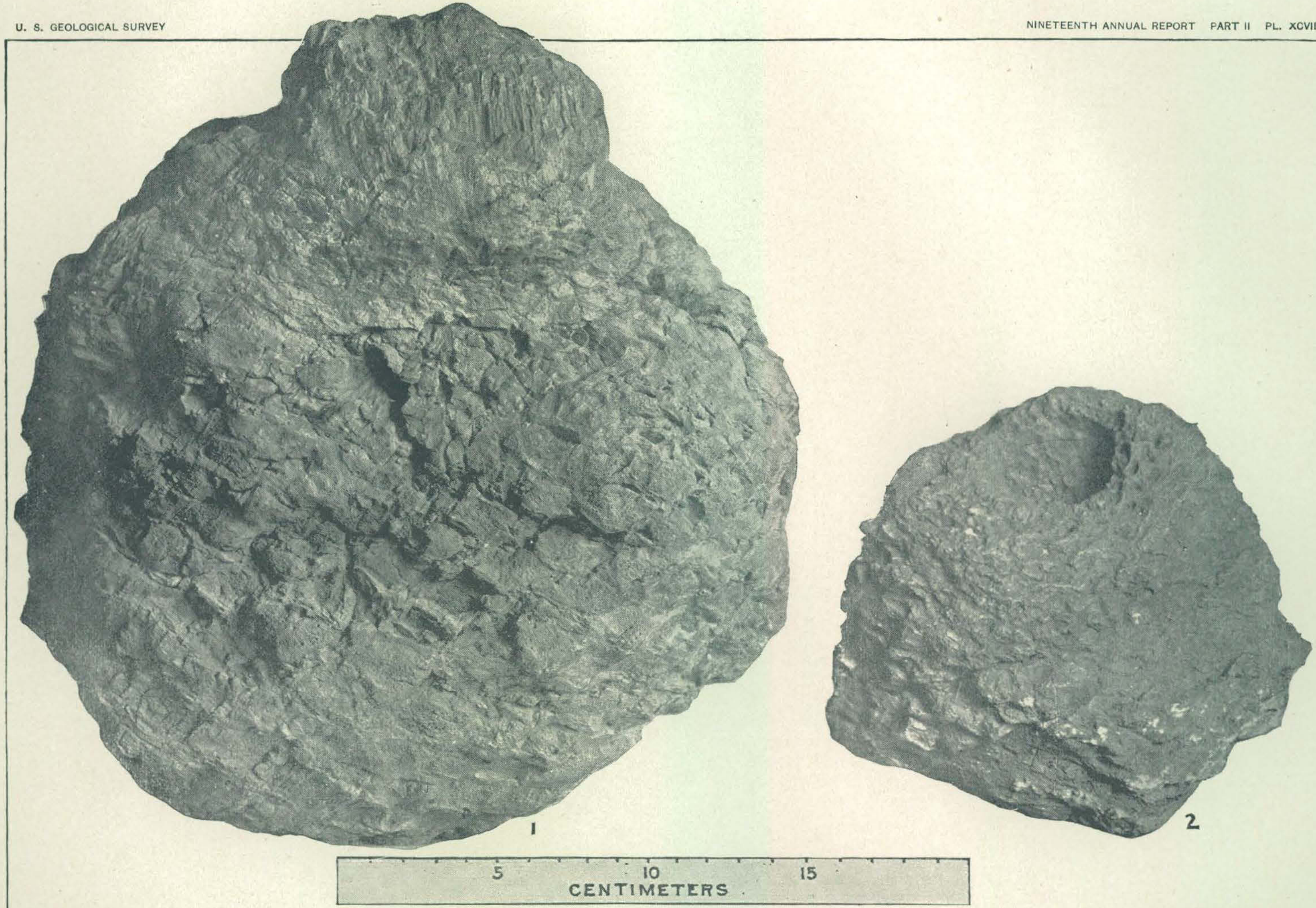
PLATE XCVIII.

Page.

FIG. 1. Trunk No. 29 of the Yale collection, supposed to represent a dwarf form of this species.

FIG. 2. Trunk No. 53 of the Yale collection, supposed to represent a young form of this species.

Scale, 20 cm.



CYCADEOIDEA McBRIDEI.

PLATE XCIX.

PLATE XCIX.

View of the external surface of No. 110 of the Yale collection.
Scale, 10 cm.

CYCADEOIDEA McBRIDEI.

PLATE C.

PLATE C.

View of the exposed inner wall of the woody zone and sections of the armor and axis of No. 110 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA McBRIDEI.

PLATE CI.

PLATE CI.

	Page.
CYCADEOIDEA MARSHIANA n. sp	616

Side view of trunk No. 11 of the Yale collection.

Scale, 20 cm.

CYCADEOIDEA MARSHIANA.

PLATE CII.

PLATE CII.

806

CYCADEOIDEA MARSHIANA.

PLATE CIII.

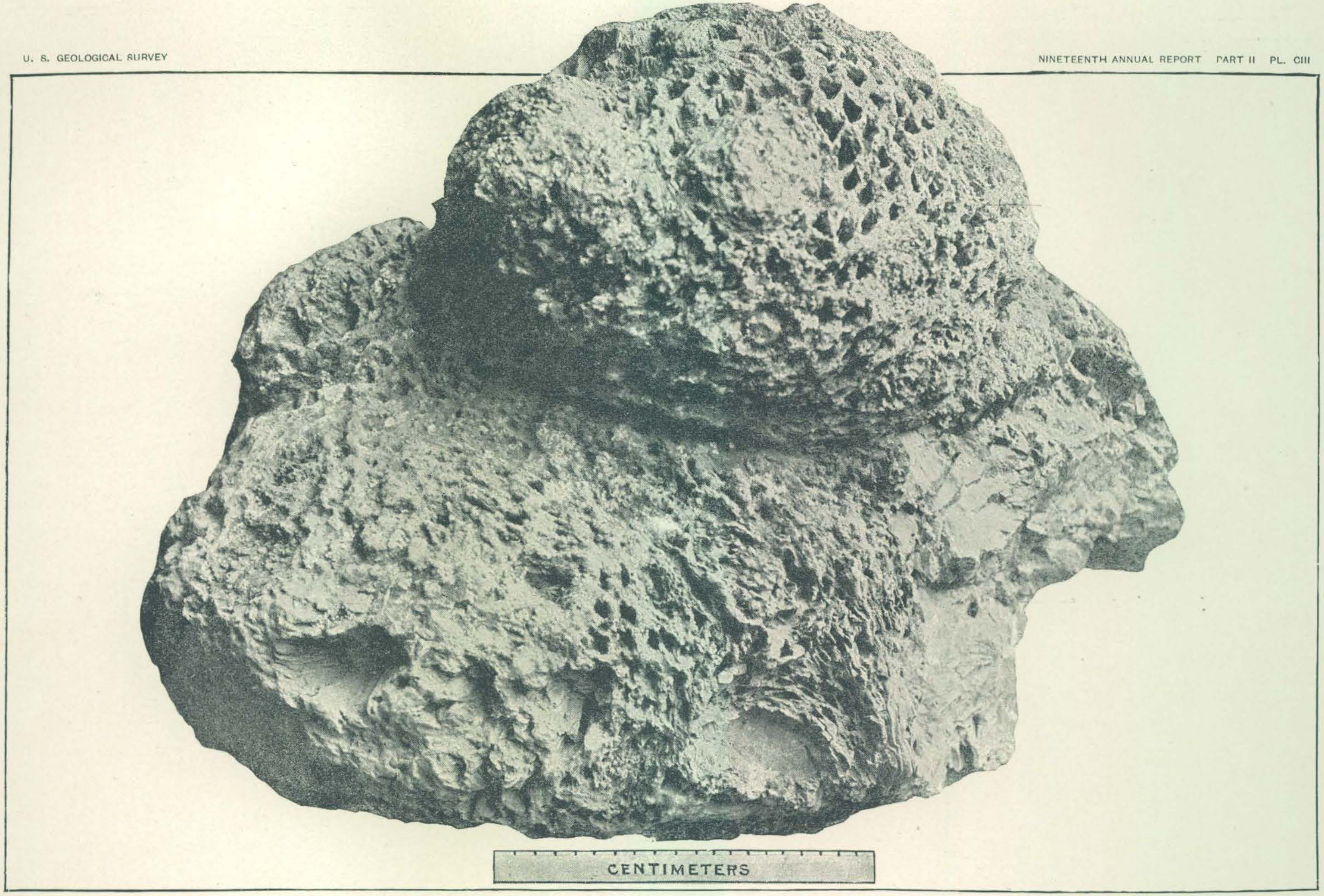
PLATE CIII.

Page.

CYCADEOIDEA MARSHIANA n. sp. 616

Front view of trunk No. 11 of the Yale collection.

Scale, 20 cm.



CYCADEOIDEA MARSHIANA.

PLATE CIV.

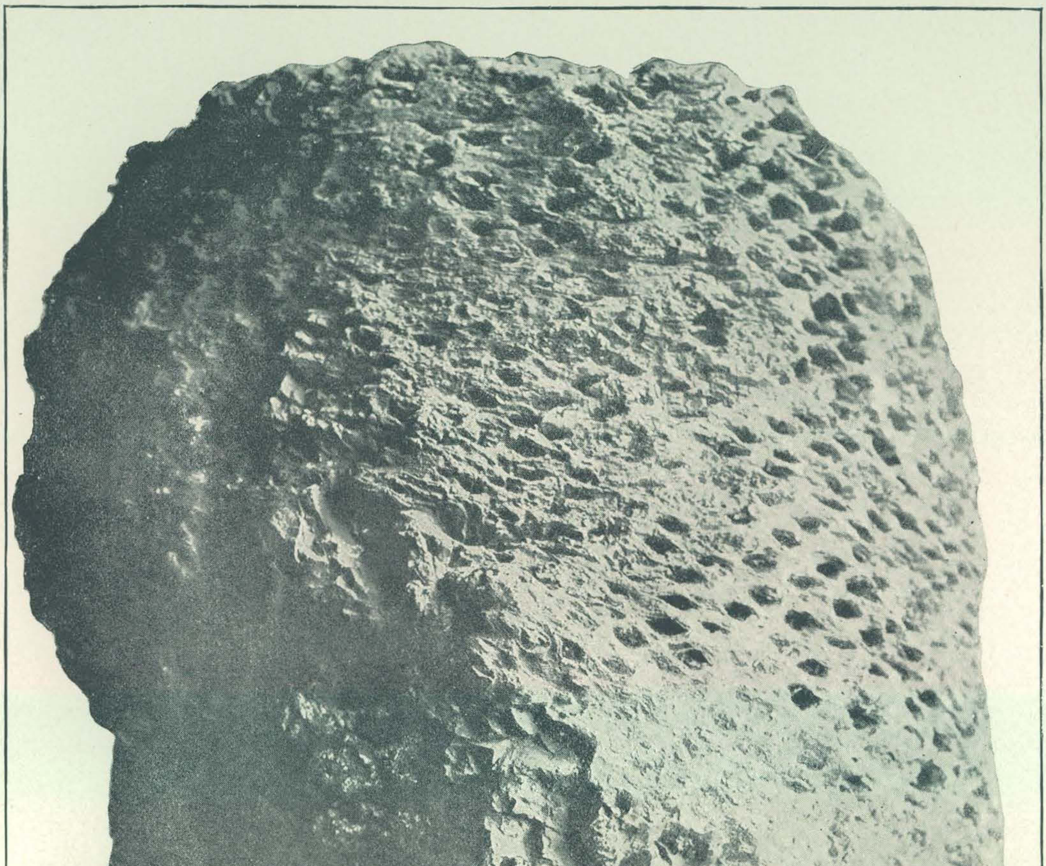
PLATE CIV.

View of the branch No. 47 of the Yale collection.
Scale, 20 cm.

CYCADEOIDEA MARSHIANA.

PLATE CV.

PLATE CV.



CYCADEOIDEA MARSHIANA.

PLATE CVI.

PLATE CVI.

CYCADEOIDEA FURCATA.

PLATE CVII.

PLATE CVII.

	Page.
CYCADEOIDEA FURCATA n. sp.	618

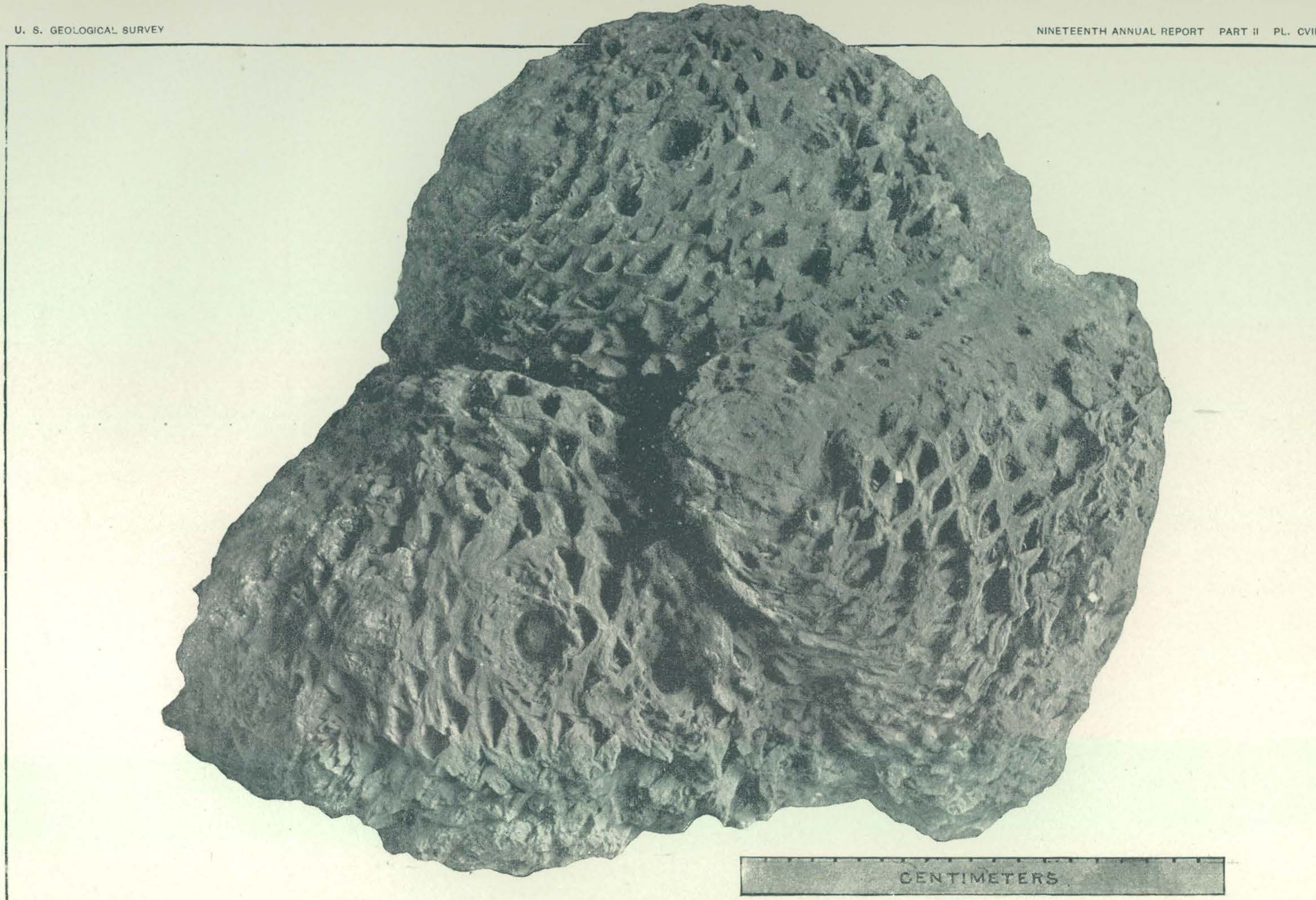
View of the flat side of trunk No. 60 of the Yale collection.

Scale, 20 cm.

CYCADEOIDEA FURCATA.

PLATE CVIII.

PLATE CVIII.



CYCADEOIDEA FURCATA.

PLATE CIX.

PLATE CIX.

CYCADEOIDEA FURCATA.

PLATE CX.

PLATE CX.

Page.

CYCADEOIDEA COLEI n. sp 619

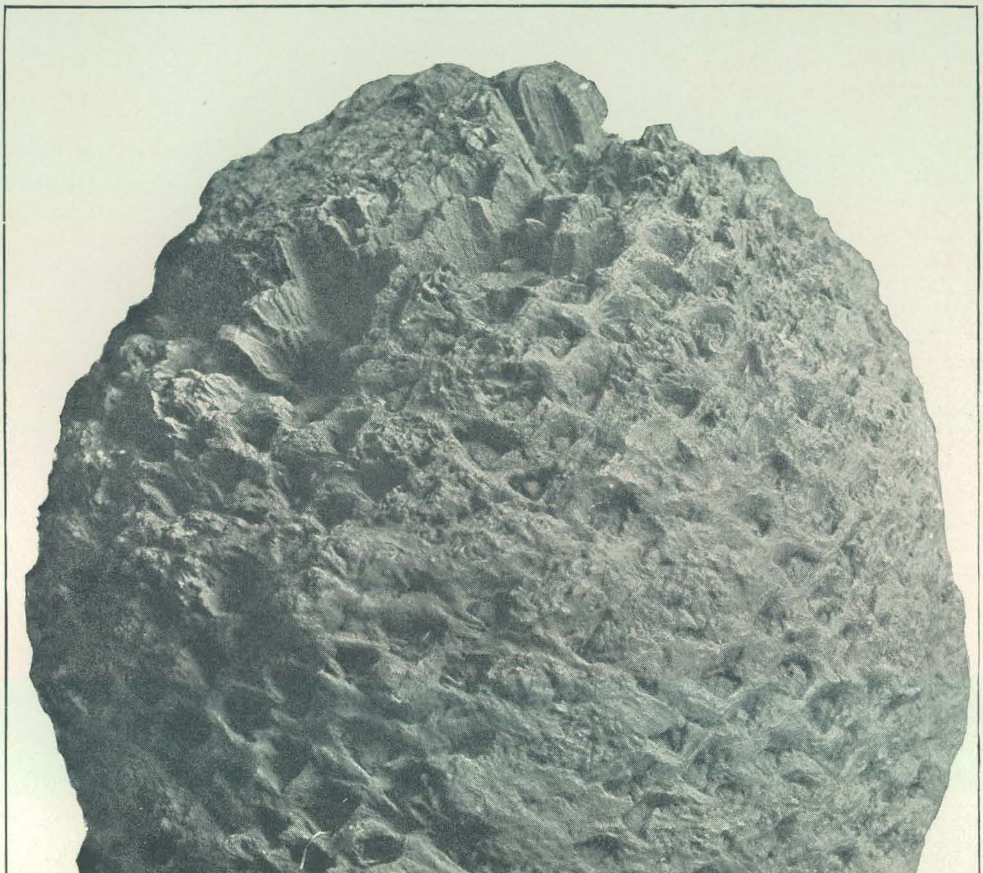
Side view of No. 2 of the U. S. National Museum collection.

Scale, 20 cm.

CYCADEOIDEA COLEI.

PLATE CXI.

PLATE CXI.



CYCADEOIDEA COLEI.

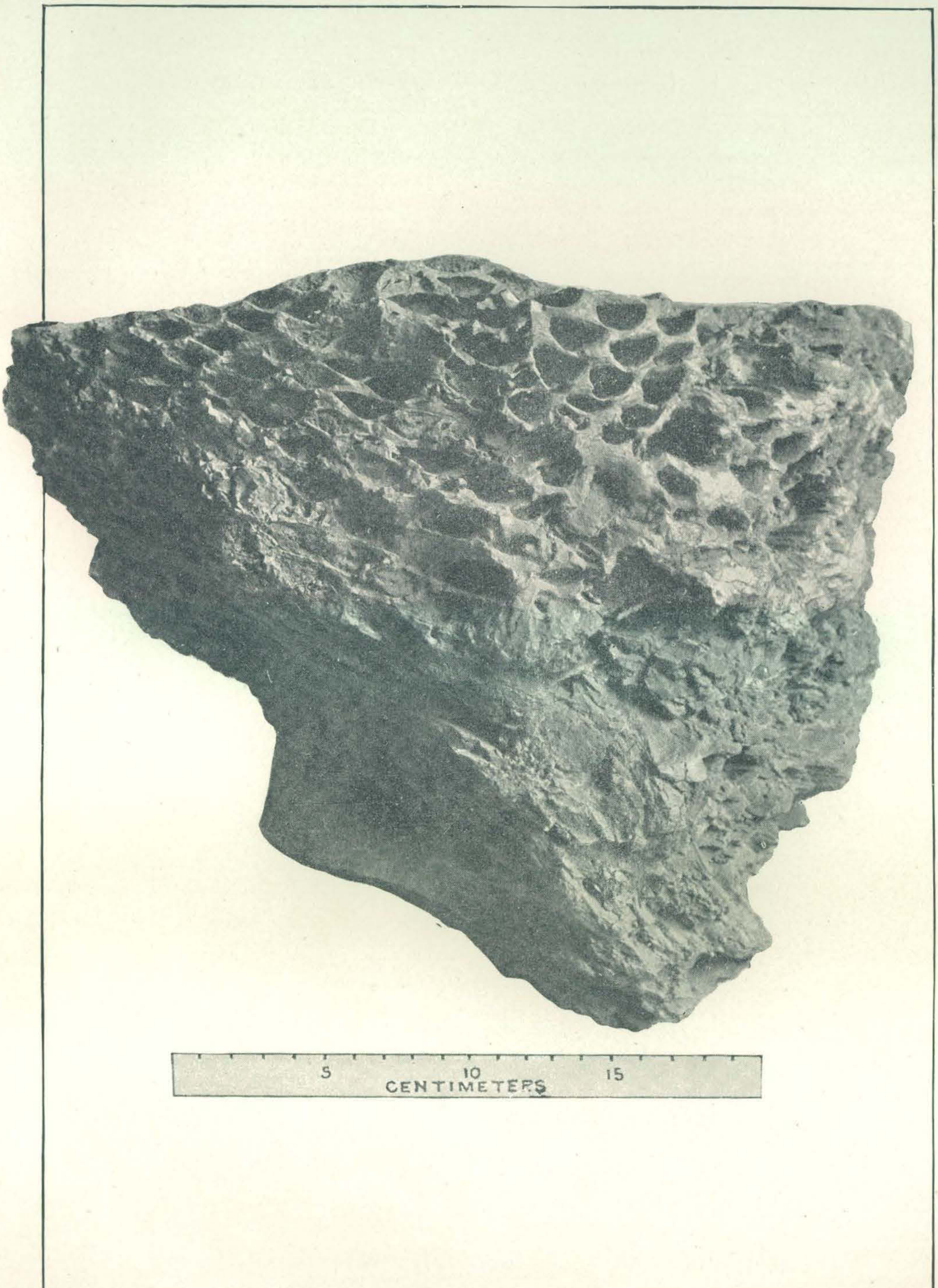
PLATE CXII.

PLATE CXII.

	Page.
Cycadeoidea Colei n. sp	619

Fragment No. 12 of the Yale collection.

Scale, 20 cm.



CYCADEOIDEA COLEI.

PLATE CXIII.

PLATE CXIII.

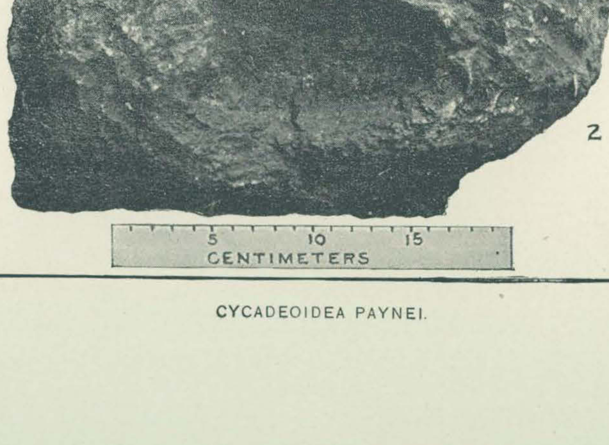
Trunk No. 4 of the U. S. National Museum collection.

FIG. 1. Side view.

FIG. 2. View of the base.

Scale, 20 cm.

1



2

CYCADEOIDEA PAYNEI.

PLATE CXIV.

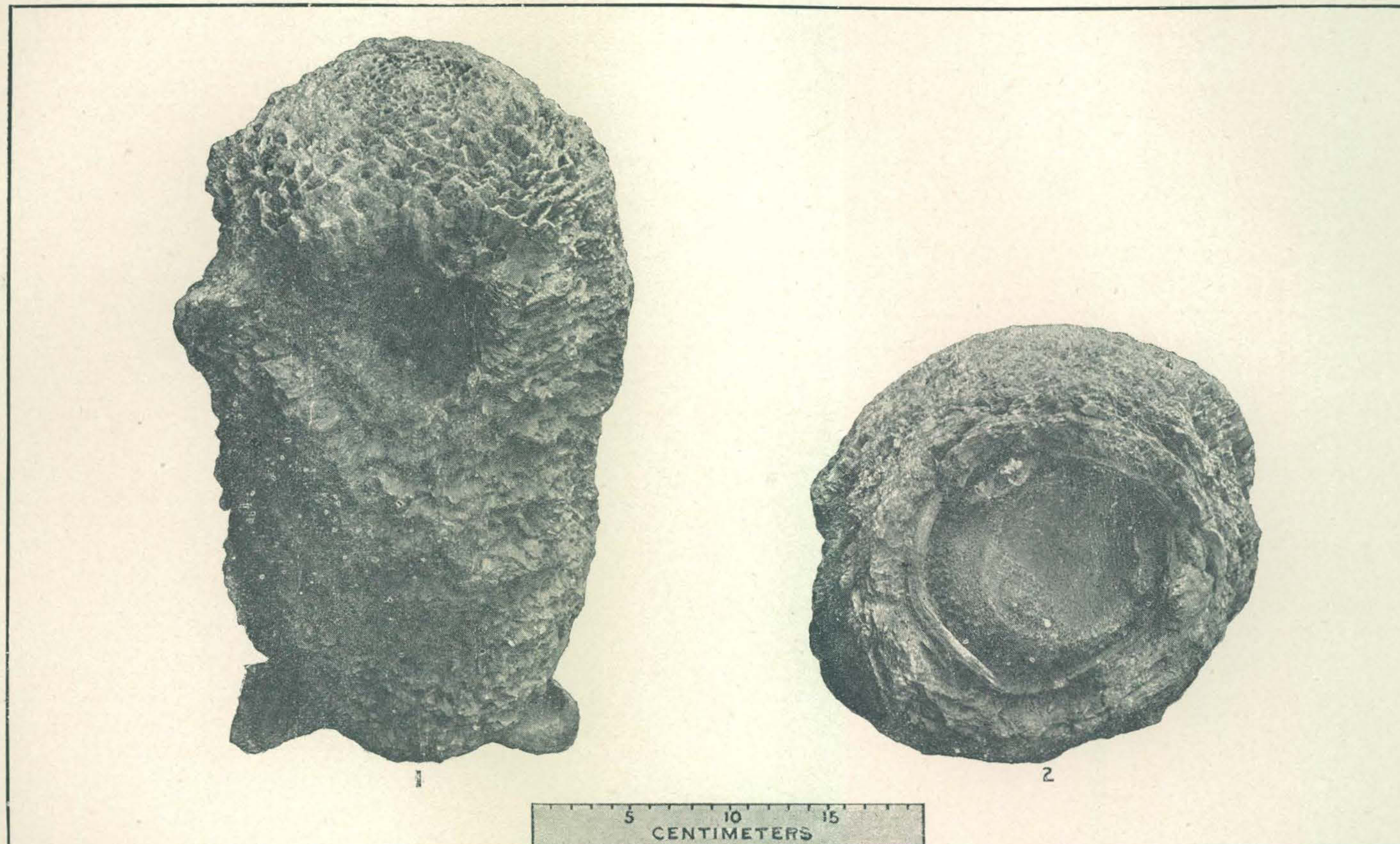
PLATE CXIV.

Trunk No. 5 of the U. S. National Museum collection.

FIG. 1. Side view, also showing the apex.

FIG. 2. View of the base.

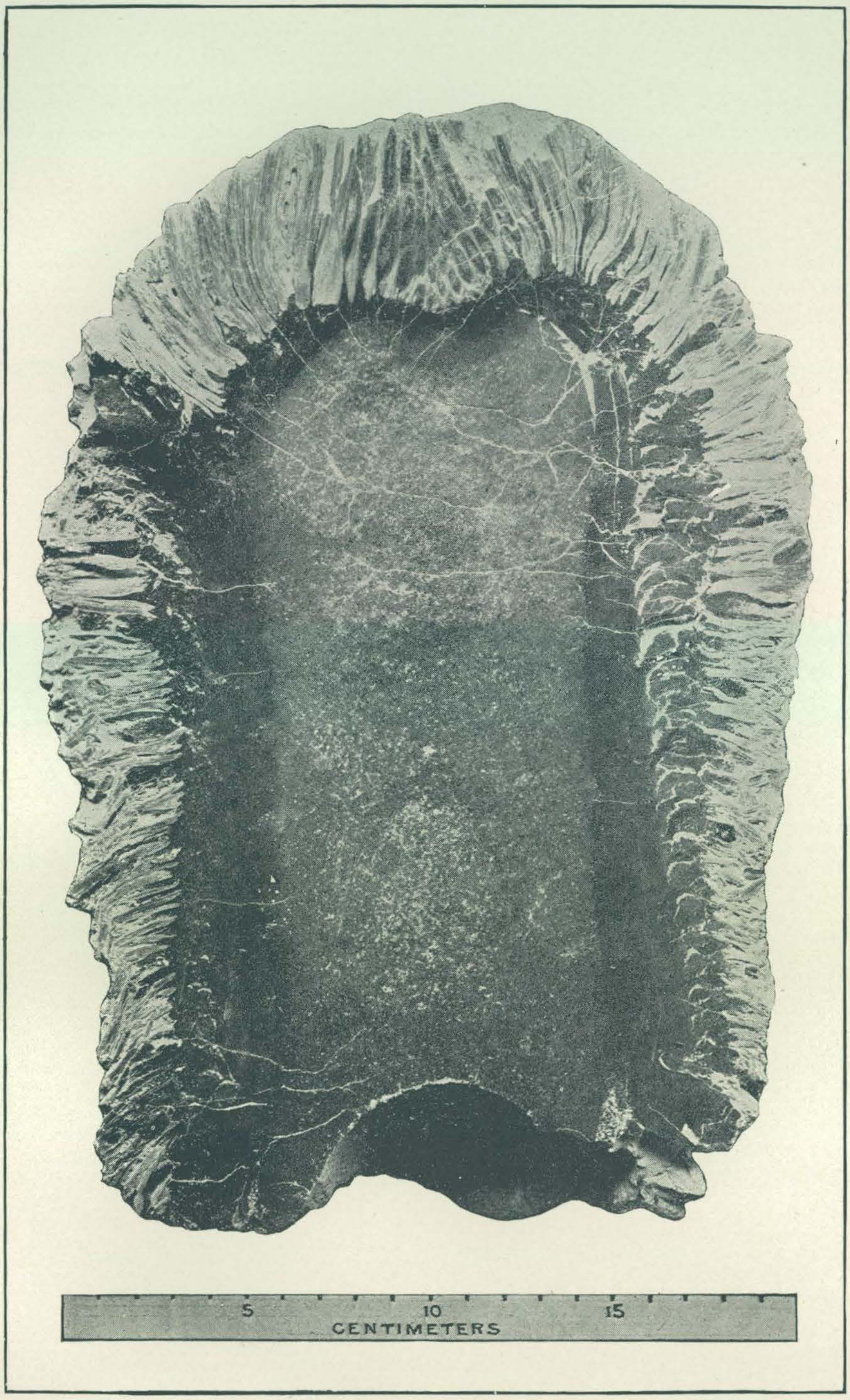
Scale, 20 cm.



CYCADEOIDEA PAYNEI.

PLATE CXV.

PLATE CXV.



CYCADEOIDEA PAYNEI.

PLATE CXVI.

PLATE CXVI.

Page.

CYCADEOIDEA WIELANDI n. sp 621

Side view of trunk No. 77 of the Yale collection.

Scale, 20 cm.

CYCADEOIDEA WIELANDI.

PLATE CXVII.

PLATE CXVII.

Page.

CYCADEOIDEA ASPERA n. sp. 624

No. 104 of the Yale collection.

FIG. 1. External surface.

FIG. 2. Inner face, showing armor and axis in longitudinal section.

Scale, 20 cm.

CYCADEOIDEA ASPERA.

PLATE CXVIII.

PLATE CXVIII.

Page.

CYCADEOIDEA INSOLITA n. sp. 625

FIG. 1. Partially lateral view of trunk No. 64 of the Yale collection.

FIG. 2. View of the base of the same specimen.

Scale, 20 cm.

CYCADEOIDEA INSOLITA.

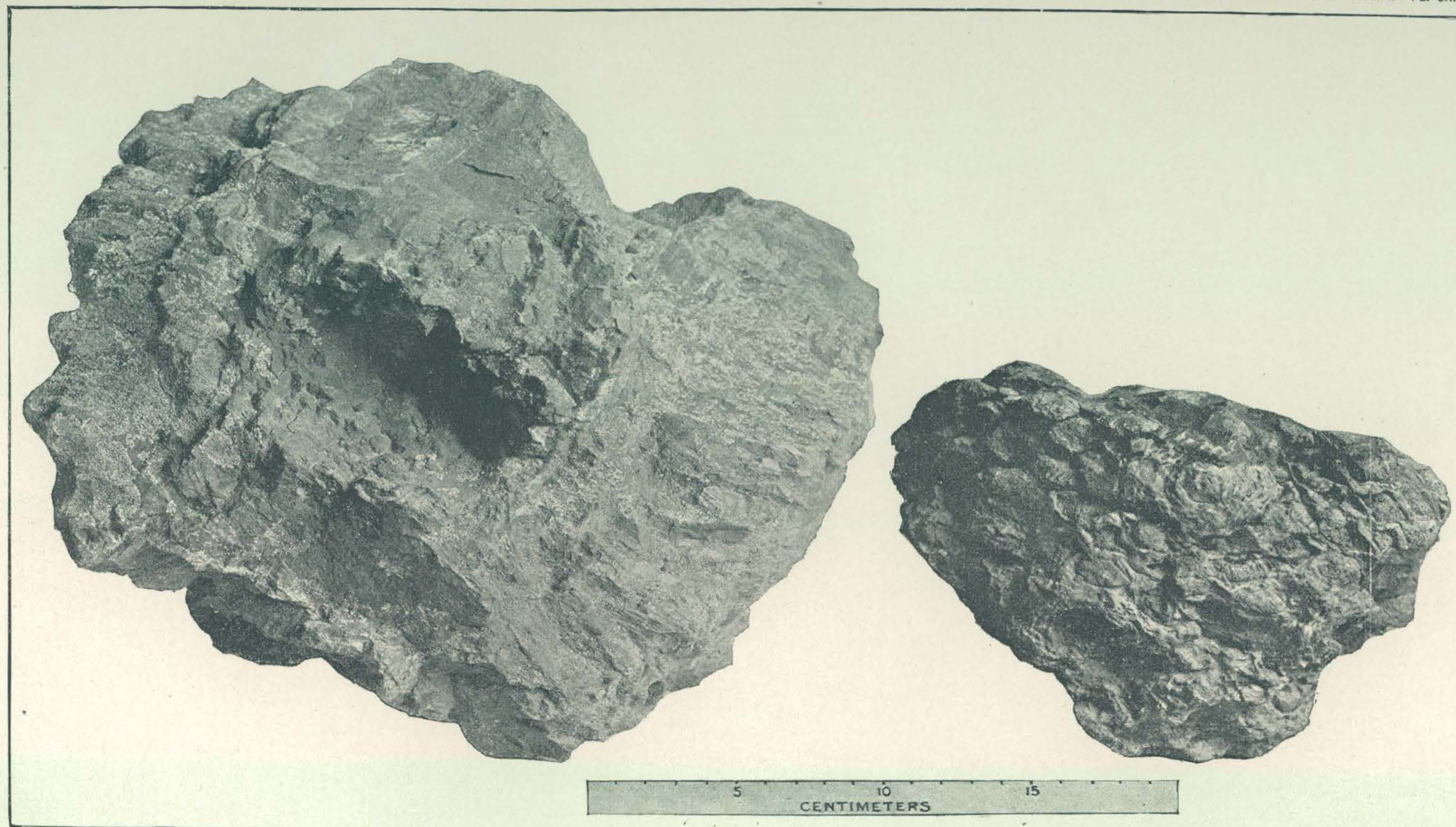
PLATE CXIX.

PLATE CXIX.

FIG. 1. View of the interior of trunk No. 64 of the Yale collection.

FIG. 2. View of the external surface of fragment No. 50 of the Yale collection.

Scale 20 cm.



CYCADEOIDEA INSOLITA.

PLATE CXX.

PLATE CXX.

Enlarged view of a polished section through the armor and woody zone of fragment No. 11 of the U. S. National Museum collection, showing internal structure, including one of the fruits cut longitudinally.

CYCADEOIDEA OCCIDENTALIS.

PLATE CXXI.

PLATE CXXI.

Page.

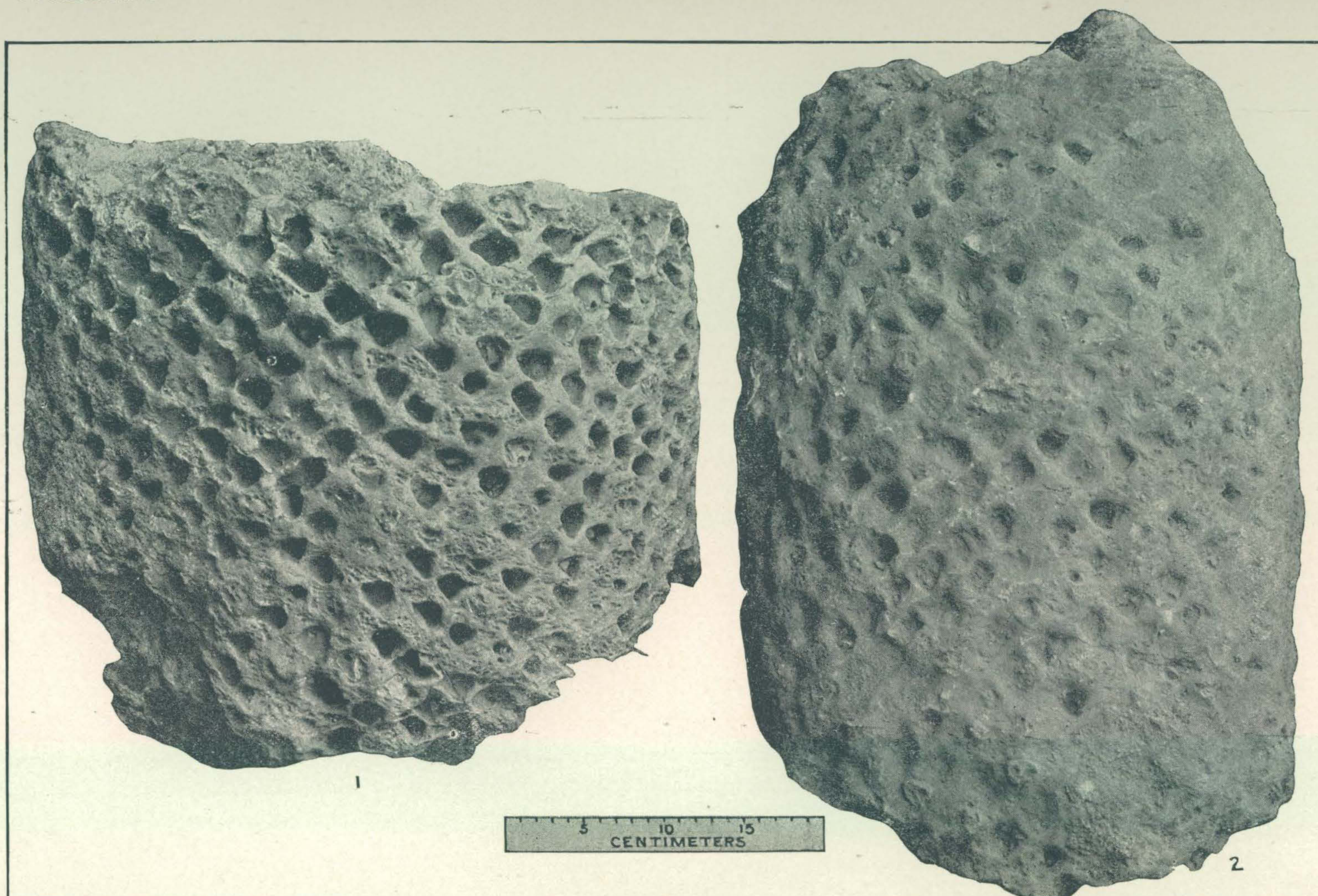
CYCADEOIDEA JENNEYANA Ward 627

Specimens belonging to the State School of Mines of South Dakota.

FIG. 1. Longest side of specimen No. 1, representing the lower portion.

FIG. 2. Longest side of specimen No. 2, representing the upper portion.

Scale, 20 cm.



CYCADEOIDEA JENNEYANA.

PLATE CXXII.

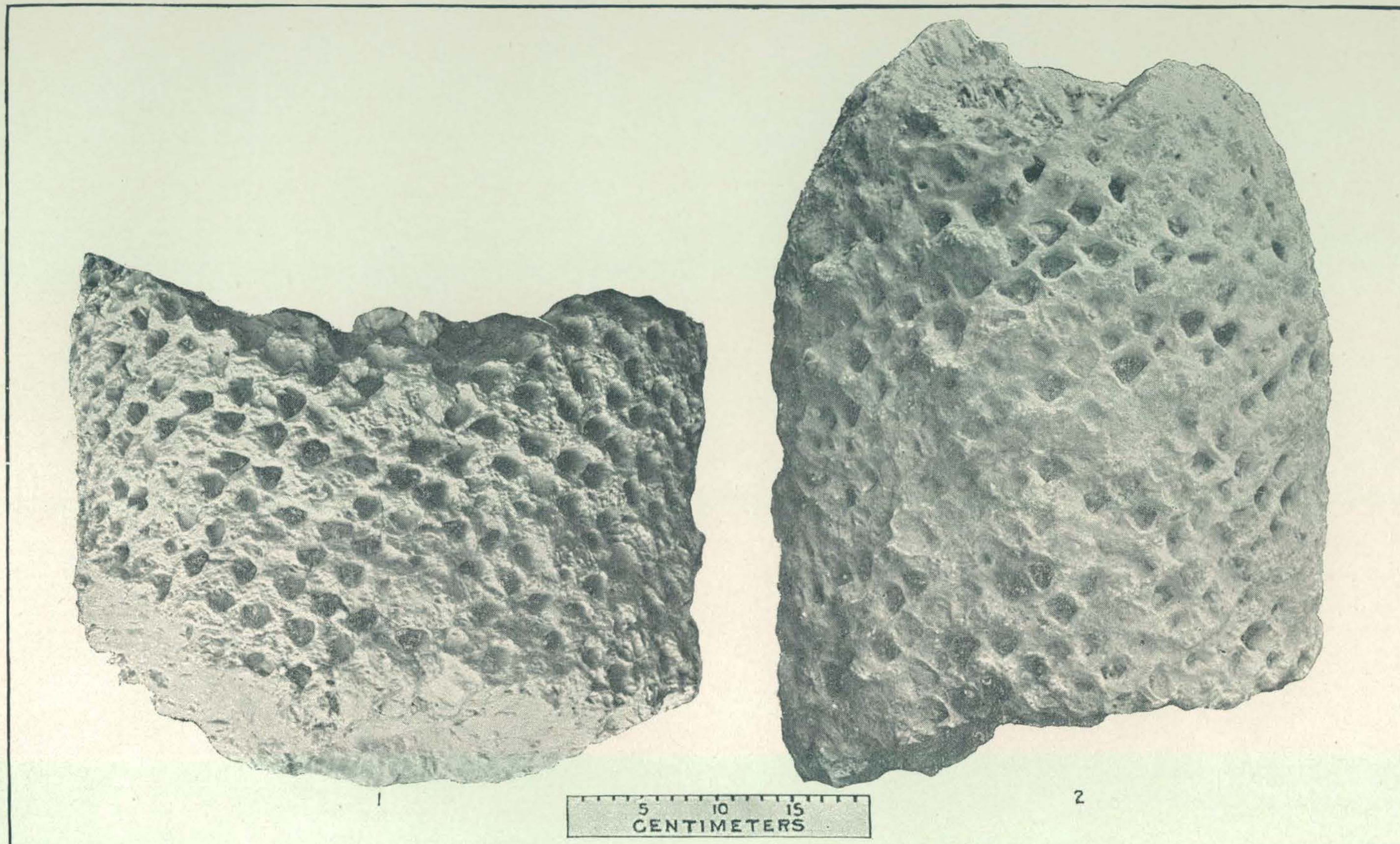
PLATE CXXII.

Specimens belonging to the State School of Mines of South Dakota.

FIG. 1. Shortest side of specimen No. 1, representing the lower portion.

FIG. 2. Shortest side of specimen No. 2, representing the upper portion.

Scale, 20 cm.



CYCADEOIDEA JENNEYANA.

PLATE CXXIII.

PLATE CXXIII.

Specimens belonging to the State School of Mines of South Dakota.

FIG. 1. View of the base of specimen No. 1, representing the true base of the trunk.

FIG. 2. View of the apex of specimen No. 2, showing the "crow's nest."

Scale, 20 cm.

CYCADEOIDEA JENNEYANA.

PLATE CXXIV.

PLATE CXXIV.

Page.

CYCADEOIDEA JENNEYANA Ward 627

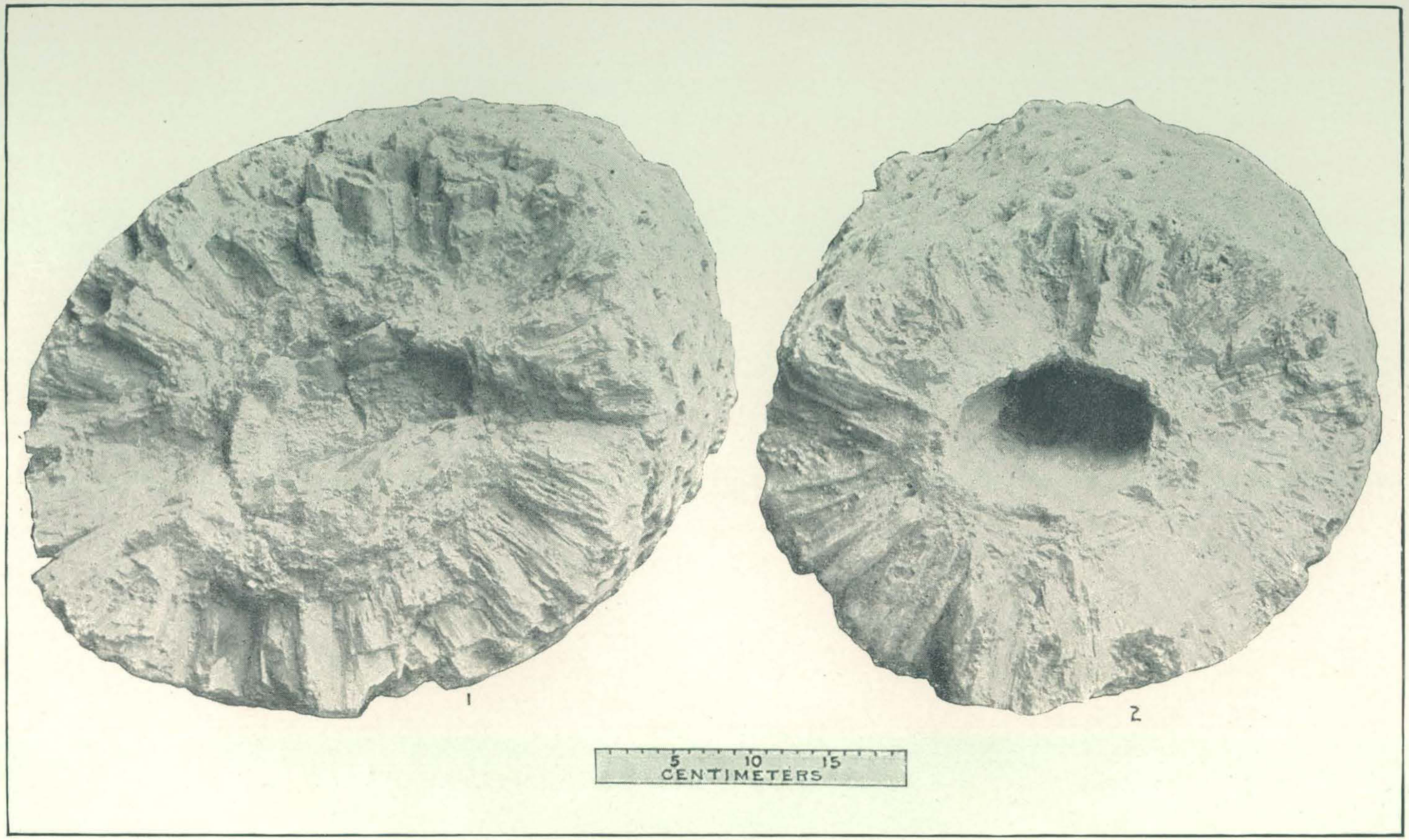
Specimens belonging to the State School of Mines of South Dakota.

FIG. 1. View of the upper end of specimen No. 1, representing the lower portion.

FIG. 2. View of the lower end of specimen No. 2, representing the upper portion.

(Between these a segment of unknown thickness is wanting.)

Scale, 20 cm.



CYCADEOIDEA JENNEYANA.

PLATE CXXV.

PLATE CXXV.

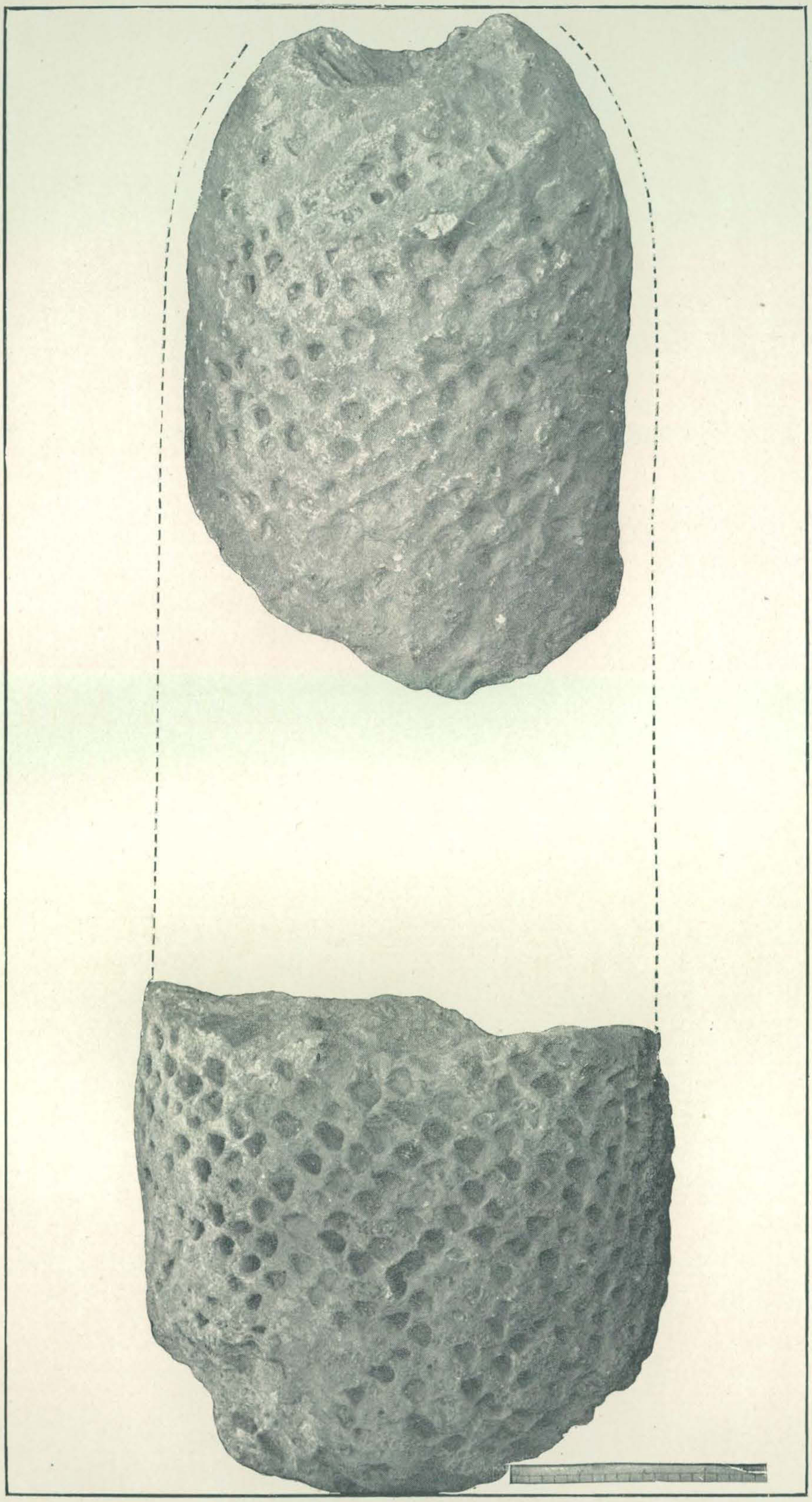
Page.

Cycadeoidea Jenneyana Ward 627

Specimens belonging to the State School of Mines of South Dakota.

Restoration of the original trunk by superposing No. 2 upon No. 1 with an interval between to supply the lost parts, the dotted lines carried around the margin of No. 2 to represent the amount of loss by erosion.

Scale, 20 cm.



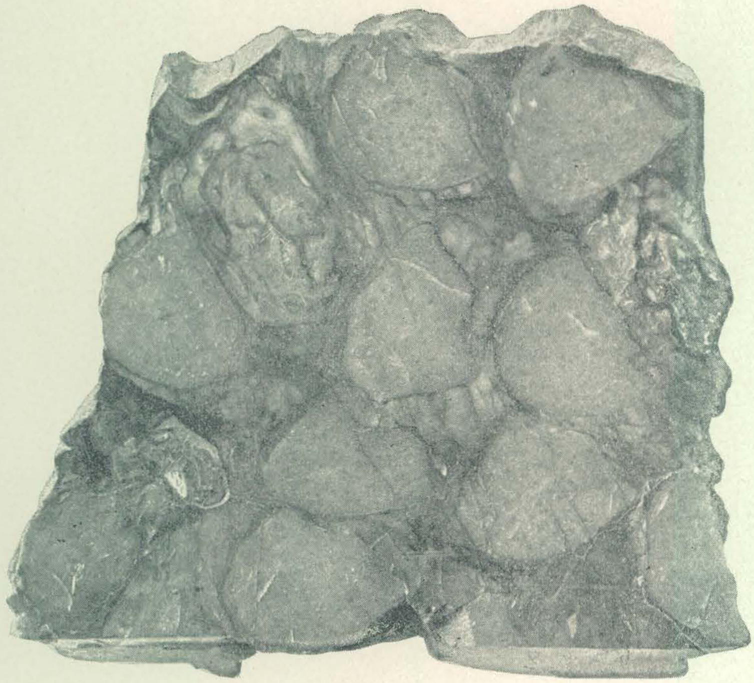
CYCADEOIDEA JENNEYANA.

PLATE CXXVI.

PLATE CXXVI.

View of the polished surface of No. 1501 of the Woman's College of Baltimore, showing leaf bases and fruits in cross section.

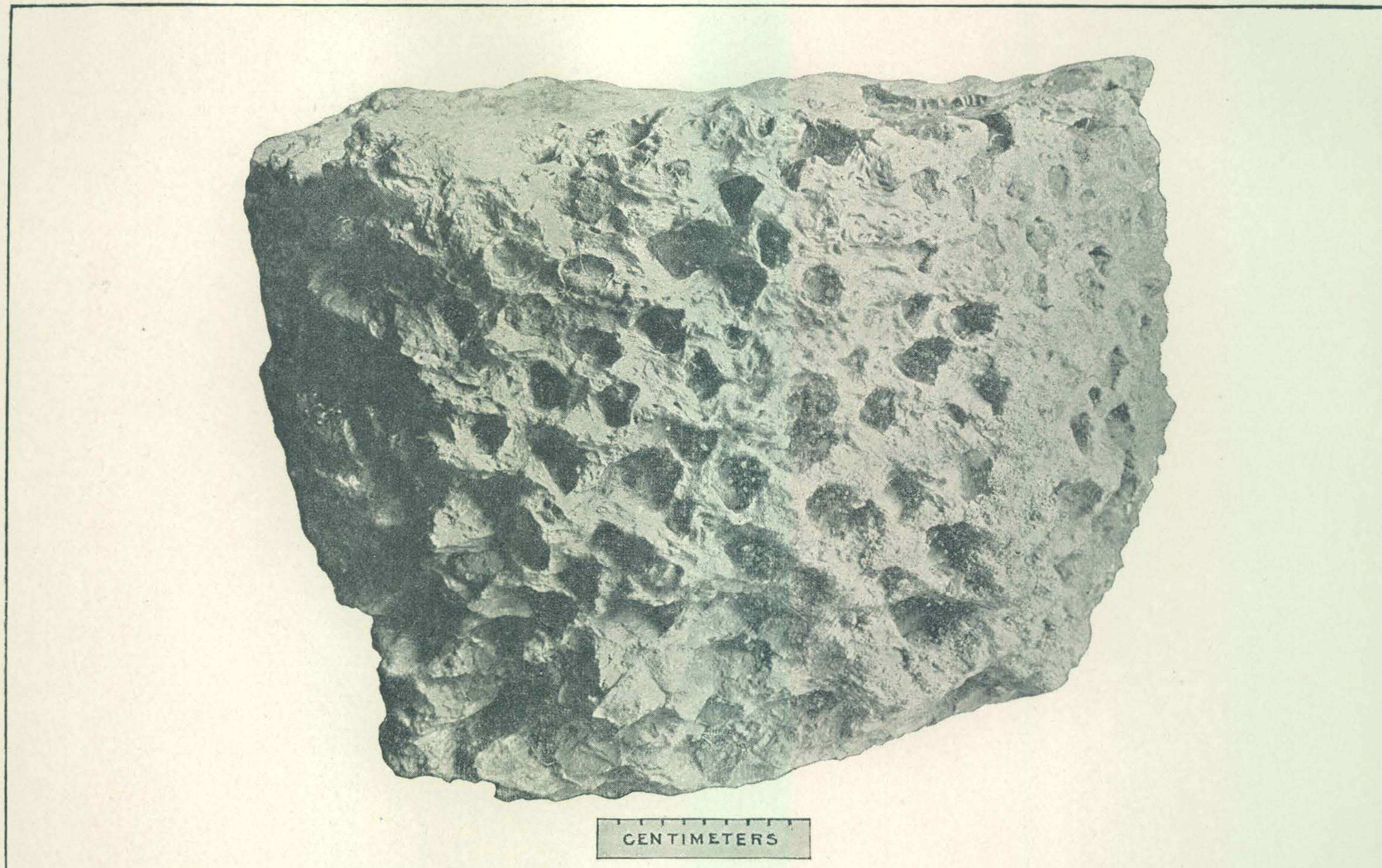
Natural size.



CYCADEOIDEA JENNEYANA.

PLATE CXXVII.

PLATE CXXVII.



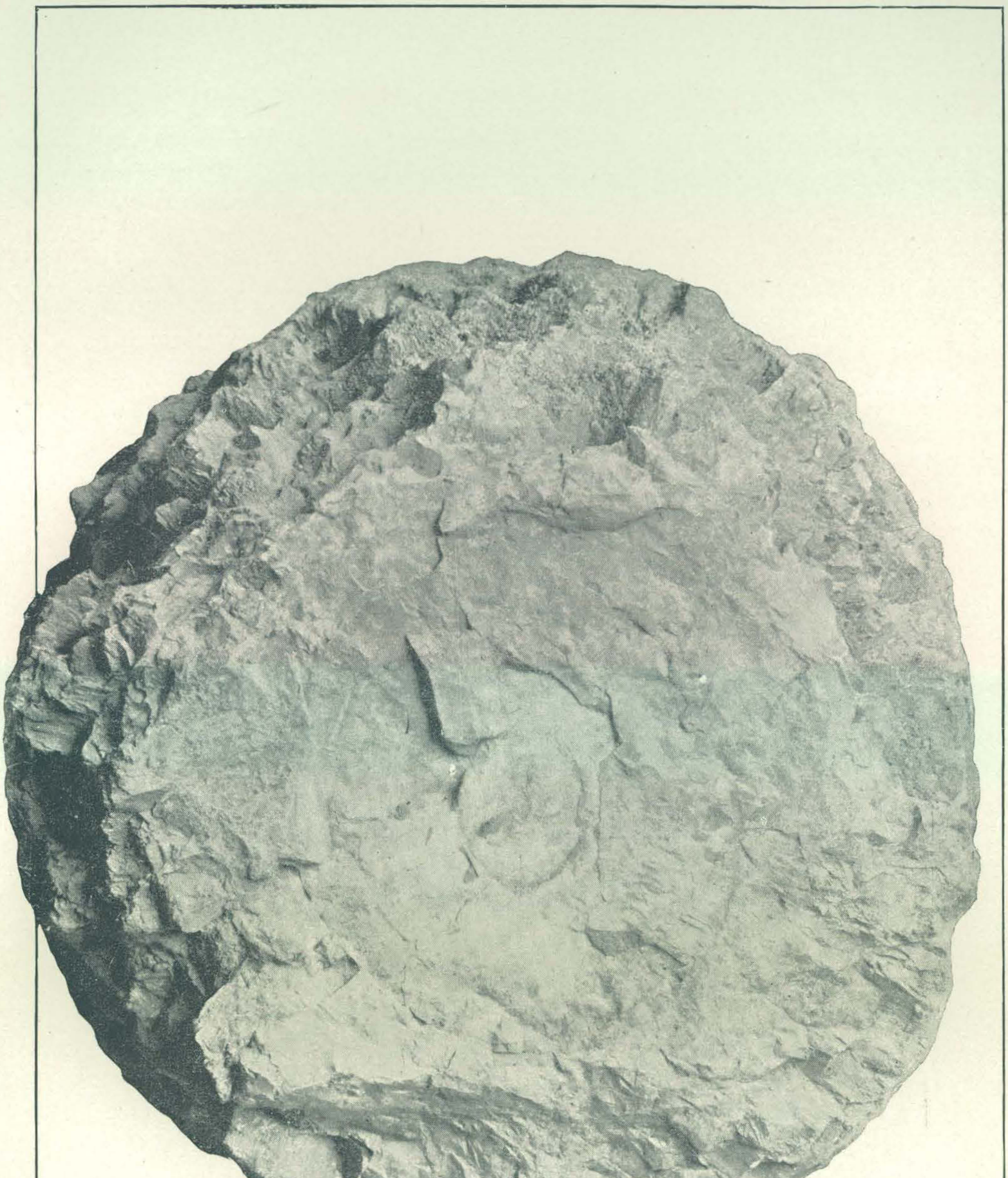
CYCADEOIDEA JENNEYANA.

PLATE CXXVIII.

PLATE CXXVIII.

View of the base of No. 102 of the Yale collection.

Scale, 10 cm.



CYCADEOIDEA JENNEYANA.

PLATE CXXIX.

PLATE CXXIX.

Page.

CYCADEOIDEA JENNEYANA Ward 627

View of the transverse fracture at top of No. 102 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA JENNEYANA.

PLATE CXXX.

PLATE CXXX.

Side view of No. 115 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA JENNEYANA.

PLATE CXXXI.

PLATE CXXXI.

Page.

CYCADEOIDEA JENNEYANA Ward? 627

View of No. 91 of the Yale collection from the side which best shows the terminal bud.

Scale, 10 cm.

CYCADEOIDEA JENNEYANA.

PLATE CXXXII.

PLATE CXXXII.

CYCADEOIDEA JENNEYANA.

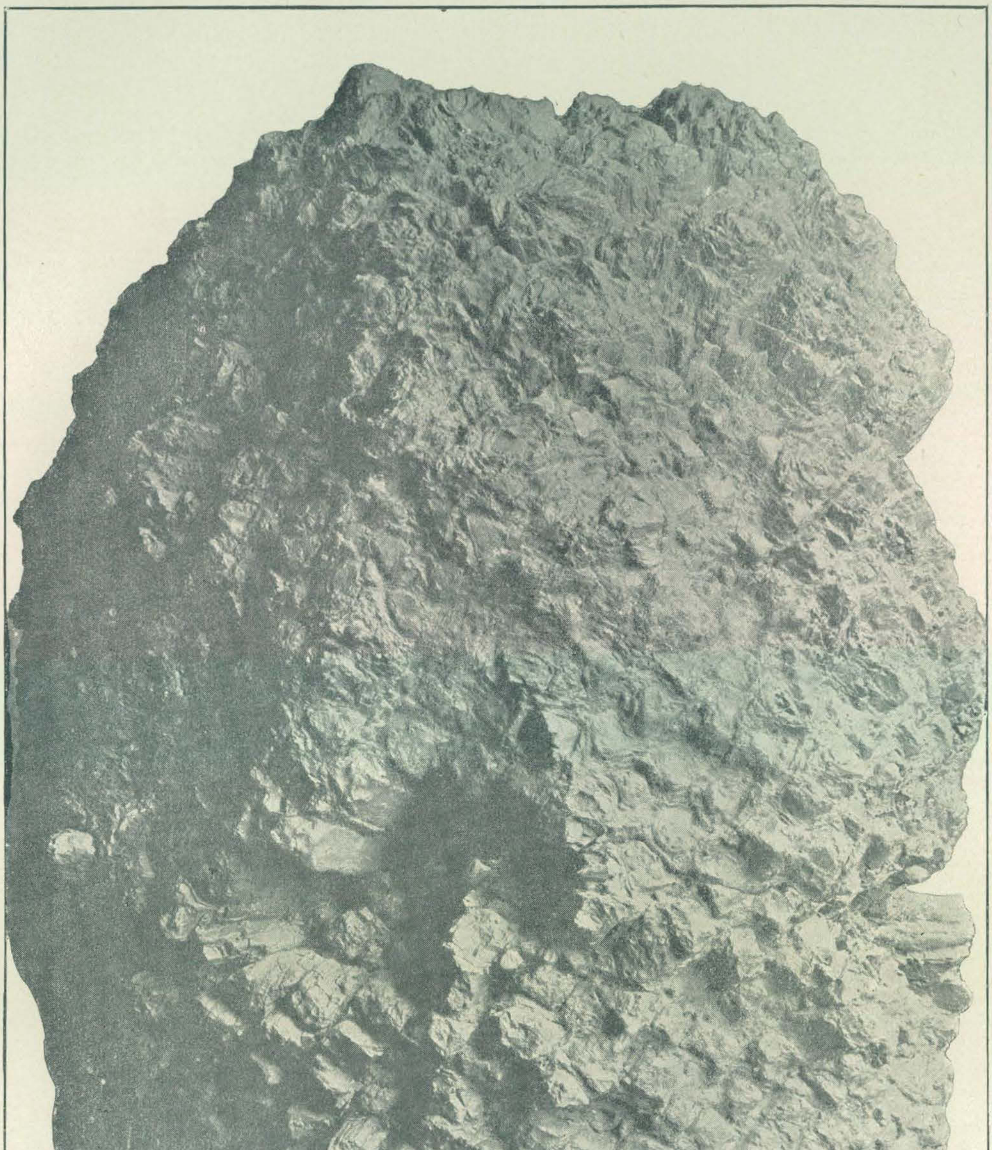
PLATE CXXXIII.

PLATE CXXXIII.

	Page.
CYCADEOIDEA INGENS n. sp	632

Side view of trunk No. 100 of the Yale collection.

Scale, 10 cm.



CYCADEOIDEA INGENS.

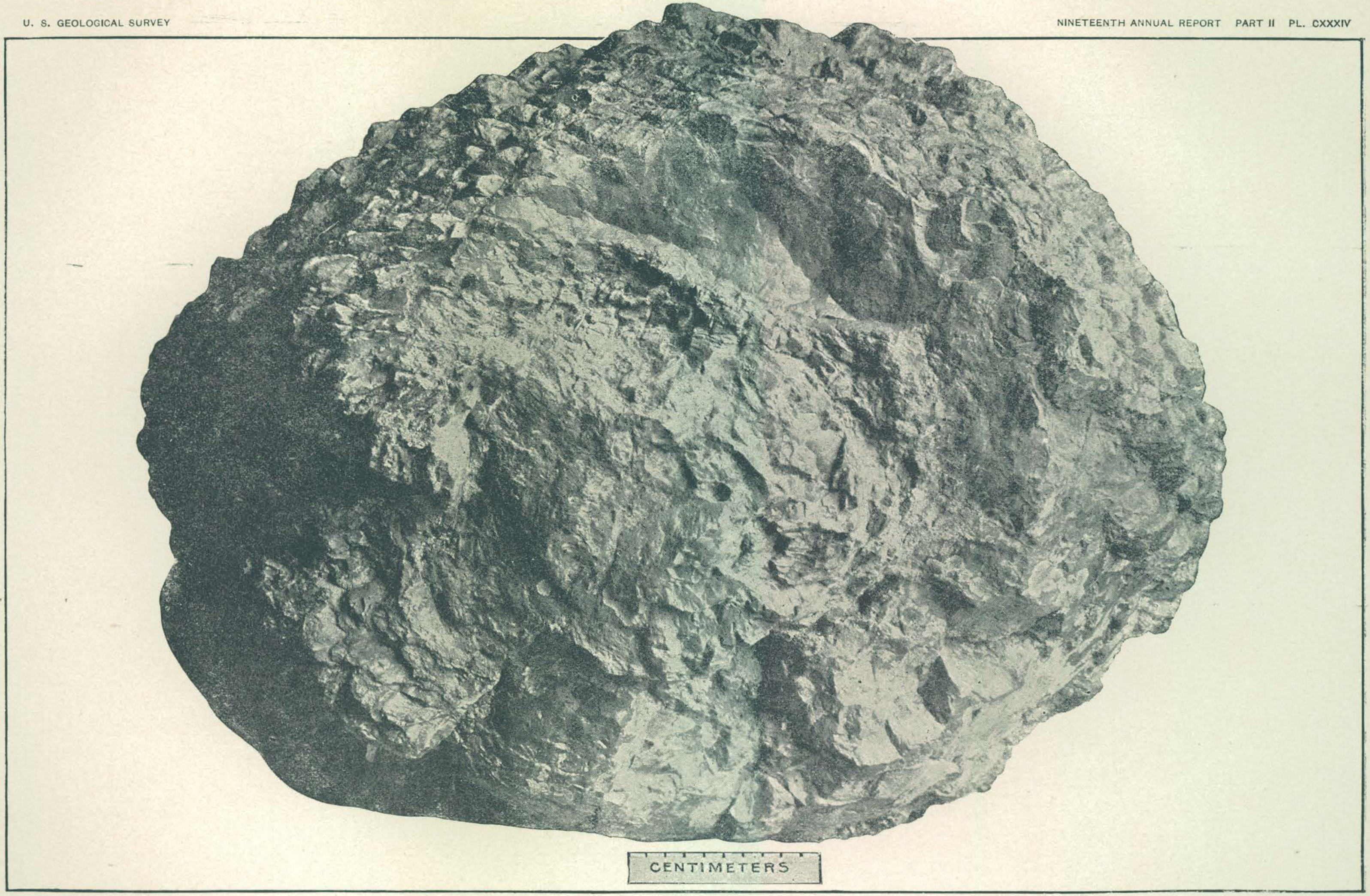
PLATE CXXXIV.

PLATE CXXXIV.

	Page.
CYCADEOIDEA INGENS n. sp	632

View of the base of No. 100 of the Yale collection.

Scale, 10 cm.



CYCADEOIDEA INGENS.

PLATE CXXXV.

PLATE CXXXV.

View of the apex of No. 100 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA INGENS.

PLATE CXXXVI.

PLATE CXXXVI.

Page.

CYCADEOIDEA INGENS n. sp. 632

Side view of No. 103 of the Yale collection.

Scale, 10 cm.

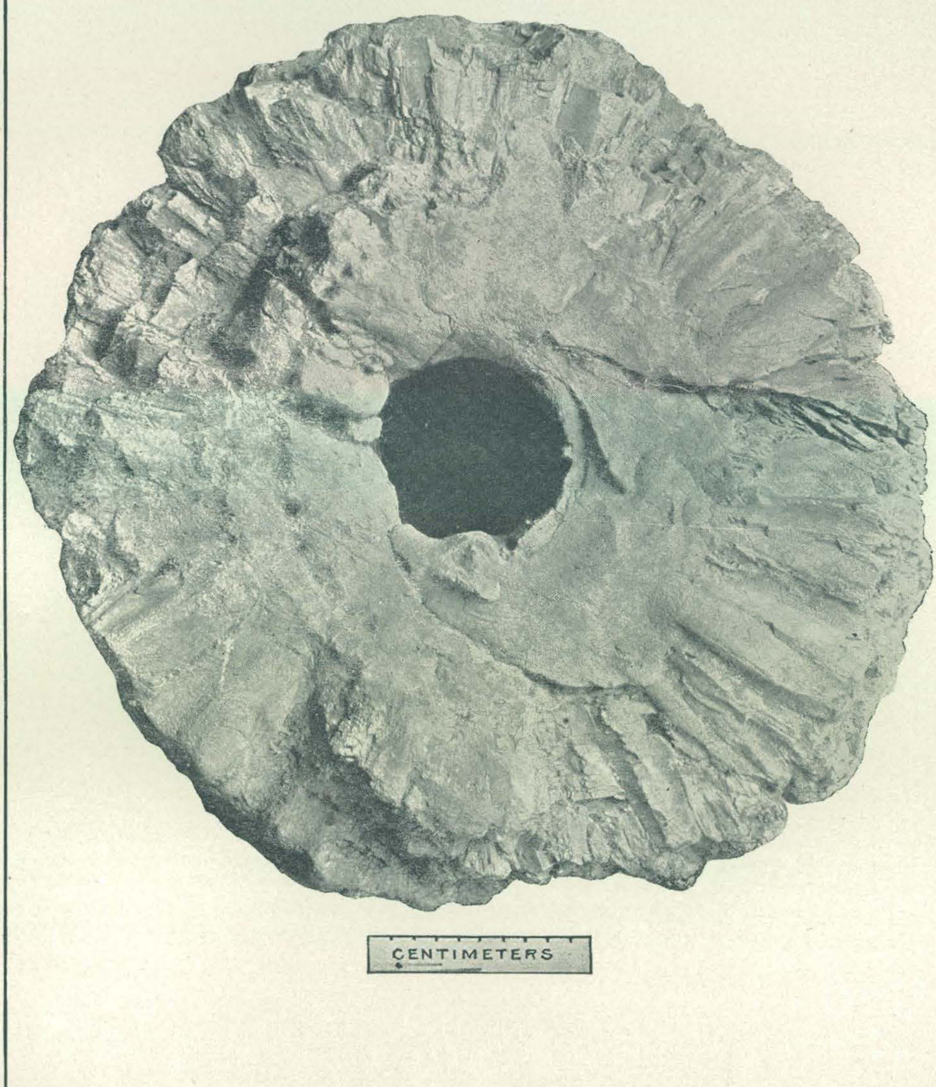
CYCADEOIDEA INGENS.

PLATE CXXXVII.

PLATE CXXXVII.

View of the transverse fracture at top of specimen No. 103 of the Yale collection, showing the axis with hollow center.

Scale, 10 cm.



CYCADEOIDEA INGENS.

PLATE CXXXVIII.

PLATE CXXXVIII.

CYCADEOIDEA INGENS.

PLATE CXXXIX.

PLATE CXXXIX.

	Page.
CYCADEOIDEA INGENS n. sp.	632

View of the base of No. 117 of the Yale collection.

Scale, 10 cm.

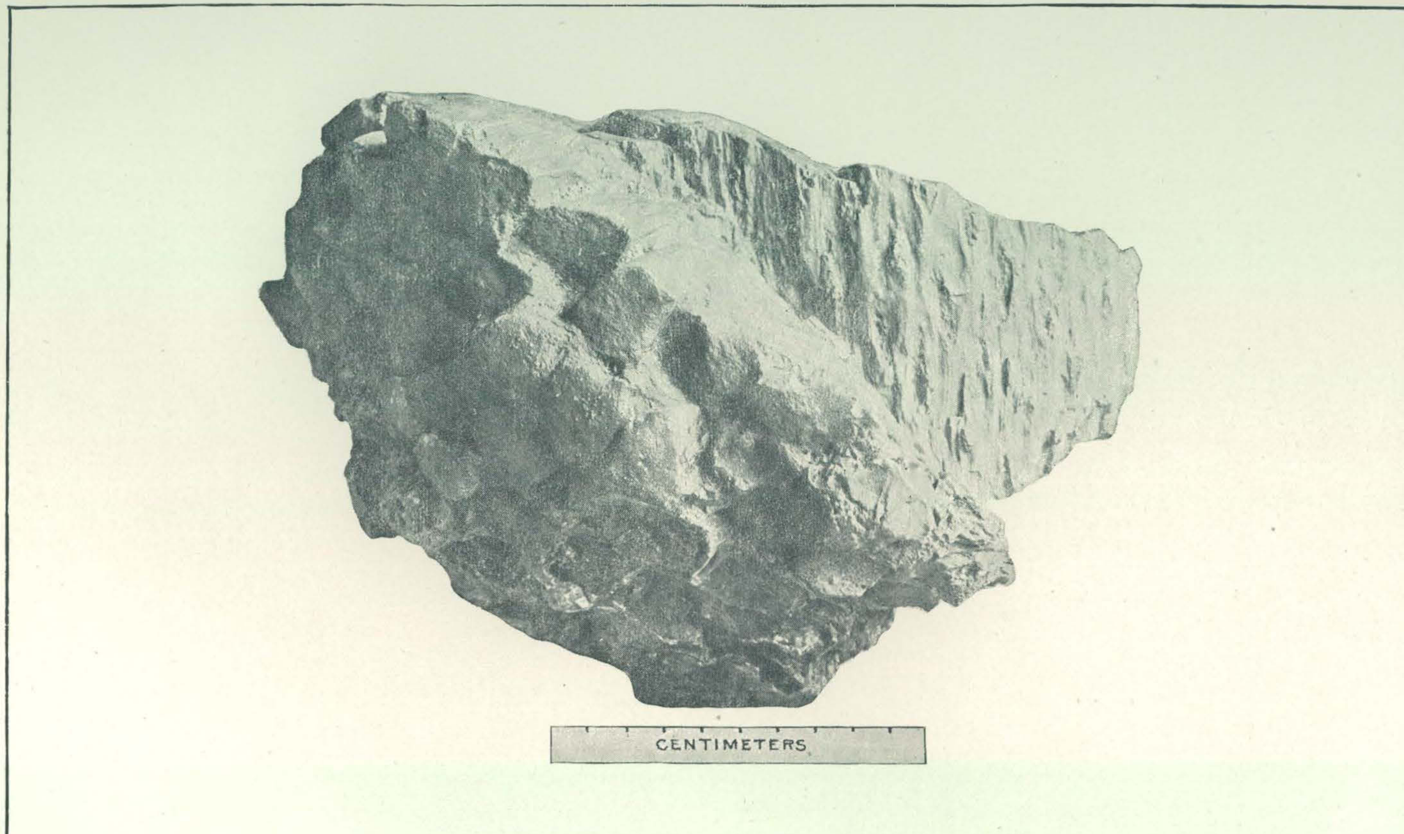
CYCADEOIDEA INGENS.

PLATE CXL.

PLATE CXL.

View of a portion of the exterior and part of the exposed surface of the medulla No. 94 of the Yale collection.

Scale, 10 cm.



CYCADEOIDEA INGENS.

PLATE CXLI.

PLATE CXLI.

	Page.
CYCADEOIDEA INGENS n. sp	632

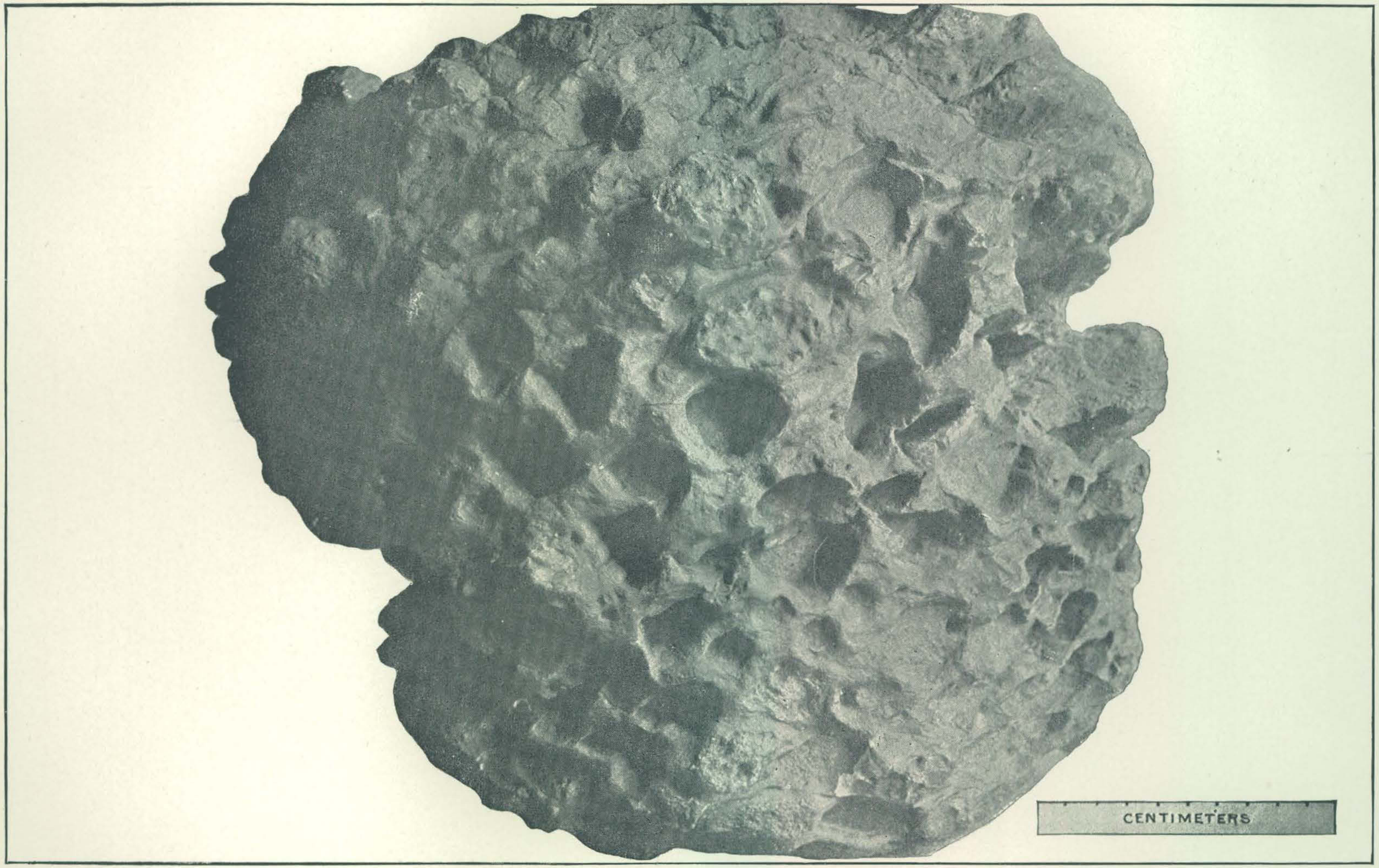
View of the transverse fracture of the upper side of No. 94 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA INGENS.

PLATE CXLII.

PLATE CXLII.



CYCADEOIDEA INGENS.

PLATE CXLIII.

PLATE CXLIII.

Page.

CYCADEOIDEA INGENS n. sp. 632

View of the base of No. 123 of the Yale collection.

Scale, 10 cm.

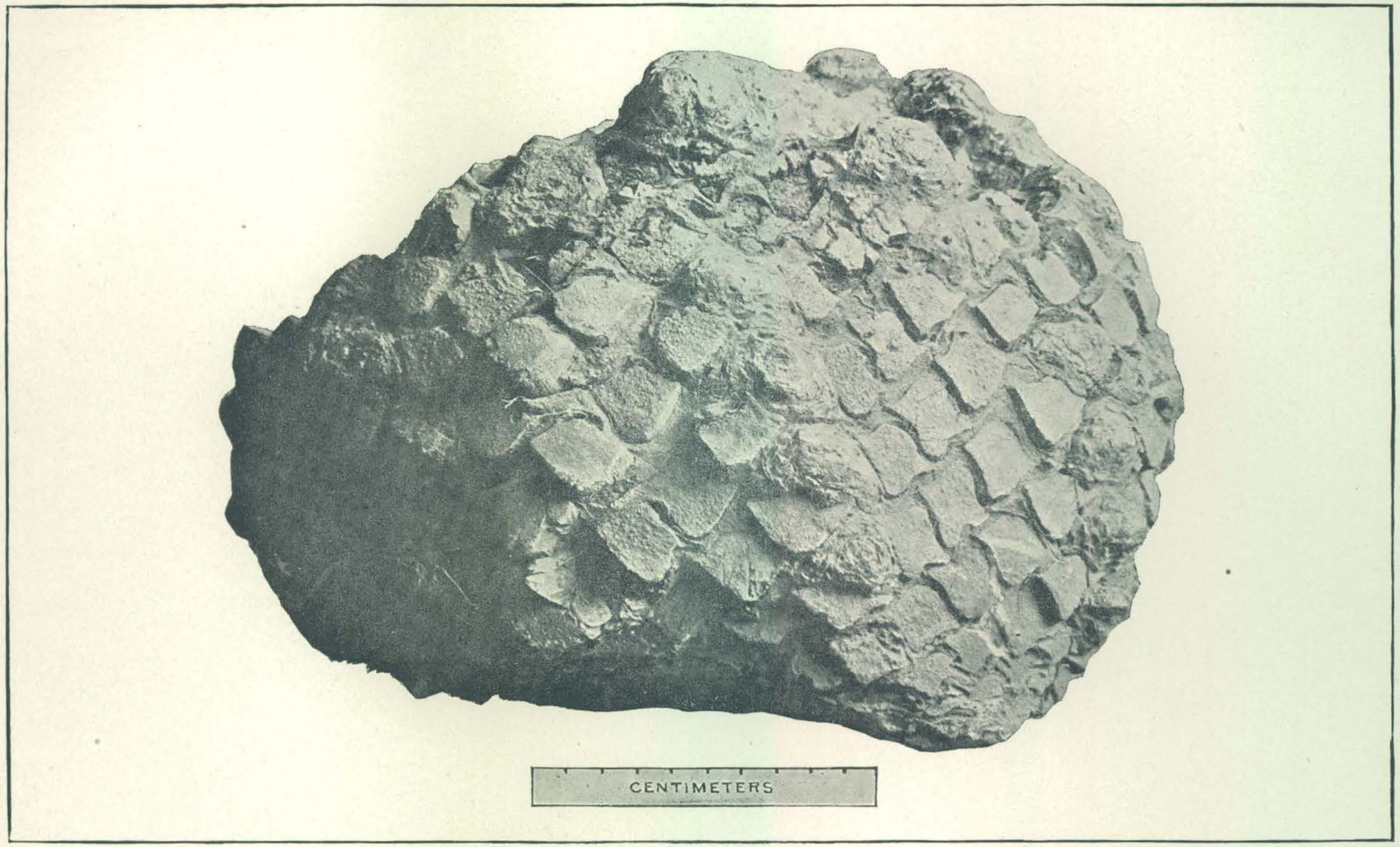
CYCADEOIDEA INGENS.

PLATE CXLIV.

PLATE CXLIV.

Side view of trunk No. 89 of the Yale collection.

Scale, 10 cm.



CYCADEOIDEA FORMOSA.

PLATE CXLV.

PLATE CXLV.

View of the base of No. 89 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA FORMOSA.

PLATE CXLVI.

PLATE CXLVI.

Page.

CYCADEOIDEA FORMOSA n. sp 634

View of the apex of No. 89 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA FORMOSA.

PLATE CXLVII.

PLATE CXLVII.

Side view of Stillwell fragment No. 2 of the U. S. National Museum collection. Scale, 10 cm.

CYCADEOIDEA STILLWELLI.

PLATE CXLVIII.

PLATE CXLVIII.

Page.

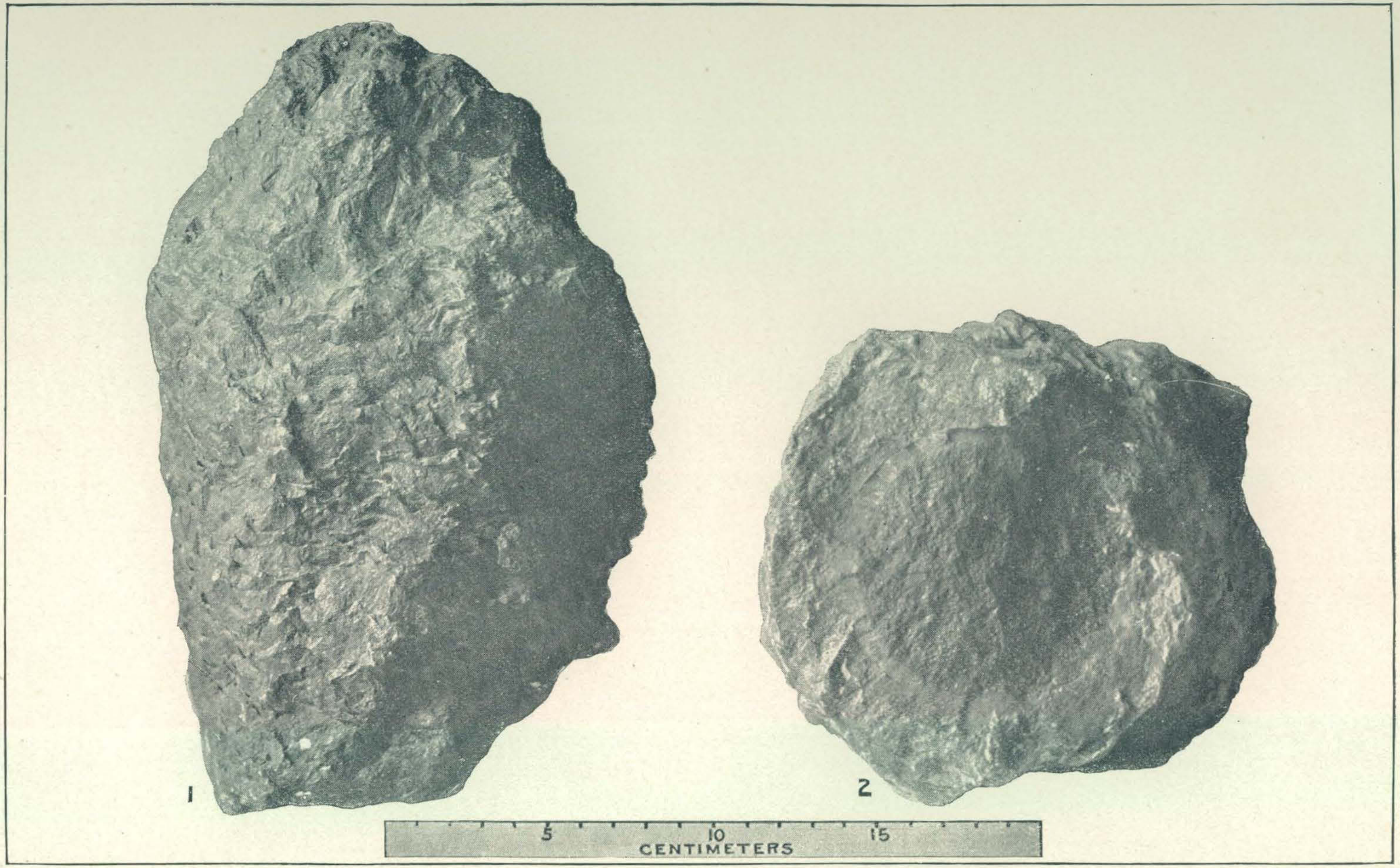
CYCADEOIDEA STILLWELLI n. sp 635

Trunk No. 36 of the Yale collection.

FIG. 1. Side view.

FIG. 2. View of the transverse fracture at lower end of specimen.

Scale, 20 cm.



CYCADEOIDEA STILLWELLI.

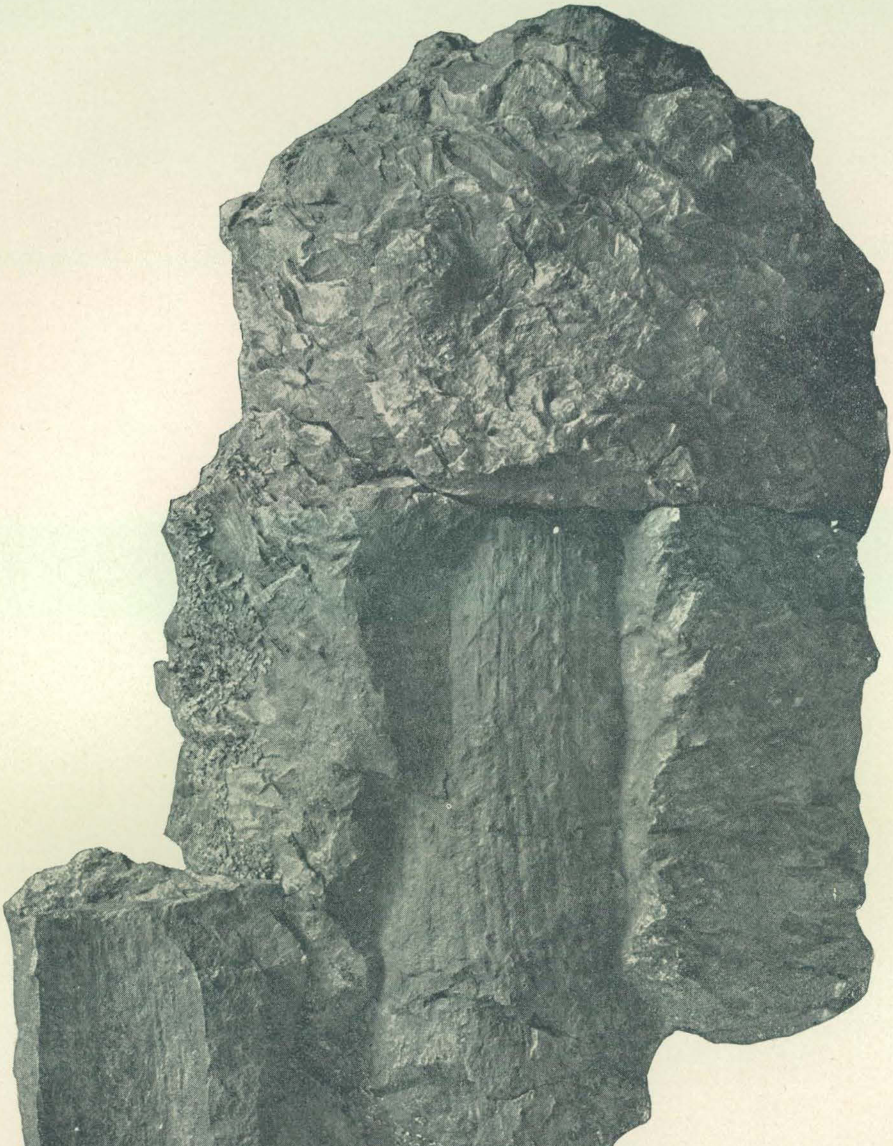
PLATE CXLIX.

PLATE CXLIX.

Trunk No. 56 of the Yale collection. Side view showing the exposed surface of the medulla and the corresponding inner wall of the woody zone in the detached fragment.

Scale, 10 cm.

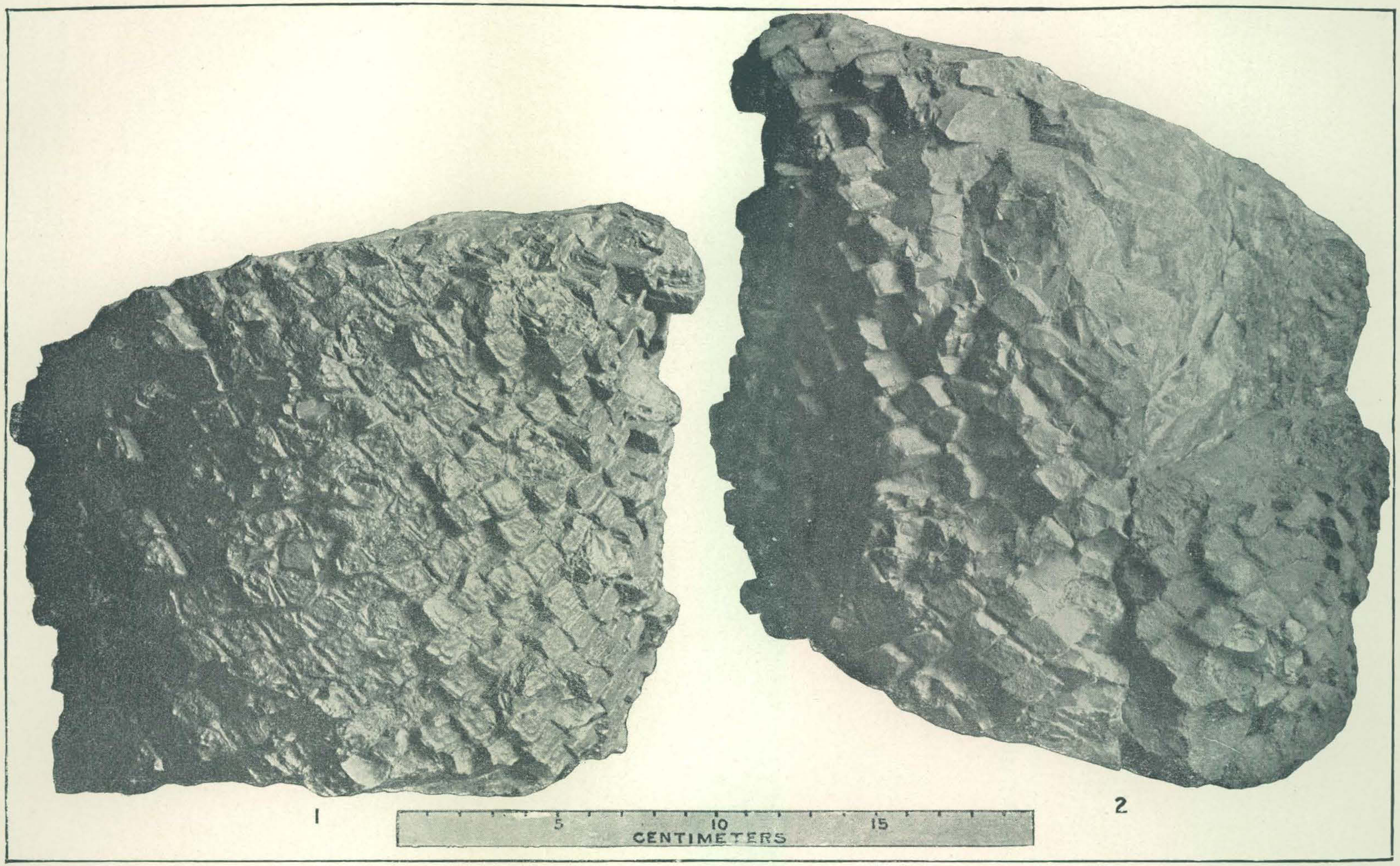
900



CYCADEOIDEA STILLWELLI.

PLATE CL.

PLATE CL.



CYCADEOIDEA STILLWELLI.

PLATE CLI.

PLATE CLI.

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CYCADEOIDEA STILLWELLI n. sp.	635

No 107 of the Yale collection.

FIG. 1. View of the side on which the scars are most distinct.

FIG. 2. View of the oblique base and broadest side.

Scale, 20 cm.

CYCADEOIDEA STILLWELLI.

PLATE CLII.

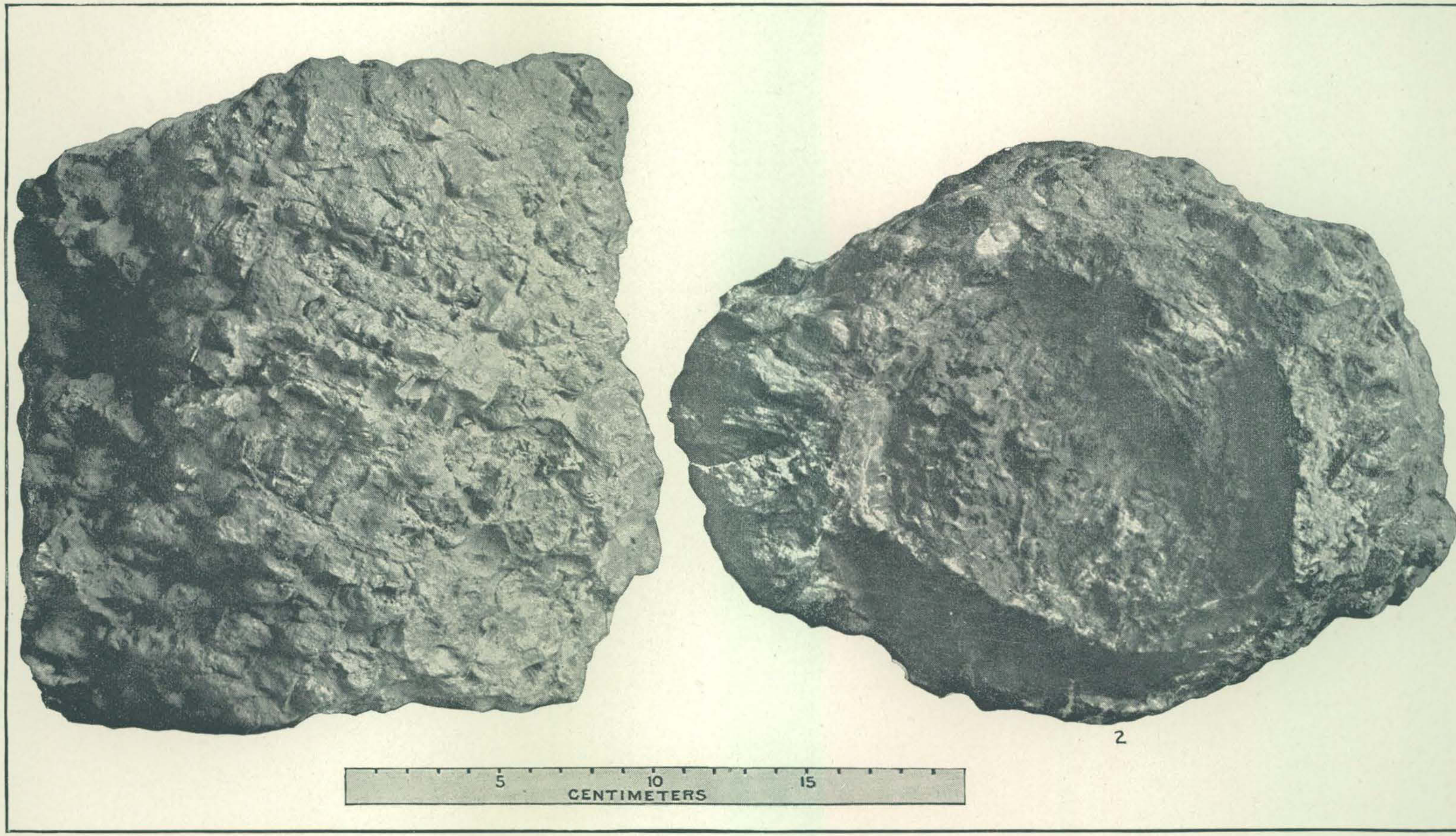
PLATE CLII.

No. 119 of the Yale collection.

FIG. 1. Side view.

FIG. 2. View of the base.

Scale, 20 cm.



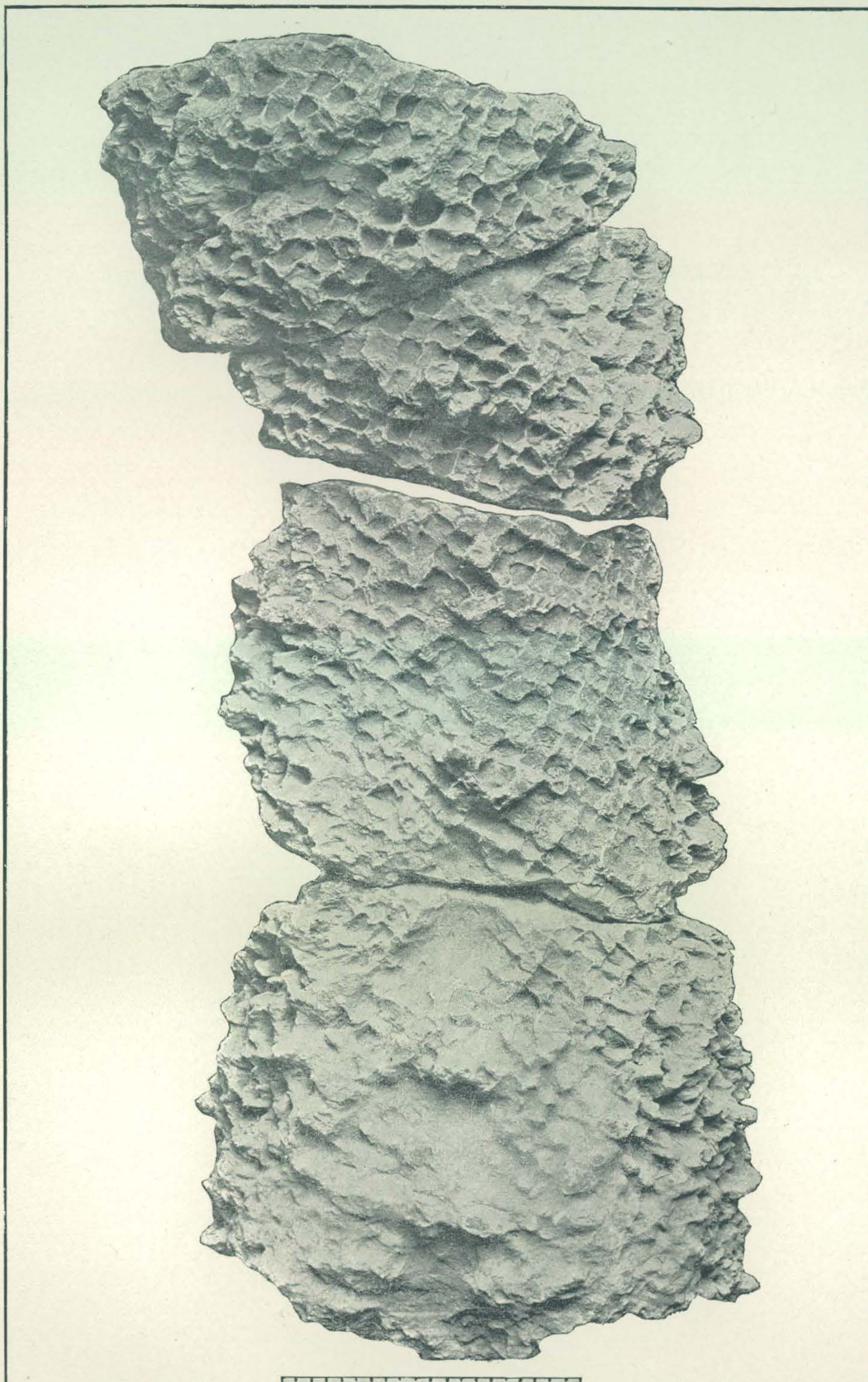
CYCADEOIDEA STILLWELLI.

PLATE CLIII.

PLATE CLIII.

View of the best preserved side of the "Noble Cycad" of the U. S. National Museum collection.

Scale, 20 cm.



CYCADEOIDEA EXCELSA.

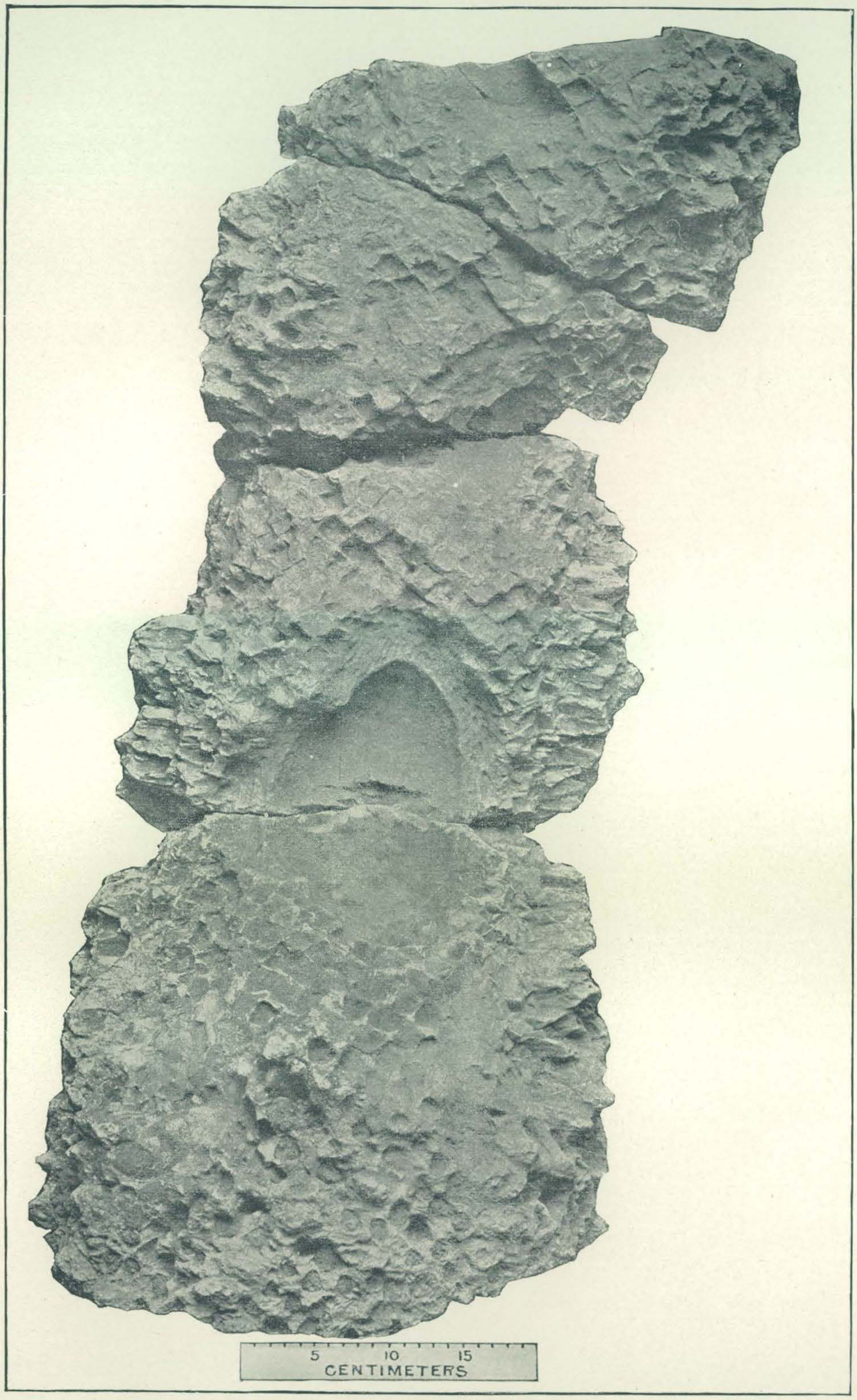
PLATE CLIV.

PLATE CLIV.

View of the somewhat decayed side of the "Noble Cycad" of the U. S. National Museum collection.

Scale, 20 cm.

910



CYCADEOIDEA EXCELSA

PLATE CLV.

PLATE CLV.

Page

Cycadeoidea excelsa n. sp 637

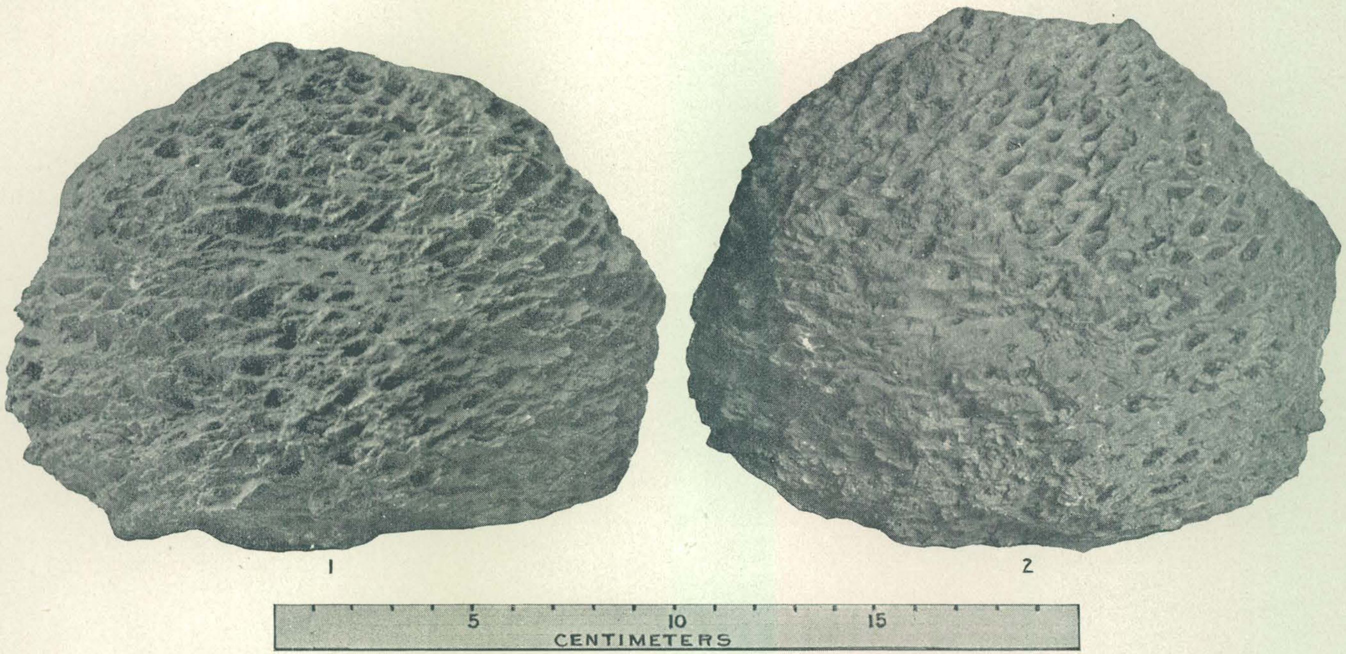
View of the base of the "Noble Cycad" of the U. S. National Museum collection.

Scale, 20 cm.

CYCADEOIDEA EXCELSA.

PLATE CLVI.

PLATE CLVI.



CYCADEOIDEA NANA.

PLATE CLVII.

PLATE CLVII.

Page.

CYCADEOIDEA NANA n. sp. 639

View of the base of trunk No. 84 of the Yale collection.

Scale, 10 cm.

CYCADEOIDEA NANA.

PLATE CLVIII.

PLATE CLVIII.

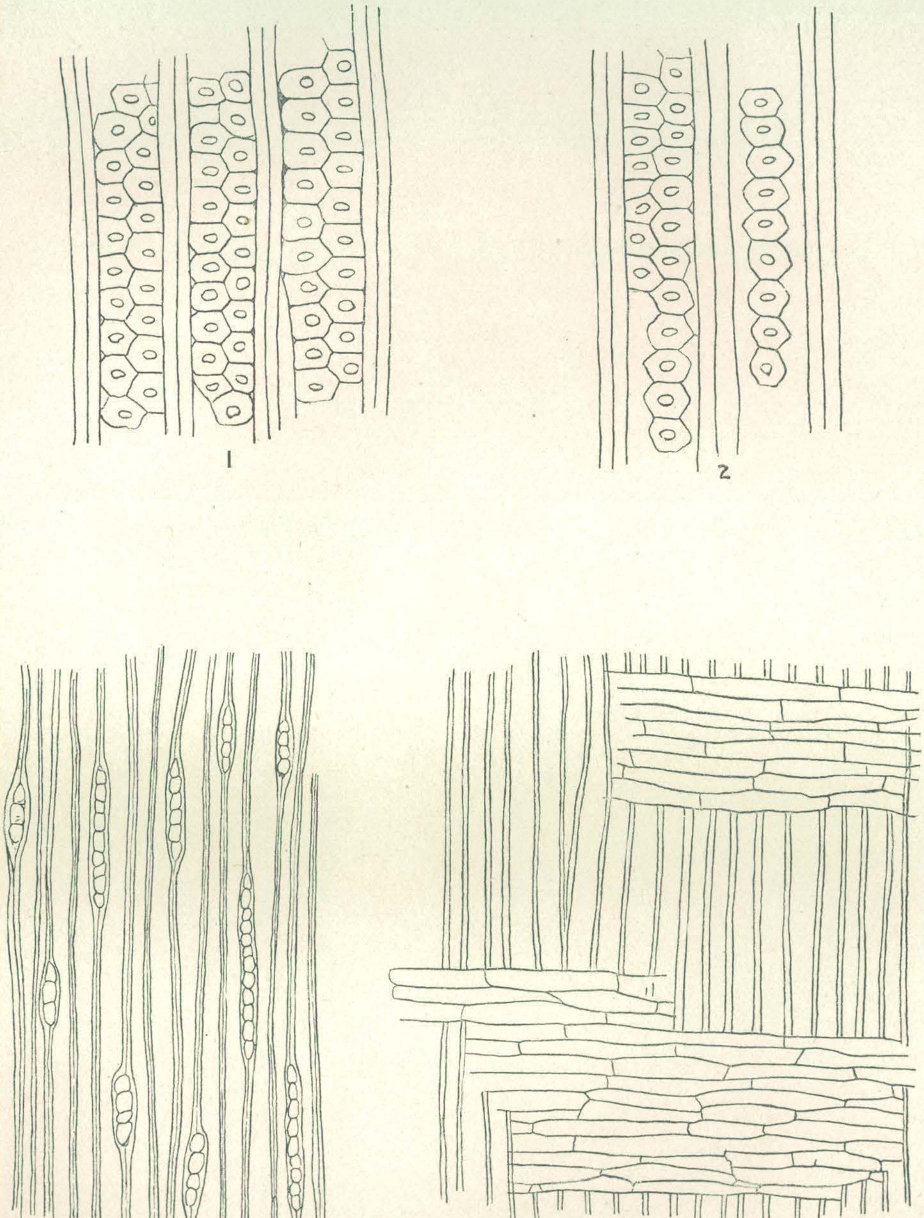
	Page.
FIGS. 1–4. ARAUCARIOXYLON HOPPERTONÆ Kn. n. sp........................	644

FIG. 1. Radial section showing bordered pits covering entire wall. × 320.

FIG. 2. Radial section showing walls with one row, or changing to two rows, of bordered pits. × 320.

FIG. 3. Tangential section showing wood cells and medullary rays. × 90.

FIG. 4. Radial section showing wood cells and longitudinal section of medullary rays. × 90.



ARAUCARIOXYLON HOPPERTONÆ.

PLATE CLIX.

PLATE CLIX.

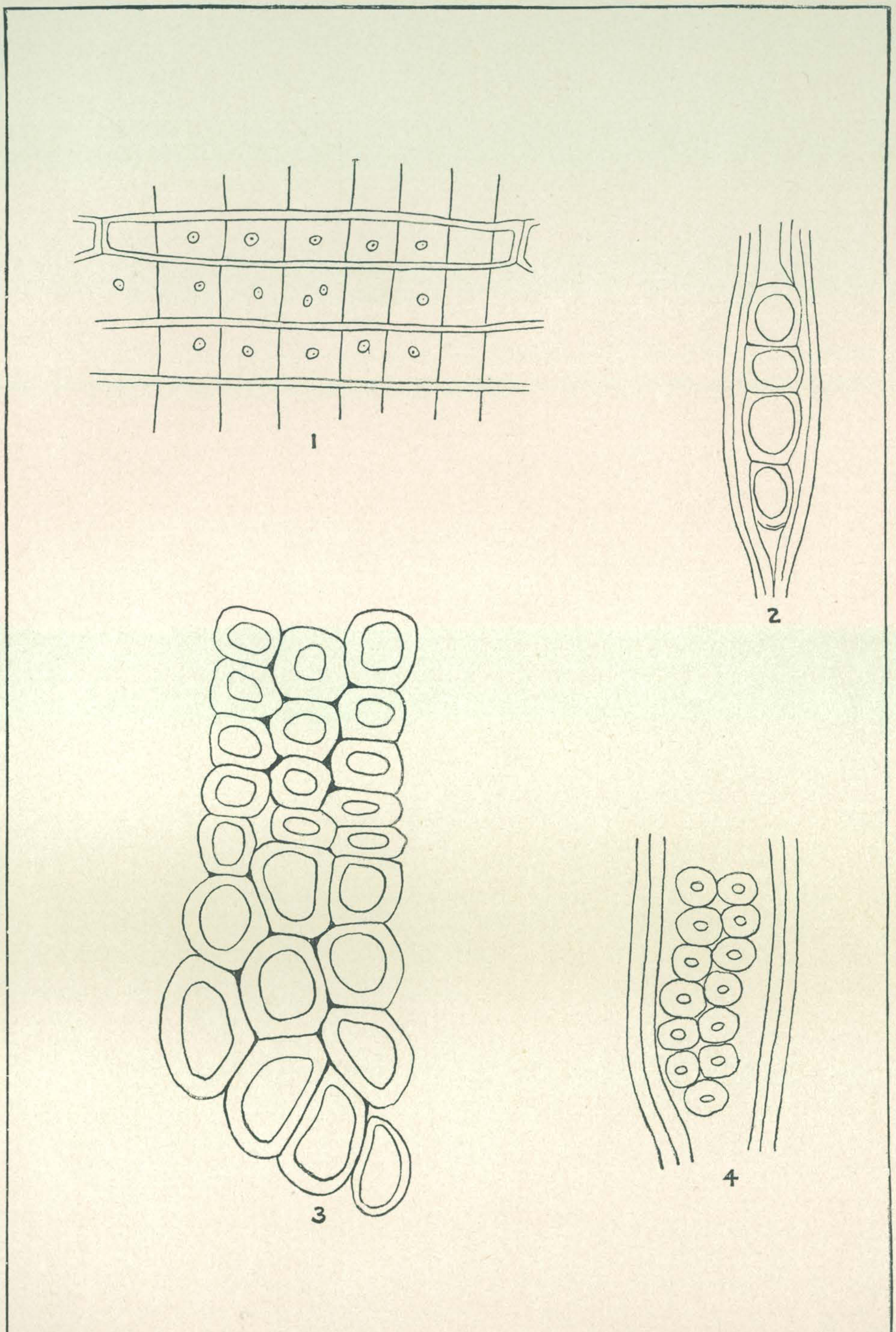
	Page.
FIGS. 1–4. ARAUCARIOXYLON HOPPERTONÆ Kn. n. sp.	644

FIG. 1. Radial section showing portion of medullary rays with minute bordered pits. × 320.

FIG. 2. Tangential section showing ends of medullary rays. × 320.

FIG. 3. Transverse section showing portions of fall and spring wood. × 320.

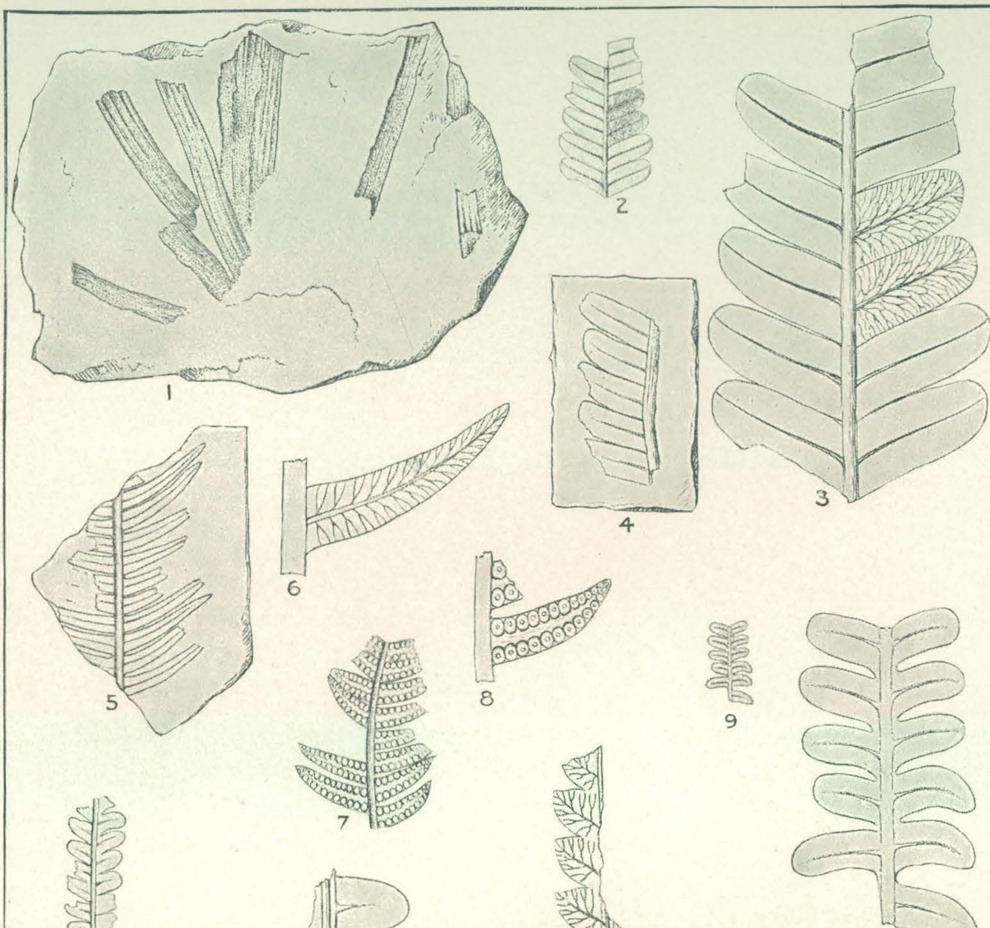
FIG. 4. Radial section showing portion of very broad wood cell with two rows of nearly circular bordered pits. × 320.



ARAUCARIOXYLON HOPPERTONÆ.

PLATE CLX.

PLATE CLX.



JOINT RUSHES AND FERNS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

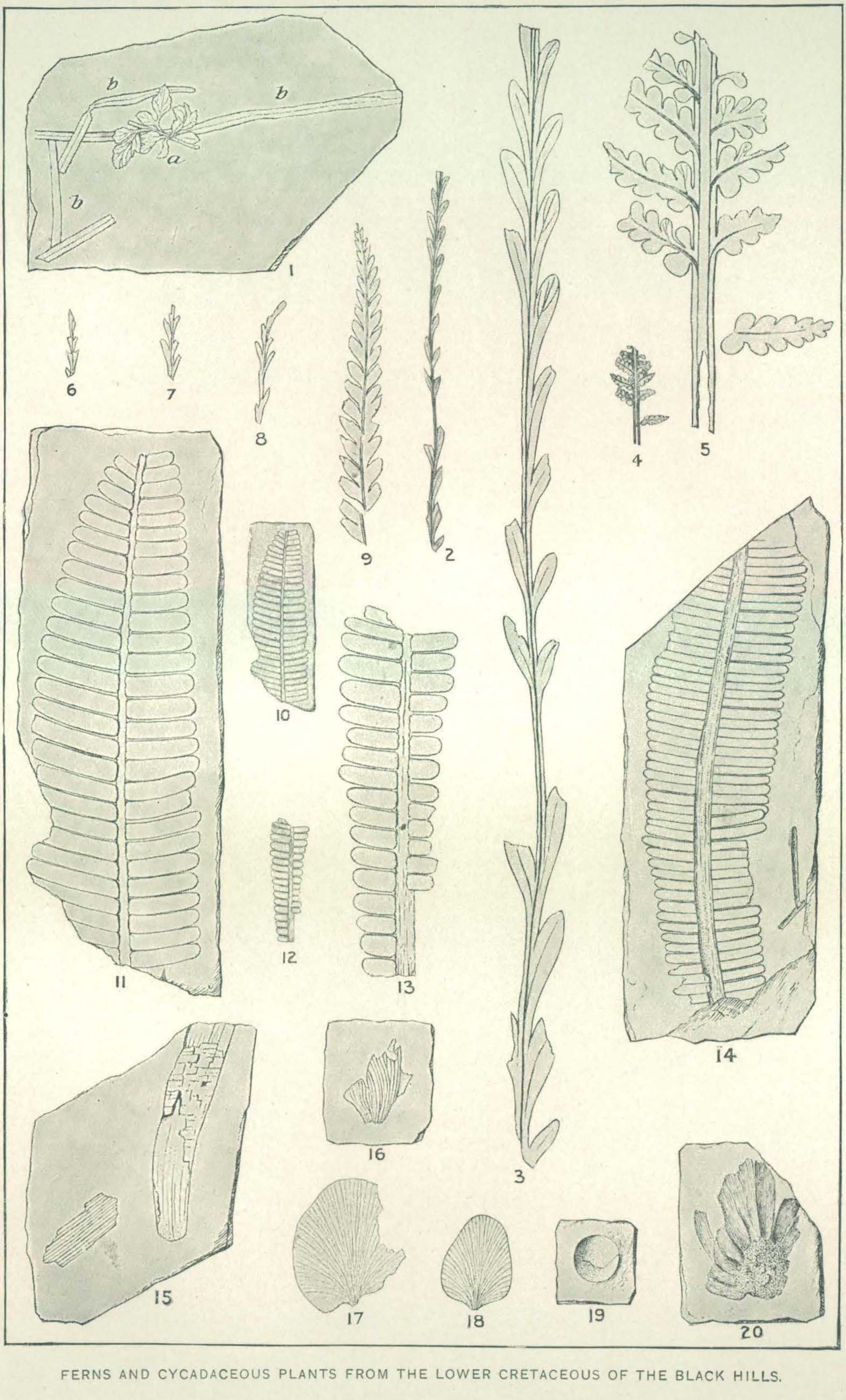
PLATE CLXI.

PLATE CLXI.

FERNS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE CLXII.

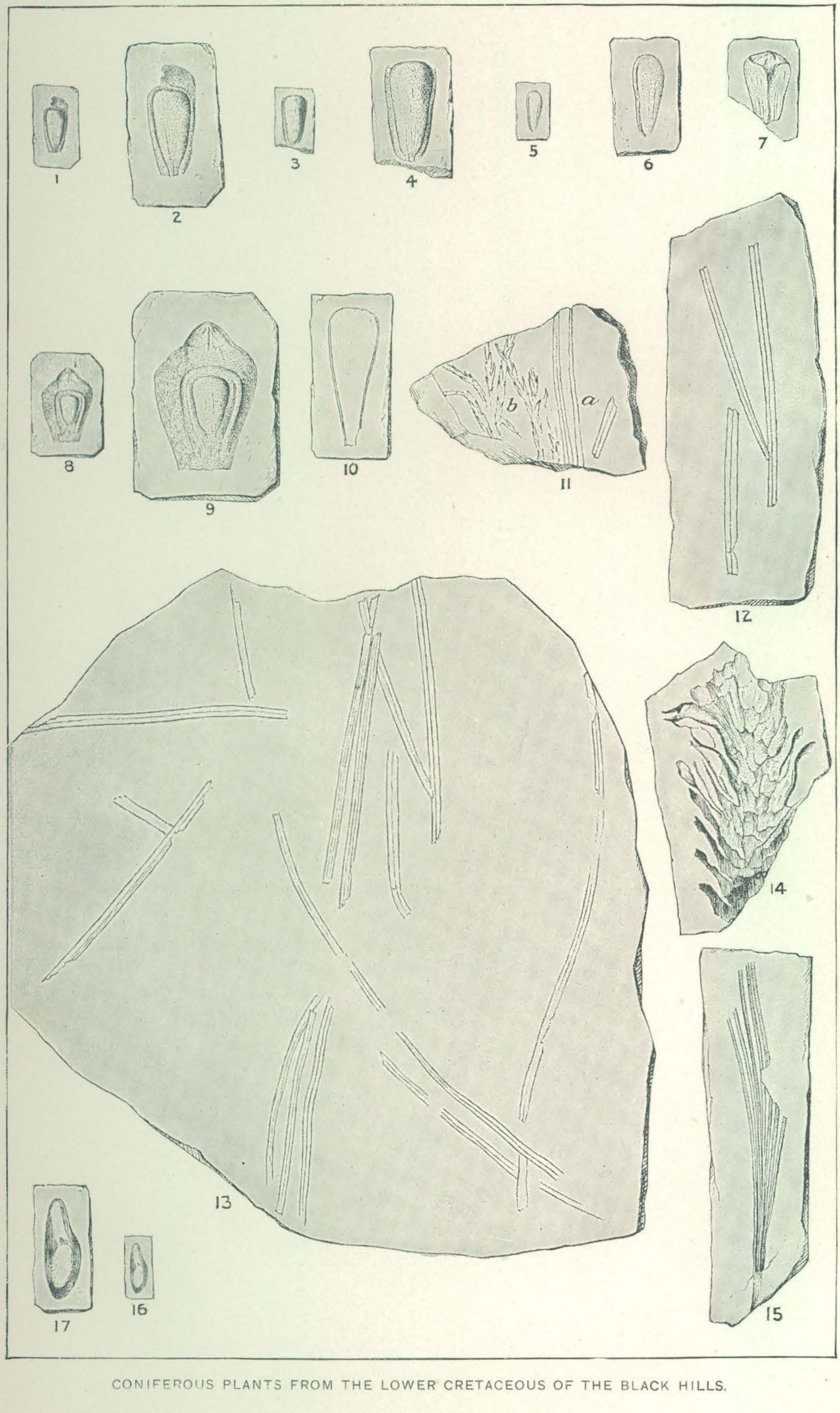
PLATE CLXII.



FERNS AND CYCADACEOUS PLANTS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE CLXIII.

PLATE CLXIII.



CONIFEROUS PLANTS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE CLXIV.

PLATE CLXIV.

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FIGS. 1–4. ATHROTAXOPSIS TENUICAULIS Font 674

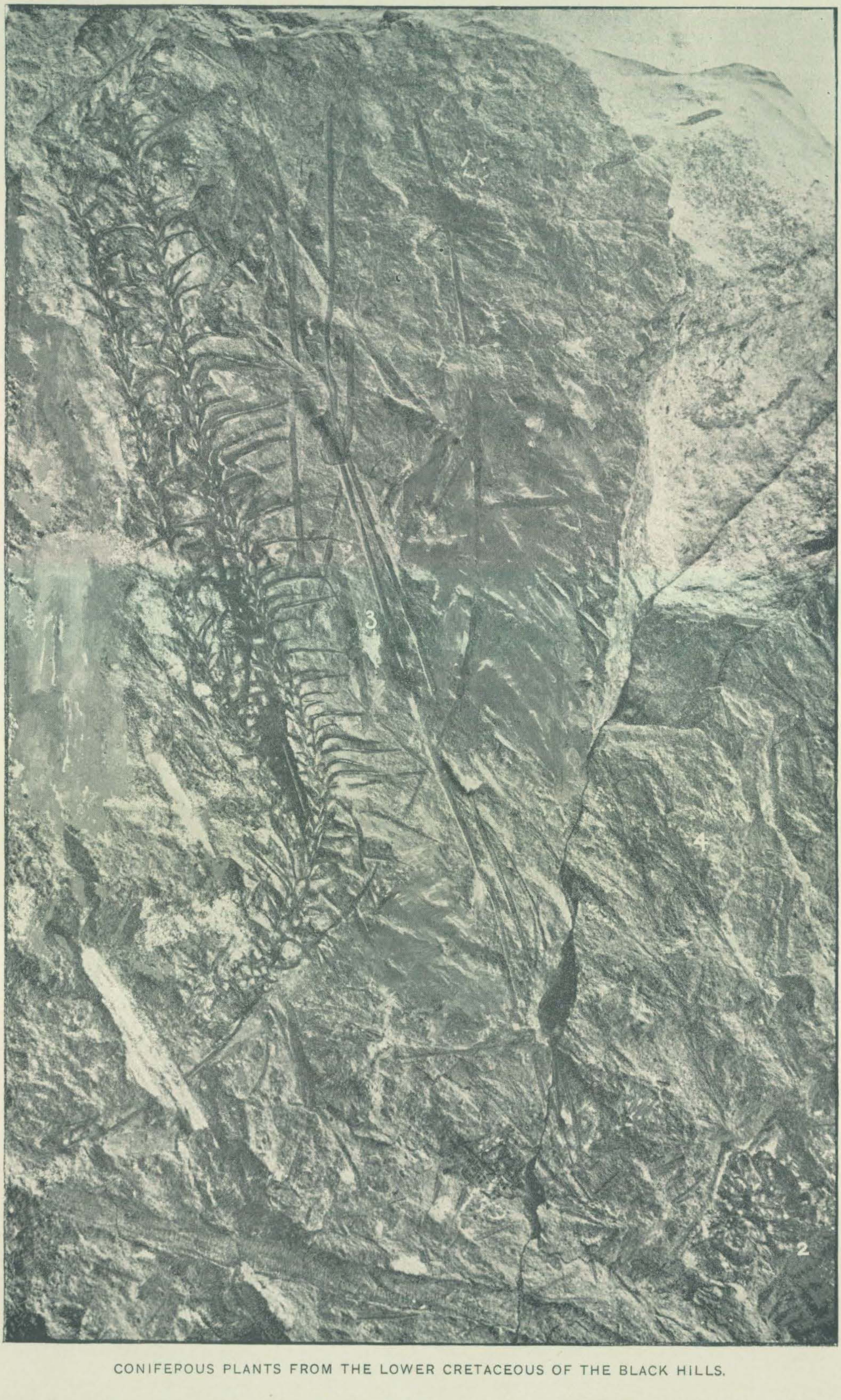
FIGS. 1–3. Stems and leaves.

FIG. 4. Cone.

CONIFEROUS PLANTS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE CLXV.

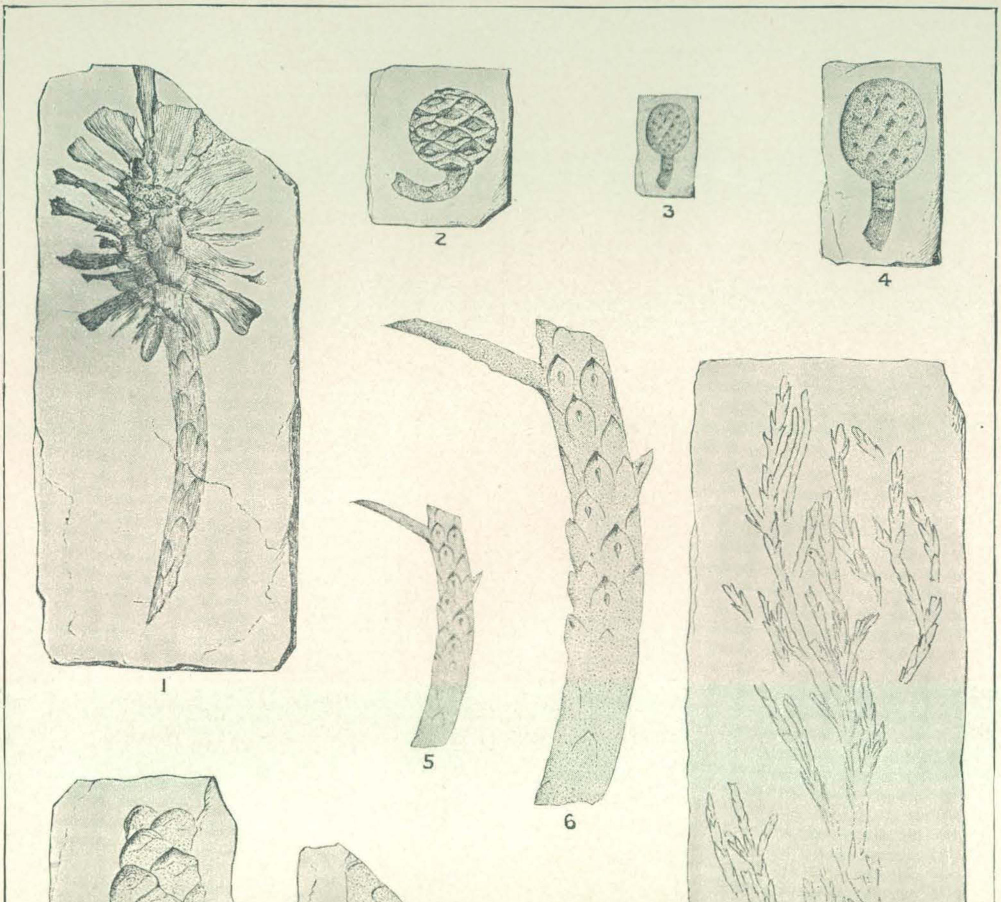
PLATE CLXV.



CONIFEROUS PLANTS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE CLXVI.

PLATE CLXVI.



CONIFEROUS PLANTS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE CLXVII.

PLATE CLXVII.

	Page.
GEINITZIA JENNEYI n. sp	676

FIG. 1. Large stem natural size, from a photograph.
FIG. 2. One of the scales enlarged 3 diameters.

1 2

GEINITZIA JENNEYI.

PLATE CLXVIII.

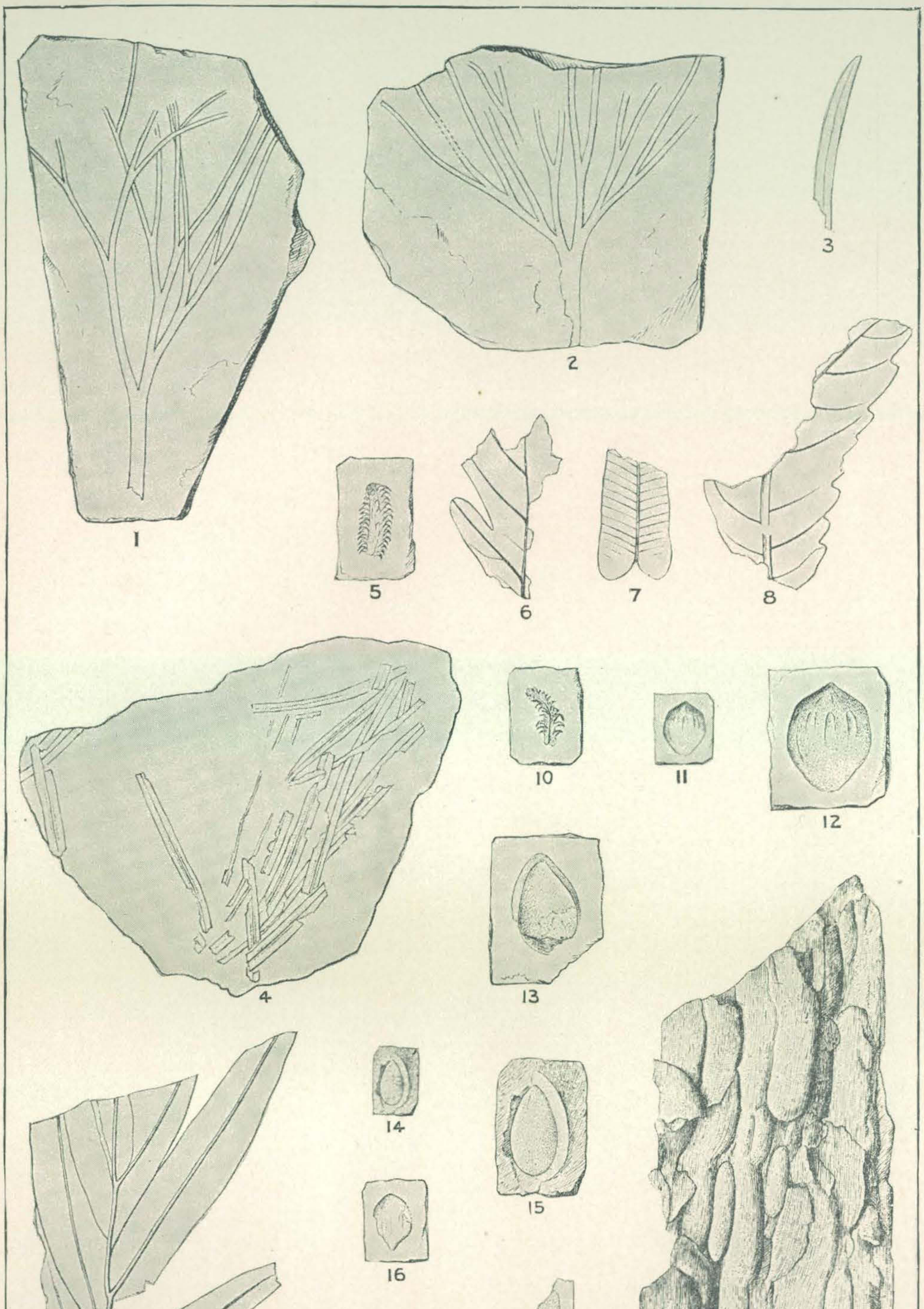
PLATE CLXVIII.

FIGS. 10 and 12. Enlargements of Figs. 9 and 11 (twice).

CONIFEROUS AND TAXACEOUS PLANTS FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE CLXIX.

PLATE CLXIX.



TAXACEOUS AND DICOTYLEDONOUS PLANTS AND PLANTS OF UNCERTAIN SYSTEMATIC POSITION FROM THE LOWER CRETACEOUS OF THE BLACK HILLS.

PLATE CLXX.

PLATE CLXX.

FERN AND DICOTYLEDONOUS PLANTS FROM THE DAKOTA GROUP PROPER OF THE BLACK HILLS.

PLATE CLXXI.

PLATE CLXXI.

DICOTYLEDONOUS PLANTS FROM THE DAKOTA GROUP PROPER OF THE BLACK HILLS.

PLATE CLXXII.

PLATE CLXXII.

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FIGS. 1, 2.	CISSITES INGENS Lx	708
FIGS. 3, 4.	VIBURNITES EVANSANUS Ward	709

DICOTYLEDONOUS PLANTS FROM THE DAKOTA GROUP PROPER OF THE BLACK HILLS.

INDEX.

Numbers in *italics* are those of pages on which illustrations (plates or figures) appear; numbers in **black-faced** type are those of pages on which detailed descriptions of species are given.

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