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CHARLES D. WALCOTT, DIRECTOR

GEOLOGY OF THE BOULDER DISTRICT, COLORADO

BY

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LETTER OF TRANSMITTAL.

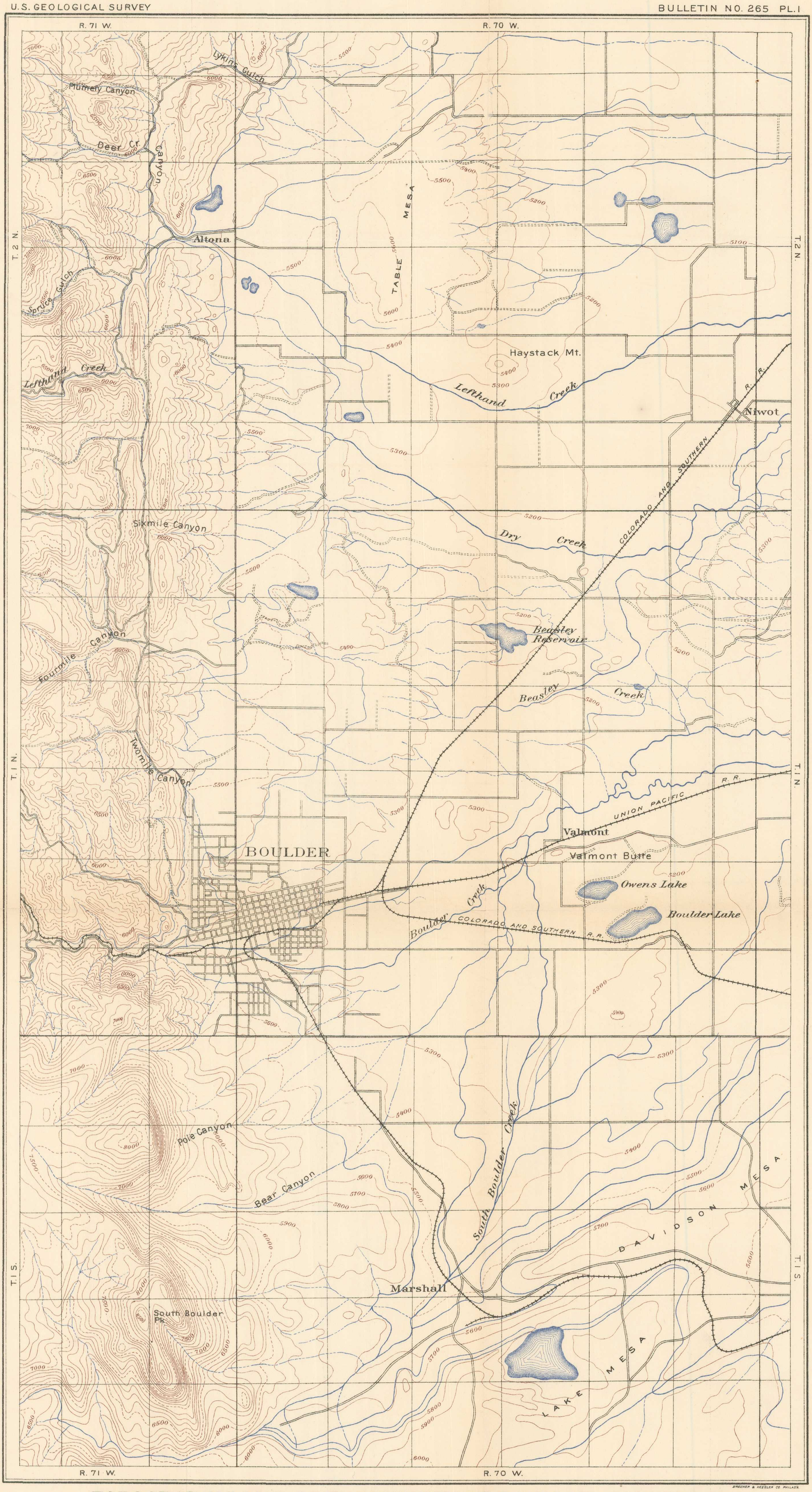
Department of the Interior,
United States Geological Survey,
Washington, D. C., November 18, 1904.

Sir: I transmit herewith the manuscript of a report on the geology of the Boulder district, Colorado, by N. M. Fenneman, and recommend its publication as a bulletin. The report has grown out of a study of the Boulder oil field, begun by Doctor Fenneman in 1902, when this field first came into prominence. Two preliminary reports, giving the more important facts of economic interest bearing on the oil field, together with records of drilling and production, have been published in Bulletins 213 and 225, Contributions to Economic Geology, 1902 and 1903. The present report covers the general geology of the district, its physiography, stratigraphy, and structure, as well as its economic mineral resources, including water, stone, clay, coal, oil, and gas. It is a model discussion of a small but exceptionally interesting district, and will prove of both economic and scientific value.

Very respectfully,

C. W. Hayes,
Geologist in Charge of Geology.

Hon. Charles D. Walcott,
Director United States Geological Survey.



TOPOGRAPHIC MAP OF THE VICINITY OF BOULDER, COLORADO.

Compiled from U.S. Geological Survey Atlas Sheets.

1905

Scale

0 1 2 3 4 miles

GEOLOGY OF THE BOULDER DISTRICT, COLORADO.

By N. M. Fenneman.

INTRODUCTION.

The area described in this report is a rectangle 16 miles north and south by 9 miles east and west. The city of Boulder is situated southwest of its center. The immediate occasion of the survey was the finding of petroleum, supposedly in paying quantities. The chief exploitation for oil has been near the center of the area, from 2 to 4 miles northeast of Boulder.

The study was extended southward beyond the village of Marshall, where the structure is more apparent than it is farther north. The northern limit of the area mapped was determined largely by the broad elevation known as "Table Mesa," whose mantle of gravel conceals all the older strata for several miles, and which has not been pierced by the drill. It was found necessary to extend the work to the north side of this mesa, where there are exposures that furnish essential data for the structural problems. The work was carried east far enough to include the excellent exposures of the "White Rocks" at the south end of Gunbarrel Hill; it was extended west beyond the stratified-rock foothills, which contain the chief evidences of the structure.

It was necessary to make a careful study of areas at considerable distances from the oil wells, because the wells are located in the broad central portion of the district on the outcrop of the Pierre shales, which are in general so nonresistant and homogeneous that exposures of solid rock are extremely rare. Here and there in the fields, or on the side of an irrigating ditch, the presence of a thin harder bed may be indicated by a few rock fragments and a sandier soil, but generally the bed is not strong enough to cause even a small ridge, although a little excavation may sometimes reveal its position. Such indications and the inferences from the comparison of not very satisfactory well records are the only direct means by which the structure in the immediate vicinity of the oil wells can be determined.

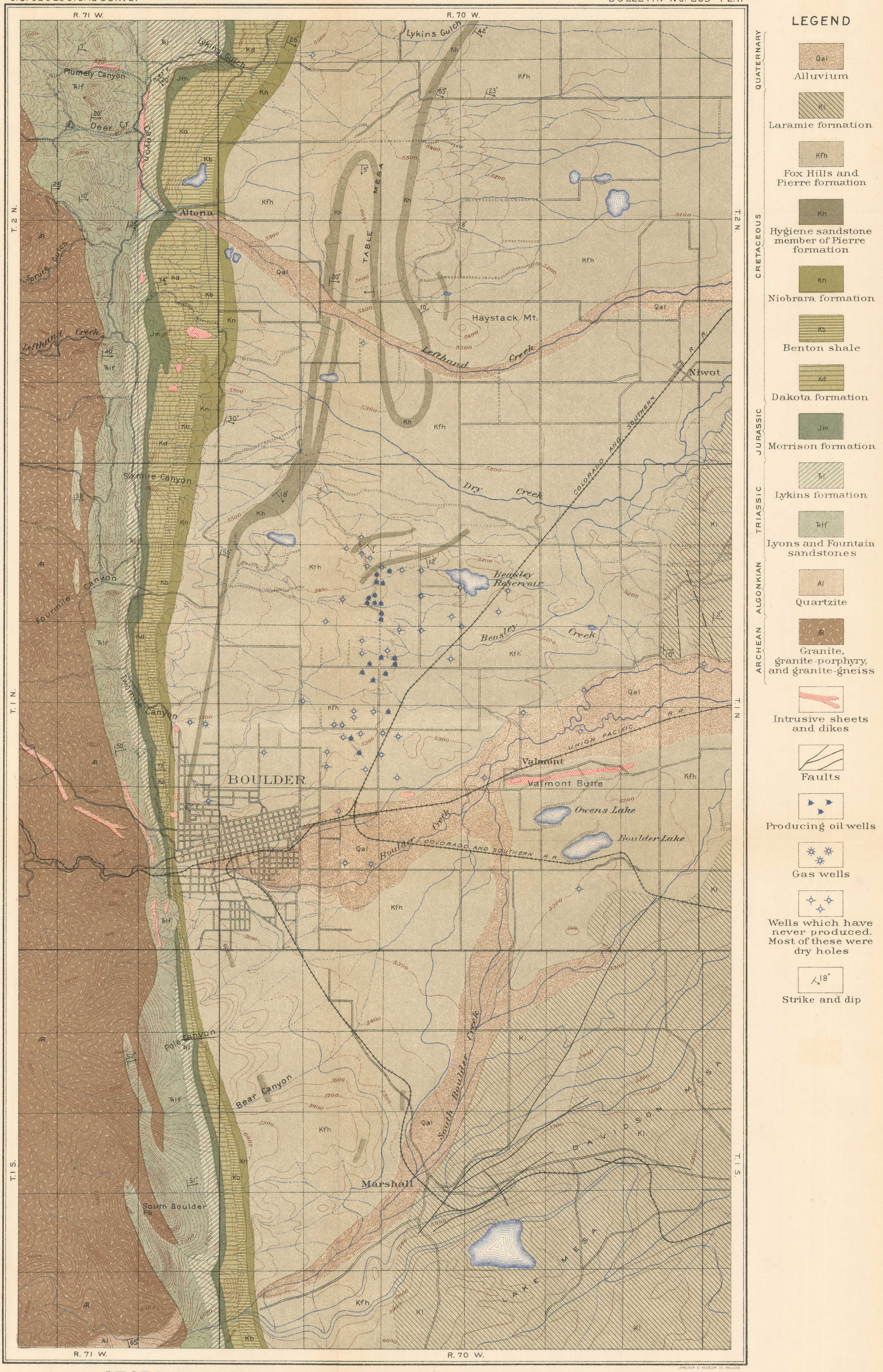
It is otherwise on the borders of the area. On the west are fine exposures of the firm rocks of the foothills. On the south, in the

Marshall coal field, are the eroded folds and scarps of the Laramie sandstone. On the east the Fox Hills and Laramie sandstones offer good exposures. At the north end Haystack Mountain, the only remnant of a terrace higher than Table Mesa, affords an excellent opportunity to study the Pierre shales. At this end of the field even the Pierre contains one or more sandstone strata, which outcrop in definite ridges. The structure of these surrounding districts affords a good basis from which to infer the probable deformations of the strata in the oil territory. It is evident that the structural features so clearly revealed in the foothill belt correspond to those of the oil field. Although the structural features of the shales of the oil field can be made out only by wearisome search, their correlatives in the foothills are open to the light of day. The practical significance of this relation will be evident to any who may be prospecting for similar deposits of oil along the front of the range.

The district here described was studied by the Hayden Survey, and its general features are discussed in the reports of that organization published in 1869 and 1872. The portion of the district south of Fourmile Canyon is included in the Denver basin, which is discussed in Monograph XXVII of the United States Geological Survey by Emmons, Eldridge, and Cross. The southern limit of the area mapped by the Fortieth Parallel Survey is a few miles north of this district, but the description of the major features of the stratigraphy of the east slope of the Front Range as given in the report of that organization is applicable to this field.

ACKNOWLEDGMENTS.

The preparation of the map accompanying this report was made possible by the excellent base map prepared by Mr. Hugh F. Watts, of Boulder, a large part of the geological field work having been done before the publication of the survey atlas sheets. Mr. Watts had also made a geologic map of a part of the region, a generalized reproduction of which is given in this paper as fig. 2 (p. 37). His careful observations were useful at various places, and a few of them are given specific mention in footnotes. Judge Junius Henderson has systematically collected fossils from the district and his cooperation was found valuable. At th present stage of the study, however, it was not deemed advisable to attempt a systematic treatment of fossils. Mr. William R. Rathvon, who has handled for the United Oil Company practically the entire product of the oil field, has generously furnished exact data regarding shipments, and has given much general information concerning the industrial phases of the subject. The plates used are from photographs by Prof. J. R. Brackett. Over half of them were taken expressly for this publication. Prof. R. D.



GEOLOGIC MAP OF THE VICINITY OF BOULDER, COLORADO.

By N. M. Fenneman.

1905

Scale

0 1 2 3 4 miles

George, of the University of Colorado, has been consulted on various questions; at the request of the writer he has studied several points in the field, and his conclusions have been received with much confidence. He has read the entire manuscript and his suggestions have been most helpful. The manuscript was subsequently submitted to Mr. George H. Eldridge, a student of oil fields, and one of the authors of the monograph on the Denver basin, who is familiar with much of the area and many of the features here described. Mr. Eldridge's criticisms were found especially pertinent, and on his suggestion certain changes were made.

PHYSIOGRAPHY.

The area may be divided into three north-south strips. A narrow margin on the west belongs to the rough and dissected granite plateau, commonly considered a part of the Front Range of the Rocky Mountains. East of this is the narrow foothill belt, in which a descent of more than 1,000 feet is made to the plains, which form the eastern two-thirds of the area.

TOPOGRAPHY OF THE AREA OF CRYSTALLINE ROCKS.

In a broad sense the name Front Range includes all of the Archean strip west of the Great Plains and the foothill belt. If this part of the range is looked at in more detail, there is seen near the middle of the strip a definite north-south ridge, having its crest about 18 miles west of the upturned strata of the foothills. West of Boulder this ridge reaches an elevation of from 12,000 to 14,000 feet, and has an average slope of from 500 to 1,000 feet in a mile. At approximately the 9,000-foot contour the slope changes. On the west is a relatively abrupt ridge, and on the east a much dissected plateau reaching to the foothills. (See Pl. III, *B*, opposite p. 12.)

The belt between the restricted mountain ridge on the west and the foothills on the east is 10 to 12 miles wide. Its generalized eastward slope is about 250 feet per mile, or from one-fourth to one-half that of the range proper. This strip is cut by narrow valleys to a depth of over 1,000 feet. The interstream areas are generally steep and narrow hills without flat tops, though some ridges continue for several miles with approximately level and unbroken crests. From any high point almost all the summits appear to be in the same plane. The range proper on the west and isolated lumps on the plateau rise with conspicuous abruptness, Sugarloaf Mountain, the top of which is 1,000 feet above the general level. being a prominent example. The topography at once suggests an imperfectly base-leveled surface that has been deeply cut by streams whose erosive power has been increased by recent elevation.

FOOTHILLS.

MONOCLINAL RIDGES.

East of the granite are the red sandstones of the Fountain and Lyons formations, which have an average dip of more than 50° and form a ridge rising 1,000 feet above the plains. The sandstones have apparently resisted weathering better than the crystalline rock, as streams from the west which have cut only narrow canyons through the sandstone ridge generally receive tributaries that flow in north-south valleys in the granite just west of the contact. At places (as at South Boulder Peak) the ridge rises to several times its average height, and towers high above the plateau to the west.

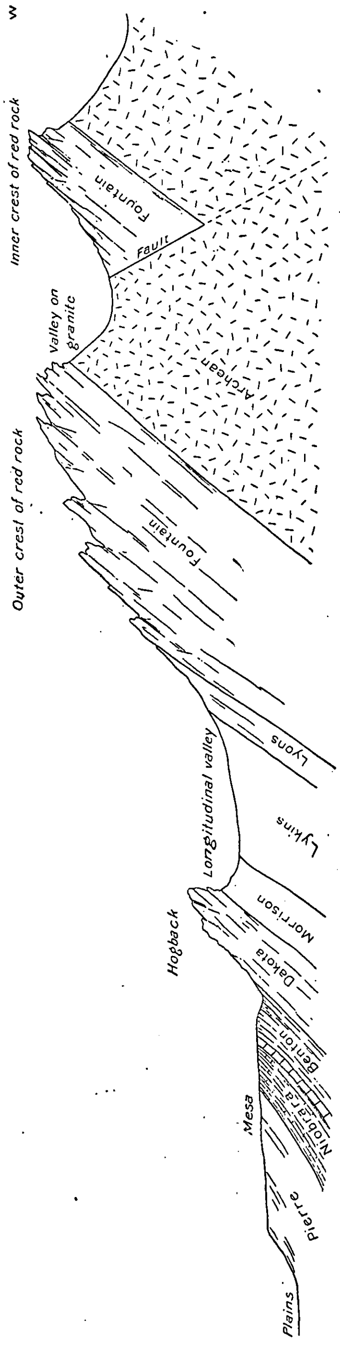
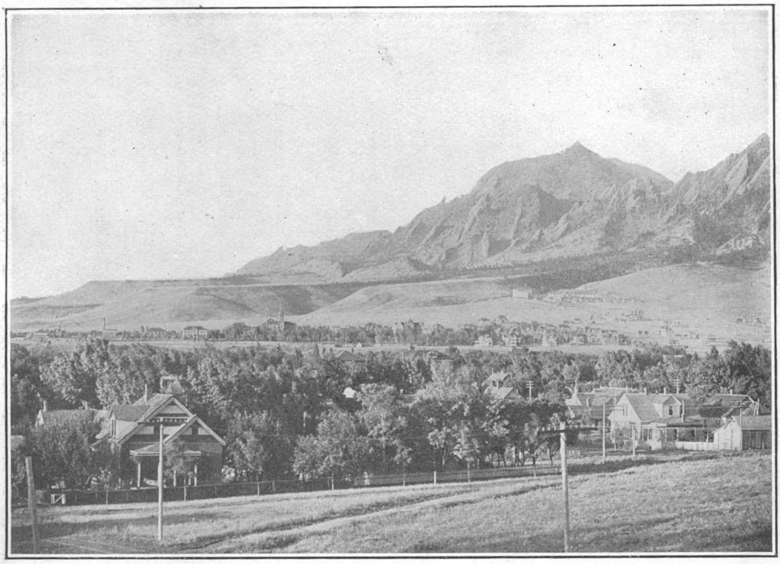


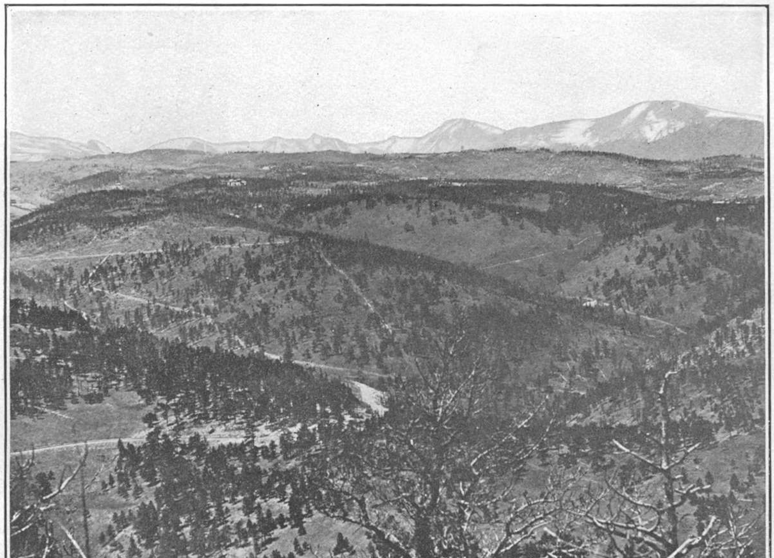
FIG. 1.—Generalized east-west cross section near Boulder. The diagram shows the structure of the South Boulder peaks, of Green Mountain, and of the ridge near Sixmile Canyon.

To these red sandstones, from 500 to 1,500 feet thick, is due a large part of the splendid scenery of this exceptionally fine stretch of foothills. At some places the ridge has an even crest and resembles a wall, while at other places its crags run upward in a long line of spires. (See Pl. III, *A*.) The bare red front of a single crag has sometimes an area of several acres. The outcrop here described may have one, two, or even three distinct crests. They are the westerly members of a series of monoclinal ridges known as "the foothills." Alternations of strong and weak strata, upturned at steep angles, offer the necessary conditions for the carving of these ridges and valleys.

The ridge-making outcrops, taken in order from west to east, are composed of the Fountain, the Dakota, and the Niobrara formations, the last named appearing as a prominent ridge only in the northern part of the area. The order of



A. MESAS AND FOOTHILLS SOUTH OF BOULDER.



B. VIEW WESTWARD FROM GREEN MOUNTAIN.

size is the same as that here given, the height decreasing from west to east.

The Dakota "hogback" is second in prominence to the Fountain crags. It is absent between Sunshine and Pole[a] canyons, but elsewhere it rises steeply to heights of from 100 to 500 feet. The light-gray color of its sandstones is frequently in strong contrast with the red of the rocks farther west. Its crest is commonly covered with pines.

LONGITUDINAL VALLEYS.

Between the red-rock ridge and the Dakota the weaker rocks of the Lykins and Morrison have been cut out in a valley from one-fourth to one-half mile wide. (See fig. 1; also Pl. IV, *A*.) The brilliant color of the former, especially north of Boulder, has given an almost blood-red hue to the soils of the valley. A similar valley, though lacking the color, marks the outcrop of the Benton, where the Niobrara ridge is present. Where the latter forms no ridge, the Benton occupies a long slope from the Dakota hogback to the mesas. This slope is characteristically marked by landslides. At frequent intervals may be seen the typical hummocky topography due to this agency.

MESAS.

East of the last foothill ridges the slope to the plains may be continuous or may be broken by a sharp step, leaving a high terrace adjacent to the foothills. This terrace is called a mesa, or locally "the mesa" (Pl. III, *A*). It occurs in fragments of unequal height abutting against the most easterly foothill ridge or separated from it by a trough due to recent erosion. (Compare Pl. V, *A*, p. 30.) These fragments are commonly separated from one another by ravines. These mesas have a height of from 100 to 300 feet above the lower plains, and a west-east width in this vicinity varying from a fraction of a mile to 3 miles.

SLOPE AND HEIGHT.

The eastward slope of the terraces may be as great as 10° on the foothill side, but it diminishes rapidly toward the plains. At 1 mile east from the foothills a slope of 3° to 4° is common, and at 3 miles the slope is about 1°. An east-west cross section shows an even curve, like the profile of a stream. In addition to the east-

[a] This small gorge in the outer foothills, 2 miles south of Boulder Creek, is locally known as Skunk Canyon. It appears on the maps of the Denver basin as Pole Cat Canyon. For convenience the abbreviated form is here used. The small stream issuing from it is rarely spoken of by any name.

ward slope there is generally a distinct northward or southward inclination toward a lower bench quite similar to the higher, but separated from it by a steep bluff, or more commonly by a ravine. In a general way the highest mesas are farthest from the larger streams, and the height diminishes as these streams are approached.

STRUCTURE AND COVERING.

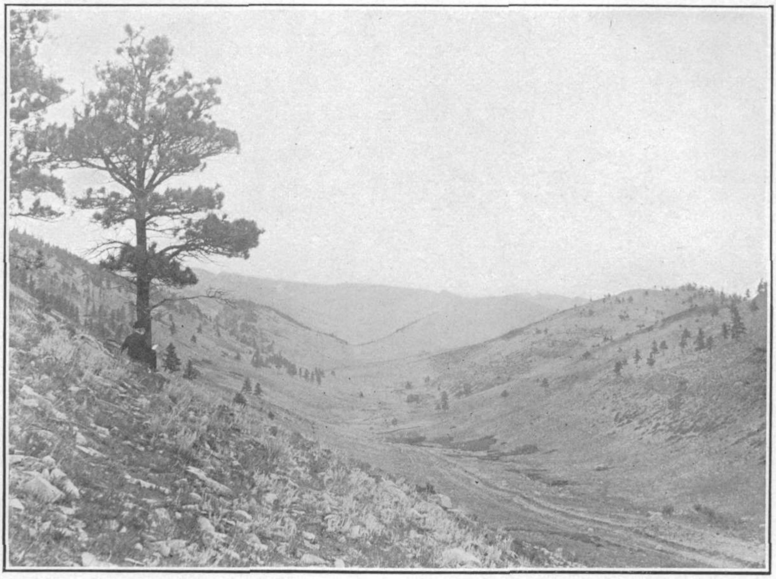
These mesas are essentially rock benches covered 10 or 20 feet deep with unassorted rock waste. The rocks, chiefly Pierre shales, are steeply upturned, being affected by the mountain uplift. They have been smoothly planed off, not to a flat but to an inclined surface. The débris covering may have a fairly uniform thickness of 20 feet on the highest benches. Generally speaking, the thickness is less in proportion as the mesa surface is lower. This thoroughly unassorted débris comprises fragments of all sizes from sand grains to bowlders more than 10 feet in diameter. The heaviest bowlders are close to the foothills, but fragments a foot or more in diameter are found some miles to the east. On the highest mesas these fragments are almost exclusively from the red rock. The lower benches contain varying proportions of crystalline rock mixed with the débris of red sandstone. The bowlders of the present flood plains are almost exclusively from the crystalline rocks.

ORIGIN.

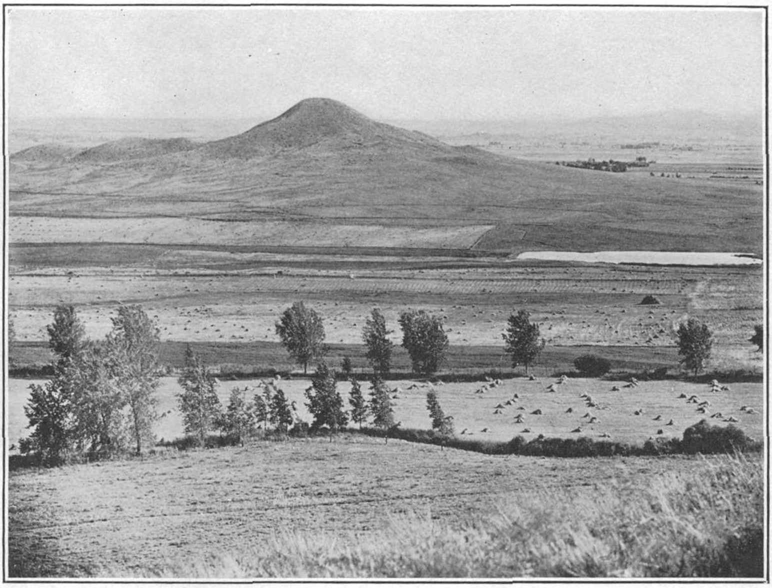
Some similar mesas farther south have been described as river terraces; others have been ascribed to the cutting of lake shores.[a] It is believed that the mesas in the area here described are remnants of stream terraces,[b] and that the underlying rocks were planed off by the streams that deposited the unassorted débris, just as the present streams are eroding the shales and depositing unassorted material on the new surfaces—that is, on the present flood plains. This conclusion is based on the following facts: (1) The resemblance of the eastward slope of the mesas to the stream profile; (2) the northward or southward inclination of the mesa tops; (3) the variations in the heights of the mesas, the lower in general being nearer the larger streams; (4) the general resemblance of the escarpments to old river bluffs, the higher and lower mesas having the same relationship as higher and lower terraces, except that the mesa remnants are often widely separated by erosion. It is not to be

[a] Emmons, S. F., Geology of the Denver basin: Mon. U. S. Geol. Survey, vol. 27, 1896, p. 9.

[b] Compare Lee, W. T., The origin of the débris-covered mesas of Boulder, Colo.: Jour. Geol., vol. 8, p. 504.



A. LONGITUDINAL VALLEY IN THE FOOTHILLS NORTH OF BOULDER.



B. HAYSTACK MOUNTAIN.

View southward from Table Mesa.

understood that all the mesas are the terraces of existing streams. The general decrease in height as the larger streams are approached might suggest such a relation, but this conclusion is not intended. In the discussion of drainage the location of several former streams concerned in mesa making is indicated.

The hypothesis that these mesas are stream terraces is strengthened by the objections to the hypothesis that they are lake terraces. On the latter assumption, there existed over the adjacent parts of the Great Plains a water body of large but unknown dimensions. The western shore of this lake lay, at first, a few miles east of the present foothill belt. The rocks of this shore were the upturned shales and soft sandstones of the higher Cretaceous series; the original offshore slope was relatively abrupt. Cliff cutting then caused the shore to recede to the present foothill belt. There was left a broad wave-cut terrace, of which the present mesas are remnants, and this marginal terrace was covered with the sheet of débris which now appears as the mesa covering. The facts not readily accounted for on this hypothesis are the following: (1) The absolutely unassorted nature and the frequent angularity of the débris; (2) the entire absence of the outer detrital or built portion of what must in all probability have been a cut-and-built terrace; (3) the difference in the height of terrace remnants abutting against the foothills; (4) the lateral (north or south) slope of the mesas; (5) the dominance of red-rock fragments on the higher mesas and of crystalline rock on the lower terraces, and (6) the lack of well-attested lacustrine deposits over the adjacent plains.[a]

In regard to (1) the fact that the débris is angular and is not assorted, it may be stated that detritus on marginal lake terraces is always assorted, while the thoroughly heterogeneous nature of the mesa gravels agrees to a nicety with that of the deposits of many overloaded streams in arid regions where the small streams are subject to quick alternations of flood and drought. With reference to (2) the absence of the built portion of a cut-and-built terrace, it may be noted that the mesas abut against the mountain front in a kind of embayment, and that a wave-cut terrace in such a situation might be expected to show a lakeward extension of detrital material. The absence of such materials is not believed to be adequately accounted for by subsequent erosion. In fact, a mesa composed entirely of such loose and porous materials as the present surface deposit would, in such a climate as this, be extremely unfavorable to the development of surface streams on account of the ready percola-

[a] Compare Johnson, W. D., The High Plains and their utilization: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 4, 1901, p. 653.

tion of surface waters, and would therefore endure longer than a terrace of shales thinly covered by gravels. The significance of (5) the dominance of red-rock fragments on the higher mesas and of crystalline rock on the lower terraces is probably due to the fact that the streams were cutting through red rock when they were at the level of the highest mesas, but as they eroded deeper channels and flowed at lower levels they cut into and carried crystalline rocks. This is further discussed under the heading "Former westward extension of strata." The other objections enumerated above require no discussion.

Wherever the Hygiene sandstone is found it has been planed down to the level of the higher terraces. Upon their surfaces it does not appear, its edge being covered by the mesa gravels. North of Fourmile Canyon, however, wherever the higher terraces have been eroded away the Hygiene sandstone forms a bold ridge whose even crest has the same height as one of the widest terraces. When the sandstone was planed off to its present height this terrace was continuous across the present lowlands.

FORMER WESTWARD EXTENSION OF STRATA.

Whatever streams may have built up any terrace, it is manifest that the oldest mesas are the highest and that the age decreases with diminishing height. Furthermore, the proportion of fragments of red rock to those of crystalline rock decreases as the terraces become lower or as the present flood plains are approached. From these facts it is fair to infer that when the streams were running at the level of the highest mesas they were cutting through red rock for some distance west of the present foothill belt. As a result of the headward elongation of the valleys and of down cutting through the stratified rocks to the granite, the streams carried increasing proportions of crystalline rock, until at present the red rock forms a very small part of the load and hence of the flood-plain débris. As there are no outliers of the red rock on the crystalline area to the west, it is impossible to make any but the roughest estimate of the width of the belt from which the stratified rocks have been denuded.

DRAINAGE.

The district is drained by eastward-flowing streams, which are consequent upon the tilted surface, and is crossed by the two largest creeks—Lefthand and Boulder. South Boulder Creek, of about the same size, unites with Boulder Creek within the area. Most of the intermediate smaller streams coming from the foothills join these larger creeks within the area mapped.

ADJUSTMENT TO STRUCTURE.

In the almost uniformly strong crystalline rocks to the west all the streams are cutting gorges. There is no progressive adjustment except that which comes from the more rapid widening of the larger valleys at the expense of the smaller. In the almost uniformly weak rocks of the plains all the streams have flood plains, though meandering is but little developed. Here also progressive adjustment to structure is not prominent.

Within the foothill belt the streams from the mountains cross alternately strong and weak strata. Here tributaries are developed in the longitudinal valleys, and at some places adjustment has resulted in stream capture. Across the outcrop of the Dakota and the Fountain the streams flow in steep gorges and corrade their channels with difficulty, while their tributaries in the longitudinal valleys erode the softer strata with ease. As a result, stream capture has taken place, and in the Fountain and Dakota ridges the abandoned channels now appear as small notches analogous to the wind gaps of the Appalachians.

EXAMPLES OF STREAM CAPTURE.

In the Dakota hogback a notch representing a former stream channel appears just north of Bear Canyon. The stream flowing south of east from Green Mountain, and now tributary to the stream in Pole Canyon, lies in a direct line with this notch, and doubtless once crossed the Dakota at this place. At the same time a stream one-third of a mile farther north crossed the Dakota where the ridge was not only much lower and narrower, but was broken by the Pole Canyon transverse fault. In this gap the northern stream lowered its channel rapidly and a vigorous tributary from the south developed on the weak beds west of the Dakota ridge. The development of this tributary gorge was further favored by the eastward slipping of the Dakota ledges. (See p. 48.) The tributary gorge elongated headward until it captured the headwaters of the southern stream and caused its lower course to be abandoned. After this capture and sudden acquisition of more water the valley west of the Dakota ridge was rapidly cut down, and as the support of the steep slope on the west side of the hogback was removed landslipping occurred. (See p. 51.) A similar notch cuts the Dakota hogback 2 miles farther south and a large one occurs north of Fourmile Gulch. West of the place where Twomile Gulch breaks through the Dakota the ridge of red rock is indented by a notch whose history is similar to that of the notch near Bear Canyon.

The largest stream affected by capture is Lefthand Creek, which approaches the foothills from the west in sec. 26, 6 miles north of Boulder. When this creek reaches the middle of the belt of red rock it turns at right angles and flows north for 1½ miles; it again turns east at Altona, crosses the remaining foothill outcrops, and emerges upon the plains. Almost directly east of its last bend to the north is a sag of more than 100 feet in the Dakota ridge to the east. The drainage channel leading east from this sag, though occupied by a very small stream, pursues an independent course for many miles. It is locally known as Dry Creek, a name applied also to another small stream 5 miles farther south. Along the northern Dry Creek are evidences of a former larger stream—the lower course of Lefthand Creek—which once crossed the foothills in a direct easterly course. Another stream (the present Lefthand Creek) that crossed the foothills at Altona had a course more favorable to down cutting and was able to develop a tributary on its south side, whose headwaters worked far enough south to tap the former Lefthand Creek. The old valley for a short distance east of the "elbow of capture" is now occupied by a small westward-flowing stream which joins Lefthand Creek where it turns to the north.

This recent shifting of the position of Lefthand Creek explains the otherwise anomalous circumstance that Haystack Mountain (Pl. IV, *B*), the highest mesa remnant in the region, lies close to one of the largest streams, which, as already pointed out (p. 14), are near the lowest mesas. The anomalous position of Haystack Mountain is due to the fact that previous to the capture described this mesa was well removed from lines of active erosion.

The terraces to the east offer further interesting evidence concerning the former character of the streams. These terraces are planation surfaces due to meandering and are not base-levels. Some of them are miles in width, indicating that the streams which made them must either have worked a very long time at the same level or have been of considerable size. Knowledge of either one of these conditions, therefore, sheds light upon the other.

As an illustration of the above, much of the surface between Table Mesa and the high mesa 4 miles north of Boulder Creek, a stretch of 3 miles, is at one level, about 150 feet below Table Mesa. The bottoms of the present valleys are from 50 to 75 feet below this lower terrace. Where this terrace has been eroded away by the present streams the strong Hygiene sandstone stands out as an even-topped ridge, rising to the exact height of this lower terrace. Where the lower terrace has not been eroded the Hygiene sandstone does not appear, having been planed off by meandering streams and covered with the coarse gravel that mantles the mesas and terraces. Small streams now cross the Hygiene sandstone in narrow gorges. All flood plains and low terraces of present streams are narrow in comparison with the broad surface of planation, which has the same height as the top of the sandstone ridge. If the present small streams planed off the broad surface 150 feet below that of Table Mesa, they must have worked longer at one level than would be consistent with the present rate of down cutting.

On the other hand, it is noteworthy that this broad planation surface lies along the course followed by Lefthand Creek before the stream had been shifted northward by the capture described above. This stream was approximately as large as Boulder Creek, and its planation surface is as broad as that of the latter. The supposition that the present small streams meandered at one level long enough to make such a broad planation surface would involve conditions of level or of climate which are not supported by the other evidence.

NATURAL LAKE BASINS.

Scattered over the plains is a considerable number of ponds, some of which have an area of 100 or 200 acres. All of these are used for storage of irrigation waters, and have had their capacities materially enlarged by dams. Some are due entirely to the damming of valleys or "draws," but others are natural basins. Marshall Lake and Boulder (Weisenhorns) Lake are good examples of the latter type. These natural basins are not confined to the surficial sheet of rough gravel, but are often deep in the shales. They originated later than the mesas or terraces which surround them. Some of the small ones might have originated by small landslips or creep, resulting in the damming of small valleys, but most of them can not be thus explained. Boulder Lake has a nearly flat bottom at a depth of approximately 20 feet. The fraction of this depth due to damming, either natural or artificial, is insignificant.

STRATIGRAPHY.

The classification and nomenclature of formations used by Emmons and Eldridge for the Denver basin [a] is in the main followed in this paper. For the area here concerned the succession is as follows:

Quaternary	Alluvium and terrace gravels.
Cretaceous	Laramie. Fox Hills. Pierre. Niobrara. Benton. Dakota.
Jurassic	Morrison.
Triassic (?) [b]	Lykins. Lyons. Fountain.
Algonkian	Quartzite of South Boulder Canyon.
Archean	Granites, etc.

ARCHEAN SYSTEM.

The sedimentary rocks of this district rest upon a basement of granite, granite-porphyry, and granite-gneiss, which are at some places gray, but more commonly range from flesh color to red. This basement is cut by frequent dikes; several prominent ones have a north-northwest direction, others trend south of east. These dikes are commonly composed of pegmatite, but there are also several of a light-greenish felsitic porphyry, similar to those which intrude the sedimentaries of the foothills.

The contact of this Archean foundation with the overlying sedimentaries is not a plane, but, in this district at least, the undula-

[a] Mon. U. S. Geol. Survey, vol. 27, 1896.

[b] The writer is indebted to Mr. George H. Eldridge, one of the authors of the monograph on the Denver basin, for the following note on the group heretofore called Wyoming and tentatively regarded as Triassic:

"Mr. N. H. Darton, of the United States Geological Survey, has had, since the publication of the Denver monograph, especial opportunity to study the sedimentary formations from the Black Hills in South Dakota to the southern portion of the frontal ranges of the Rocky Mountains in New Mexico, and is of the opinion, from evidence accumulated by him, that the "Red Beds" [Fountain] and their overlying "Creamy Sandstone" [Lyons], designated the Lower Wyoming in Monograph 27 of the United States Geological Survey, are Pennsylvanian in age, and that the series known as Upper Wyoming [Lykins] in that monograph is possibly Permian in the lower part and Triassic in the upper.

"The evidence leading to such an inference consists of the presence in the Red Beds, at one or more localities, of limestones containing Pennsylvanian fossils and of the presence of Permian fossils in the Black Hills in what he there correlates with the lower portion of the Upper Wyoming, in the Denver foothill region—that is, with the portion here consisting of the pink shales, fine sandstones, and curly limestones. The higher members of the Upper Wyoming may still be considered Triassic in the absence of evidence to the contrary."

tions are very broad and gentle. The question whether this surface is due to subaerial or to marine deundation is discussed under the heading "Geologic history" (pp. 54–57).

SEDIMENTARY ROCKS.

ALGONKIAN SYSTEM.

QUARTZITE OF SOUTH BOULDER CANYON.

The oldest and lowest sedimentary rock is a quartzite which appears only at the extreme southern end of the area, in South Boulder Canyon. It is regarded as of pre-Cambrian age.[a] It is for the most part white, or stained pink with iron oxide; of medium texture, except at what seems to be the base, where it is a pebble conglomerate. One mile south of the southwest corner of the area mapped the beds are almost vertical and are cut across by the newly constructed grade of the Denver and Northwestern Railroad. The stratum is here 550 feet thick.

This formation does not rest upon the Archean surface at the same angle as the remaining strata. From a point at the base of the Fountain sandstone, which in general rests upon the granite, the quartzite strikes southwest, then for a space nearly west, and then S. 27° W. to far beyond the limits of the area mapped. It dips throughout to the southeast at angles ranging from 60° to 90°. Both north and south of it the same granite complex underlies the Fountain. In its relations to the higher stratified rocks the quartzite is only a part of the complex, on whose nearly plane surface the Fountain is laid down.

The structural relation of this single, steeply upturned stratum, outcropping in a narrow belt for many miles between inclosing granites, is not clear from observations made within this area. So small a part of its entire outcrop is included in this area that the attempt to decide its structural relations will not be made here. Marvine, in his description of the Front Range,[b] regards the granite as a mass of metamorphosed sedimentaries. According to this supposition, the quartzite is merely one of many metamorphosed strata, this one showing plainly its sandstone origin, while its neighbors have become entirely structureless. Van Hise, who has studied the contacts in South Boulder Canyon, believes that the phenomena of contact are those of a sedimentary formation laid down on a granite and gneiss floor.[c] He also thinks it probable that the

[a] Van Hise, C. R., Correlation papers, Archean and Algonkian: Bull. U. S. Geol. Survey No. 86, p. 325.

[b] Seventh Ann. Rept. U. S. Geol. and Geog. Surv. Terr., pp. 83–192.

[c] Van Hise, C. R., Manuscript notes to be used in a revision of pre-Cambrian rocks of North America (Bull. U. S. Geol. Survey No. 86).

quartzite has been folded in, and that the structure is that of an isoclinal syncline.

TRIASSIC (?) SYSTEM.

The rocks in this region, hitherto regarded as of Triassic age and called "Wyoming," embrace three formations—the Fountain, the Lyons, and the Lykins. The term "Red Beds" is popularly used without definite limitations; but the authors of the monograph on the Denver basin have conveniently limited the use of this term to the lowest and largest member of the series. The popular use of the term "red rock" is similarly restricted.

The subdivision into "Lower" and "Upper" Wyoming, adopted for the Denver basin, would also be appropriate to the Boulder area. The lower division, however, clearly embraces two lithological units which it is desired to distinguish in this report. The lower and major part consists chiefly of rather coarse, arkose sandstones and conglomerates of reddish color, while the upper and lesser part is a finer-grained, quartzose sandstone of white, "creamy," or light-reddish color. The coarse red sandstones were called the Fountain formation by Cross in the Pikes Peak folio, a type section being crossed by Fountain Creek, near Manitou. The summit of the Fountain formation is not exposed in the Pikes Peak quadrangle, but Darton[a] has found the character of the Fountain, as described by Cross, to continue to a white sandstone corresponding with the "creamy sandstone" of Eldridge, occurring in the Garden of the Gods, to which the name Lyons sandstone is here given.

FOUNTAIN SANDSTONE.

Lithologic character.—In general the Fountain sandstone is a rough arkose, the individual feldspars often appearing in large crystals. Locally it passes on the one hand into conglomerate and on the other into quartzose sandstone, excellent for building purposes, and even into shale. Micas are frequent, especially in the finer portions.[b] The conglomerate phase may have pebbles of granite and schist or of pure quartz only. The conglomerate of fragments of crystalline rocks is found only at the base, and there not universally. At places it is a beautiful recomposed granite, which at casual glance is not different from a coarse, reddish-brown original granite. Quartz-pebble conglomerate may be found at any or all horizons.

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[a] Bull. Geol. Soc. Am., vol. 15, p. 22.

[b] Prof. R. D. George, of the University of Colorado, has examined many specimens and finds that in large part, at least, this mica may be secondary and may have been derived from the feldspar.

The cement of the mass is silica with an admixture of iron oxides; hence the quartzose beds weather with extreme slowness. Their fragments survive unchanged in the rubble of the mesas, where those of the crystalline rocks can be crushed in the hand.

The color of this rock in its coarser phases is due in part to its pink or red fragments of feldspar. In a large way this is more true of the lower horizons than of the upper, but the same factor is present in nearly all beds to a greater or less degree. In the cement, between the grains, crystals, and fragments, however, red iron oxide also appears, and in a general way affects the coloring in proportion to the fineness of the grain. Where quartz is more abundant the rock sometimes has a lighter color, which locally in loosely aggregated masses may even approach whiteness. Where this is the case it is composed almost entirely of large angular quartz grains that appear to have been assorted out of disintegrated granite, with almost no rounding by wear.

Occasional mottling in freakish forms is apparently caused by leaching of iron oxide by percolating waters. Where the differences in shade are attended by differences in texture, the darker colors occur in the denser portions where the water circulation has been least. In so far as the differential coloring is due to the action of percolating waters, doubtless a concentration of coloring matter in the denser portions has accompanied its leaching from the coarser.

Structure.—The Fountain sandstone is characterized by very thick beds throughout, and cross-bedding may be found at any horizon; at places there is a beautiful flow-and-plunge structure. It is very common to find pebble beds a few inches thick alternating with the finer sediments. Shale is found in distinct streaks or pockets. The thickness of these " Red Beds " is 500 to 600 feet at Boulder Canyon, where they are vertical, and increases both to the north and to the south, approximating 1,500 feet at Fourmile Canyon, where they dip eastward at an angle of 47°. No fossils have been found.

LYONS SANDSTONE.

Character and coloring.—Above these massive beds and more or less arkose sandstones are other beds of purely quartzose sandstone. This upper formation is best developed at Lyons, a few miles north of the area mapped. It is quarried there in large amounts. The formation is named from that locality. The siliceous cement of this sandstone has sufficient iron to produce shades of pink, but the popular name, "creamy sandstones," conveys a wrong impression as to their color. While these beds have a fairly uniform shade they are locally almost white, and at some places red. Where these extremes occur, as at Fourmile Canyon, leaching and concentration of the coloring matter have often produced gaily colored rings and bands.

An extreme phase of this feature is seen in the small red nodules which may even be found loose in their sockets in certain layers[a] and which may involve other causes in addition to those which make simple concretions. Many dendrite figures are found, some of marvelous beauty. They are sometimes obtained in thin flagstones, approximately 2 feet square, the entire side of such a slab being occupied by one symmetrical fern-like figure of exquisite delicacy. No fossils are found.

Cross-bedding.—The long washing and complete assortment which these sands underwent on the shore of the early sea was attended by cross-bedding of unusual dimensions and perfection. The angle of cross-bedding is occasionally as great as 35°. At nearly all of the many quarries opened in this stratum, flags or blocks are taken out along cross-bedding planes. This is not universally true outside the area represented by the map. At some of the Lyons quarries a part of the stone has been taken out along the true bedding, but this is not the rule.

The most striking feature of this cross-bedding, next to its universality and perfection, is its dip. With few exceptions this is at a lower angle than that of the true bedding. If, therefore, the strata were again horizontal the oblique lamination would dip toward the mountains; that is to say, toward the shore that existed at the time the beds were deposited. The significance of this is discussed under the heading "Geologic history."

This cross-bedded stratum reaches a maximum thickness of 297 feet at Fourmile Canyon, and is absent just south of Boulder Creek. It passes by gradations into the Fountain, or "Red Beds," below.

LYKINS FORMATION.

Character and thickness.—Lying conformably upon the rocks just described, which are prevailingly sandstones and strong ridge makers, is a series of sandstones and sandy shales, with a little limestone. This series is the Lykins. The name is taken from Lykins Gulch, at the north end of the area mapped, the scenery along which owes its strange and beautiful character to this formation. It is clearly distinguished from the lower formations by its softness and by its showy colors, the most striking of which is a rich brick red that characterizes its sandy shales and shaly sands. At places the color is more brownish, but it is always deep and rich, and the long foothill valley, always present upon these soft rocks (fig. 1, p. 12; also Pl. IV, *A*, p. 14), is at places brilliantly colored.

The entire series is nowhere shown in a single section because it

[a] Eldridge (Monograph XXVII, p. 54) limits those at Golden to a horizon about 20 feet below the summit.

is easily weathered and consequently thickly covered by waste. At Fourmile Canyon, where the formation is somewhat more than 800 feet thick, the lowest 230 feet are largely, if not wholly, sandstones of a clear red, a little darker than brick. These are overlain by the "crinkled" sandstone (see below), which is here 35 feet thick. Above this for 467 feet there are no exposures, but the soil is very red, and exposures not far distant indicate that most of this thickness is occupied by red arenaceous shales. Above these obscured beds are 100 feet more of the familiar red sandstone. Apparently any horizon of this formation may be slightly calcareous, but this is not general.

The section is essentially the same wherever seen, but the thickness varies greatly. The series is apparently absent just north of Gregory Canyon. If present at all it must have a thickness of only a few feet and is concealed beneath the sheet of waste which obscures almost all the strata between the Fountain and the Niobrara.

As indicated above, for a considerable portion of the column the nature of the rocks is for the most part concealed. At and beyond the north end of the area mapped there are certain slopes on which nearly the entire formation is exposed. Here it does not greatly exceed 300 feet, and, except for the "crinkled" sandstone, the whole exposure is of argillaceous sandstone, brick red in the main, but more brownish near the top. To this, however, must be added at the summit about 20 feet of light-pink or dull-yellowish, thin-bedded sandstone, slightly calcareous. This forms a kind of transition to the well-marked massive gray sandstone, which clearly belongs to the Jurassic.

Eldridge has described the Lykins under the name "Upper Wyoming" at localities farther south, where it contains "clayey strata of bright colors—gray, yellow, green, pink, and lilac."[a] Throughout much of this area there are some hundreds of feet out of the total width of the Lykins belt where beds of such colors could easily be concealed. However, with the exceptions already noted, it is doubtful if anything but ocherous reds reach the north end of the area mapped.

The brownish-red sandstone at or near the top of the series (the dull-yellow, thin-bedded sandstone noted above does not appear everywhere) has a variable thickness. It is more than 100 feet thick at Fourmile Canyon. While primarily a massive sandstone, its exposed ledges weather into shingle-like combs.

"Crinkled" sandstone.—The persistent band which is here referred to as the "crinkled" sandstone is one of the noticeable features of the series. At places it reveals the presence of the Lykins

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[a] Op. cit., p. 56.

where all other beds are covered by the abundant talus of the red rock and Lyons sandstone. This band, nowhere above 35 feet thick, is present wherever the Lykins is found. Its superior hardness causes frequent exposures where the ocherous sandstones above and below it are buried under waste. Such a line of exposures is everywhere found at a nearly uniform distance east of the Lyons sandstone outcrop. It is in the main a sandstone more or less calcareous. Locally it has a bed of dense limestone at its base and sometimes other limestone beds above. Some of these have been quarried for lime. It is of a light-pink or purplish color, clearly and minutely laminated. These laminæ are almost universally deformed, are closely crumpled, and serve to make prominent the effects of a north-south stress which has at places minutely brecciated the rock. The evidences of such a stress are all but lost in the softer massive rocks which are conformable with this layer above and below.

JURASSIC SYSTEM.

MORRISON FORMATION.

Limits.—At the top of the brownish sandstone above mentioned there is an abrupt change to light colors, or at most there may be about 20 feet of beds of intermediate character. The sudden transition is readily seen at many places and is the convenient indication of the division between the Lykins formation and the Morrison, as the overlying Jurassic beds are called. The upper limit of the Morrison is quite as clearly marked by the hard sandstones and conglomerates of the Dakota, but the body of the formation shows considerable variation from place to place. Its maximum thickness may be taken at a little less than 400 feet (as at Bear and Fourmile canyons).

Generalized section.—Sections of the Morrison at various places in this area differ greatly. In the main, however, the formation contains a large proportion of light-colored clays, some moderately indurated and others of flinty hardness, much gray sandstone, often calcareous, and at various horizons beds of highly compact limestone. A very much generalized section would present the beds in about the following order, beginning at the base: Sandstone, clays, limestone, clays. The first and last members of the series are persistent, but the intervening clays and limestone may show two or three alternations and may inclose prominent sandstones.

The thickness of the important sandstone at the base is nowhere less than 10 feet, and may be twice that amount. This bed is persistent and massive, and yields the white building stone commonly known as the "Doctor Bond sandstone." It is slightly calcareous, as are the Morrison sandstones in general. In Bear Canyon it forms the western one of two strong ridges. This sandstone is everywhere overlain by soft beds which are covered by waste.

The lowest limestone is at places within 15 feet of this basal sandstone. At South Boulder Canyon there are 40 feet of it in one stratum, but at Bear Canyon it is separated into two strata by a massive sandstone. Near Altona there are three distinct limestones, the topmost being a resistant stratum 30 feet thick which may form the crest of the ridge where the Dakota ledge is locally lower. This is the case for a considerable stretch between Fourmile and Sixmile canyons. These limestones are exceedingly compact, and turn brown upon the slightest weathering, though they are normally a dark bluish gray. As the beds are much fractured or affected with incipient fractures, the brown color is so general, even in fragments broken by the hammer, that the normal gray may easily be overlooked. The sandstones above the basal bed are (1) the resistant beds between the limestones and (2) the Saurian sandstone described by Eldridge for the Denver basin.[a]

South of Boulder the intermediate sandstone beds are represented by the eastern one of the two ridges in Bear Canyon. The rock of this ridge differs little from the basal stratum. North of Boulder these beds, whether one or two, have a characteristic purplish hue, an irregular, often closely laminated bedding, a flow-and-plunge structure at places, and a wavy or scaly appearance where split along bedding planes. Where the sandstone shows this phase it may be very hard. Occasionally the crest line of the bold Dakota hogback jogs to the west and follows one of these strong ledges of the Morrison. This occurs at several places south of Altona.

The next 75 or 100 feet are everywhere obscured in this district. The space is doubtless occupied by the "Atlantosaurus clays" described by Eldridge, but their character can only be inferred from exposures farther south beyond this field. Above these softer beds, which do not outcrop, are limestones generally interbedded with clays.

The horizon above the zone of intermittent limestones is marked by a rather persistent sandstone. It is generally calcareous and stained with iron, the coloring usually taking the form of round dots, in general about the size of shot. When so marked it strongly resembles certain strata of the Dakota, but is distinguished from the latter by the fact that it effervesces with acid. The stain is not always distributed in this way, but may give an irregular rusty color to the whole rock. This is the "Saurian sandstone" described by Eldridge, but no animal remains have been found in this field. Its greatest measured thickness here is less than 15 feet.

[a] Eldridge, G. H., Geology of the Denver basin: Mon. U. S. Geol. Survey, vol. 27, 1896, p. 61.

The remaining rocks at the top of the Morrison are dense, hard clays and argillaceous sandstones. They are green, yellow, and purple, and occur in beds that are from a few inches to a few feet thick. The fine-grained indurated rocks are full of fractures and tend to crumble into minute angular fragments. Some beds are calcareous. The thickness of these clays is about 30 feet at South Boulder Canyon and nearly three times that amount at Fourmile. They are well exposed on the south side of Bear Canyon, where they are 75 feet thick.

CRETACEOUS SYSTEM.

DAKOTA FORMATION.

Above the Jurassic comes the prominent Dakota formation, easily recognized and well known in the great hogback which parallels the Front Range for hundreds of miles. It is a firm sandstone that is often quartzitic, is generally thick bedded, and is characterized by frequent cross-bedding and ripple marks. Its more resistant, heavy beds may give to the hogback one, two, or even three constituent ridges or combs.

Basal conglomerate.—At is base, though not everywhere present, is a pebble conglomerate. The constituent pebbles include "abundant limestones, quartzites, clays, flints, jaspers, and rocks of granitic composition, together with the separate mineral constituents of the last."[a] The whole is so firmly cemented that, where unweathered, the rock fractures in broad planes which pass through the pebbles. Frequently a series of thin pebble beds in a mass of sandstone takes the place of the continuous conglomerate. This alternation of beds makes the thickness of the basal zone indefinite, but there are few pebble beds above the first 20 or 30 feet.

Character of the sandstone.—Considerable variation may be discerned in the sandstone, but with the exception of the basal conglomerate no one bed has a constant position in the column. Generally the sandstone is composed of quartz grains, with a siliceous cement, and is gray or yellowish gray. With increase of iron oxide the sandstone exhibits striking features of differential coloring. The most common of these is due to the concentration of the iron into evenly distributed spherical specks, which are of uniform size in a particular bed, but which are as small as small shot in some beds and as large as peas in others. The color of these specks is light brown, but in a weathered crust of such a rock it is often bright red, due, no doubt, to the loss of water from the iron oxide. This dotted coloring is exceedingly common, perhaps more so in the upper portion than in the lower. Frequently, also, the weathered surface of a Dakota

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[a] Eldridge, op. cit., p. 63.

block or ledge is blackened by a smooth or even shining crust of manganese and iron oxide.

At intervals between the stronger ridge-making ledges occur layers of thinly laminated shaly sands, aggregating in thickness only a few feet. These crumble out in small angular fragments and their wasting accentuates the relief of the strong ledges. Fire clay is not found in this area. Fragments or impressions of wood are not infrequent, but good fossils were not observed.

Columnar jointing.—Some of the upper beds have a distinct columnar jointing. At Sixmile Canyon certain thin ledges when viewed from a short distance look like sheets of basalt. The bedding faces of these same strata are exposed and resemble a rough pavement of polygonal blocks. This jointing produces irregular columns from 2 to 8 inches in diameter. These beds are not to be confused with the igneous rocks, which are intruded.

The line between the Dakota and the overlying Benton shales, while very distinct in a large way, is not so easily located in detail. Alternations of sandstone and shale occur over a zone of 50 feet or more. The thickness of the Dakota at Bear Canyon is about 320 feet, and at Fourmile Canyon a little greater.

BENTON FORMATION.

Shales and limestone.—The Benton shales have a thickness of more than 500 feet at the north end of the field. They are somewhat thinner at the south end and taper uniformly from both ends toward Boulder Creek, where the formation almost disappears. The great body of the shale is dark. There are frequent layers a few inches thick which are strongly impregnated with iron. The formation is calcareous in varying degree. At many places some beds are composed of a black limestone showing a crystalline surface when broken and having a strong bituminous odor. Six miles north of Boulder several hundred feet of the upper strata have this nature. Elsewhere this phenomenon seems to be confined to isolated beds.

Upper beds and Niobrara contact.—As the summit is approached the blackness disappears and the last 75 feet (observed near the north end of the field) show light-colored limestone, shale, and sandstone. North of Sixmile Canyon these beds, which may be regarded as transitional to the Niobrara, show the following section:

Section of upper part of Benton formation north of Sixmile Canyon.

	Feet.
Greenish sandstone, calcareous in upper third	15
Shales, blue to yellow, noncalcareous	15
Sandstone, noncalcareous, firm, rather purplish	10
Shale, iron stained at intervals	10
Shale, calcareous (or calcareous at top).	

Below these beds is a limestone of variable thickness strongly resembling the basal Niobrara. It occurs in lenses only.

The greenish sandstone at the top is found below the basal Niobrara wherever the latter is exposed in this district. It is generally 10 or 15 feet thick, and is not calcareous except in the upper portion. As it is often very much fractured and the cracks are abundantly filled with carbonate of lime, this calcareous character may be due to infiltration from the limestone above. The blue and yellow shales below are also seen wherever the base of the greenish sandstone is exposed.

NIOBRARA FORMATION.

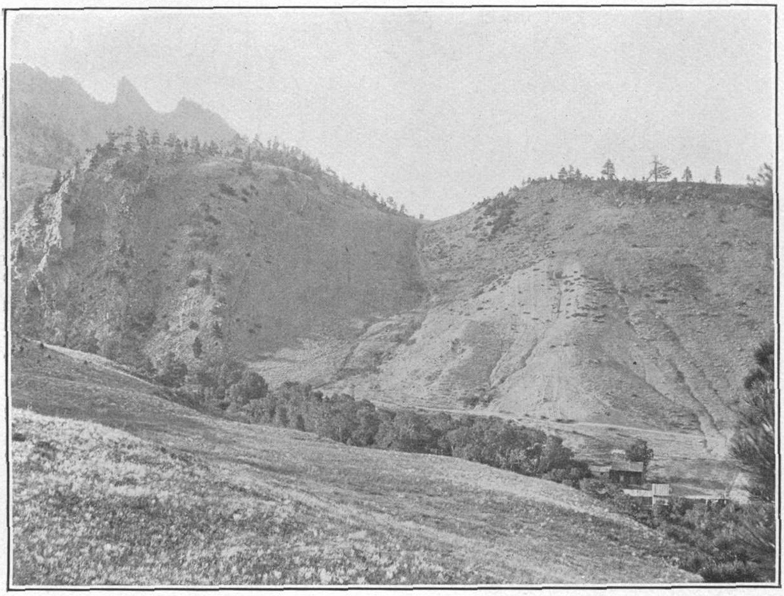
The Benton is succeeded by the Niobrara, whose prominent characteristic is its calcareous nature. It is composed in small part of true limestones, but the greater mass is made up of calcareous shales, while considerable portions are of intermediate character. Its thickness at Fourmile Canyon is a little more than 400 feet.

The basal stratum of compact limestone rests upon the greenish sandstone which is at the top of the Benton. Occasionally a foot or more of light-colored marl intervenes. Below the Niobrara, as pointed out above, are occasional beds of similar limestone and calcareous shales interbedded with noncalcareous sandstones. In lithological character these transitional beds resemble the Benton more than the Niobrara. The faunal relations are not decisive. It is therefore convenient from a field standpoint to adopt the above-named horizon as the dividing line between the Benton and the Niobrara because of the sharp change at this horizon from a sandstone to a compact limestone.

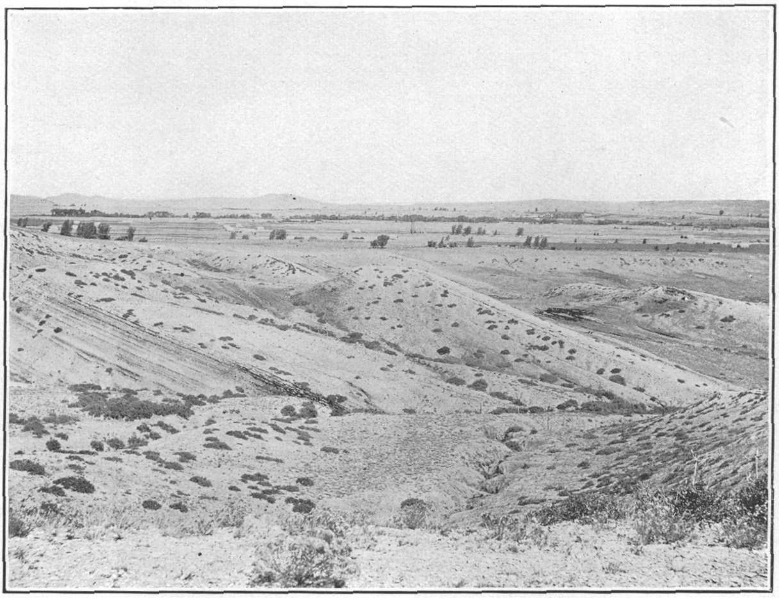
Basal limestone.—This is generally about 15 feet thick, reaching a probable maximum of 20 feet; it is light gray, dolomitic, and very compact; it breaks with a conchoidal fracture. Its individual beds may be 2 or 3 feet thick and are sometimes separated by thin layers of clay. The bedding is irregular and a 3-foot bed has been seen to pinch out within 10 feet. It abounds in shells of *Inoceramus* and has also some dendritic markings. On its upper side it passes into the calcareous shales through an alternation of thinner limestone and shale beds. These thinner limestone beds are characteristically jointed into small blocks whose edges are rounded, and when exposed in the quarry the bed has the appearance of a pavement.

The basal limestone has been frequently overturned (see p. 50) and has been much crushed by lateral stress. In outcrops it is by far the most prominent stratum between the Dakota and the Laramie, except where the Hygiene sandstone makes its prominent ridge.

Shales.—Most of the Niobrara shales are dark brown, but their outcropping edges weather light gray, sometimes almost white. The top-



A. VIEW NORTHWARD ACROSS MOUTH OF BEAR CANYON.



B. OUTCROPS OF NIOBRARA SHALES.

most beds, which are 10 or 20 feet thick, are of a much lighter brown, and weathering gives to them a characteristic yellow color. These are highly calcareous, and pass at places into impure limestones, 5 or 6 inches thick. This horizon is frequently marked by a ridge. Generally, too, about midway between base and summit, the dark shales which weather white contain harder and more calcareous beds, whose outcrops make low ridges (Pl. V, *B*). Locally these also are impure limestones. In this zone are beds several inches or even a foot thick composed entirely of *Ostrea congesta* shells. More than one of such zones occur at places. As in the basal limestone, the rock has a strongly bituminous odor when struck, especially where fossils are present.

PIERRE FORMATION.

Color.—Above the Niobrara are the Pierre shales, which are more than 5,000 feet thick. They are slate colored, leaden gray, dark brown, and sometimes nearly black. Weathering gives to them a greenish-drab hue, which, at any considerable distance from the foothills, is their color to a depth of 30 feet, more or less. It is therefore the one ordinarily seen. Near the base of the formation, however, just in front of the hogbacks, erosion is more active and the shales are often seen with their original dark colors.

Limestone beds.—While in general noncalcareous, the Pierre has local limy beds. At places these form continuous strata, as, for example, 4 miles north of Boulder, one-half mile east of the contact with the Niobrara. Here, for a thickness of nearly 40 feet, strong limestone beds are so closely grouped as to give the outcrop the appearance of the basal Niobrara. At other places the limestone beds are smaller and more isolated, or are divided into concretionary masses often containing fossils. Less prominent calcareous masses may be found at any horizon either in beds or in more or less perfect concretions.

Concentrations of iron occur in similar but less massive forms, ranging from clear-cut beds to well-formed nodules. The lime and the iron may or may not occur in the same concretionary mass. Many of the calcareous nodules mentioned contain much iron carbonate, which, in progressive oxidation toward the center, gives rise to sharply marked concentric shells differing in color.

Hygiene sandstone member.—Sandy beds may occur at any place in the section. The most prominent and persistent of these is about one-third way up from the base, or a little higher. Its outcrop is chiefly at the north end of the field, where it forms a considerable ridge, though disappearing under Table Mesa. Where it reappears north of this broad mesa its outcrop again forms a strong ridge, which is almost continuous for many miles. The ridge passes within a mile and a half of the village of Hygiene, where the sandstone is typically developed. The name Hygiene sandstone has therefore been adopted for this member of the Pierre formation. To the public it has become well known on the Culver ranch, 6 miles southwest of Berthoud, where it crosses Little Thompson Creek and where a seepage of oil has long been known. At its outcrop west of Berthoud it has a thickness of several hundred feet. At the north edge of the area described in this report it has a thickness of 250 feet. At Bear Cañyon is an isolated outcrop of an equally prominent sandstone, 150 feet thick, which is probably of Hygiene age.

The Hygiene sandstone is thick bedded and frequently cross-bedded. Much of it is dark greenish gray and gritty. The remainder is light gray. The whole is calcareous where fresh. It loses its lime in weathering, takes a paler-greenish tint, and becomes friable. It frequently contains carbonaceous matter resembling small sticks of wood turned to coal. It also contains fossils of invertebrates, but its fauna is not yet known to be distinctive of this horizon.

Near Boulder the Hygiene sandstone is within less than 1,000 feet of the base of the Pierre and is itself a very thin stratum. It thickens greatly toward the north, as do also the shales which lie below it. Five miles north of Boulder the underlying shales, which are 1,000 feet thick near Boulder, have a thickness of about 2,700 feet. Here also the sandstone begins to separate into two strata by the coming in of a shale parting. In the next 2 miles this intercalated shale becomes 200 or 300 feet thick. In so far as the upper sandstone can be identified north of Table Mesa, the indications are that this intervening stratum goes on thickening to the north, in common with other strata.

From these pure sands at one extreme to pure clay shales at the other, the Pierre shows all gradations in composition. The sandy layers are generally firm and gritty, almost as dark colored as the shales themselves, and not very porous. In rare instances light-colored, friable sands are encountered in drilling oil wells.

The thickness of the sandy beds is as variable as their constitution, while the lateral extent of such beds, as indicated by occasional outcrops and by the records of wells, is, in a large majority of cases, a small fraction of a mile. Some of these beds may be lenses, but doubtless the more common mode of lateral limitation of the sands is by a gradual change in composition of the beds into the shales. Such beds are found at irregular depths. As some of them disappear and others come in, their depths vary greatly from place to place.

The upper division of the Hygiene sandstone is characterized by large calcareous concretions several feet in diameter. Where the outcrop appears as a low ridge or only a stony band, these concretions, crumbling, form isolated rocky patches of angular fragments, frequently showing fossils. The exposures of beds of this description in or near the area described in this report are insufficient for the correlation of their outcrops, or even for the determination of their number. It seems necessary to assume, however, that there is more than one bed, and it is probable that the beds occur at any horizon and are of very limited lateral extent. The upper division of the Hygiene sandstone is here given as a typical case, except that it has far greater continuity than others of its kind. Whatever may be true of these calcareous beds, the sandy beds, except the main stratum described above, are distributed through the column of shales at irregular intervals and are generally of small extent.

FOX HILLS FORMATION.

Within the limits of this area the great body of the Fox Hills is but indefinitely distinguished from the Pierre. In mild contrast with the latter its shales are yellowish instead of slate colored, and are also more arenaceous. This latter quality is plainly shown in the soil produced. At some places the transition zone spoken of by Eldridge[a] as marked by " limestones and small ferruginous nodules " is plainly seen. No attempt has been made to trace on the accompanying map the contact between these two formations, as definite points of contact are infrequent and separation of the areas of the two terranes in a detailed way must in fact rest largely on the character of the soils. This distinction is frequently masked by outwash from the foothills.

The topmost stratum of the Fox Hills is, however, a very definite feature in the stratigraphy. For many feet below it there are occasional sandstone beds, and the intervening shales are highly sandy, but at the top is a continuous bed of sandstone 40 feet thick. It is best exemplified just east of the area mapped, where a fine fault brings it up to view alongside the basal Laramie. The sandstone is here fine grained and yellow, very slightly calcareous, and incloses great calcareous, iron-stained concretions. The entire thickness of the Fox Hills near Niwot is about 1,300 feet.

LARAMIE FORMATION.

The Laramie outcrops in the southeast corner of the area. Within the limits here defined this formation consists essentially of (1) sandstones at the base, (2) sandstones alternating with shales and coal overlying, (3) sandstones above the coal, and (4) clays containing isolated sandstone beds and lignitic streaks.

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[a] Mon. U. S. Geol. Survey, vol. 27, p. 71.

Basal sandstones.—The basal sandstones are exposed at various places in the Marshall coal field, but best of all at White Rocks, on the eastern border of the area mapped. Here the bold sandstone escarpment comprises two distinct and massive beds, whose topographic effect, however, is that of a single stratum continuous with the Fox Hills sandstone beneath. The lower Laramie sandstone is 40 feet thick, equaling the underlying Fox Hills sandstone, while between the two are a few feet of thinly laminated sandstones, varying to a lignitic shale. The second and thicker stratum of Laramie is separated from the first by gray, shaly sands, inclosing 10 inches of lignitic shale and above it 10 inches of coal.

Both Laramie beds are clearly distinguished from the Fox Hills by their gray or white color and coarser grain. They are composed of coarse quartz sand, and in addition always show some black specks of an undetermined mineral. The two sandstones differ in the following respects: The upper is distinctly whiter and, where exposed along bedding planes (and to a less degree on fracture planes), the surface is marked by weathered-out cracks, making polygonal patterns a few feet across. Both strata are weakly cemented and noncalcareous, but contain giant concretions which are very calcareous, hard, and, on weathered surfaces, are stained brown with iron oxide.

Beds associated with the coal.—The 75 feet of thinner-bedded sandstones above, containing some shale and coal, are best seen at Marshall. The shales occur at frequent intervals, and are often lignitic. The one workable coal seam is sometimes at the top of this division, but again is overlain by 5 or 10 feet of shales and thin sands; all, however, lie below the more persistent sandstone referred to under (3) above.[a] Aside from the coal seam, no horizon above the basal sandstones is more definite than the *Ostrea glabra* zone, which occurs 15 or 20 feet from the base of the series.

The sandstone above the coal is not unlike the second massive bed above the bottom. It weathers into the same angular patterns, and has the same appearance in the hand specimen. Its thickness is from 8 to 15 feet. The overlying clays, as shown in this area, are yellow and purple, and have frequent lignitic bands but no coal, at least within the limits of the area covered by the map.

QUATERNARY DEPOSITS.

There are no deposits younger than Laramie except the uncompacted mantle rock. This is the coarse mesa gravel (see p. 14), or finer alluvium, similar to the deposit formed by the present streams.

[a] The sandstone "C" of Eldridge, op. cit., p. 74; also p. 346.

In the eastern part of the area, especially in the northeastern corner, are patches of loam which plainly belong to the western margin of the great sheet which covers the surface a little farther east. This is the "loess" of Hayden and Aughey [a] and of Emmons.[b] Just what relation these patches bear to the "Plains marl" of Hay,[c] or the great silt body of the Plains Tertiary,[d] was not determined on account of the narrowness of the area studied.

The whole surface east of the foothills is, in a large way, a patchwork of stream terraces. The oldest surficial deposits are highest and farthest from the larger streams, and there is a decrease in age from those at the top of Haystack Mountain to the recent alluvium. No other time scale is suggested by the phenomena of this portion of the plains than that based on relative altitude and distance from streams. In large part, at least, these deposits are of Pleistocene age, though the time of their beginning is not definitely fixed.

IGNEOUS ROCKS.

The igneous rocks are of interest chiefly with reference to their manner of occurrence and relations to the deformation of the sedimentaries, rather than to their character. Constituent minerals and rock textures are therefore given very brief and summary mention.

ROCKS OF THE ARCHEAN AREA.

The Archean rocks are in general granite and granite-gneiss. The texture is generally coarse and the color very frequently pink on account of the pink orthoclase contained. These rocks are cut by numerous dikes, which are of all sizes up to a maximum of many miles in length and 50 or more feet wide. Their texture is as varied as the dimensions of the dikes. In direction the larger dikes show a tendency to approximate parallelism with the foothill outcrops—that is, with the axis of the foothill monocline. They would, however, if prolonged to the south, meet the foothill belt at a small angle. Their most prominent direction, therefore, is more nearly that of the axes of the échelon folds which branch out from the foothills. This comparison of the general directions of two sets of features of different age is used as a mere convenience in description; it is not intended to affirm a genetic relation.

One of these dikes passes through Orodell, 2 miles west of Boulder. It passes up the valley of Fourmile Creek for a mile north of that

[a] Eighth Ann. Rept. U. S. Geol. and Geog. Surv. Terr., 1874, pp. 245–255.

[b] Mon. U. S. Geol. Survey, vol. 27, 1896, p. 261.

[c] Water resources of a portion of the Great Plains; Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1895, p. 570.

[d] Johnson, W. D., The High Plains and their utilization: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 4, 1901, p. 653.

point and goes far to the north-northwest. Its southern end is somewhat interrupted, but its general course is in line with that of the Green Mountain fault (p. 46). The "Hoosier dike," of the same kind, lying 2 miles farther west, is even larger and more continuous.

INTRUSIVES OF THE FOOTHILLS.

In the sedimentaries the intrusion is commonly in the form of sheets. There are also series of apparently disconnected bosses, but these are ranged in lines following the strike of the strata, three or four appearing at about the same horizon within a mile.

There are here no intrusives in the foothills south of Gregory Canyon. Within the narrow limits of the area mapped, at least, such intrusion is limited to the areas of complex folding—that is, it shows a marked association with échelon folding. The greatest sheets occur at the north end, where such folding is shown on the largest scale. In view of the association of certain intrusive rocks with small deformations, the presence of similar rocks beyond the limits of the area here described may well be noted and taken tentatively as a suggestion of the presence of folds. The large importance of these minor folds in the structure of the adjacent oil field gives significance to such associated features. (Compare p. 93.)

SUNSHINE DIKE.

A large dike, 1 mile long and from 15 to 40 feet wide, follows the south side of Sunshine Canyon. A short distance beyond its western end is a similar dike that runs north-northwest parallel to the Orodell pegmatite dike for a mile and then trends northwest in an irregular course to the Orodell dike. The small interruption may be disregarded, and both dikes are here called the Sunshine dike. This dike is crooked and branching, and at places there are two or three parallel dikes, as if the main one were subdivided. The rock of this dike has a dense greenish-gray felsitic groundmass. It contains phenocrysts of quartz, feldspar, and mica, any of which may be one-fourth of an inch in diameter. The proportion of the volume of phenocrysts to that of the groundmass varies greatly. Locally the phenocrysts may constitute half the rock.

FLAGSTAFF SHEET.

On the east side of Flagstaff Hill and near the base of the red rock is an intrusive sheet of the same character as the Sunshine dike. It extends north from Gregory Canyon to within half a mile of Boulder Creek. North of that stream the sheet reappears at the same horizon, and continues a mile to the north. Its greatest width is at least 40 feet. The exact contact on its east side is seen in the Silver

Lake ditch, one-fourth mile north of Boulder Creek. The red rock has here been greatly altered by the heat and both rocks have been much weathered by spring water following the contact.

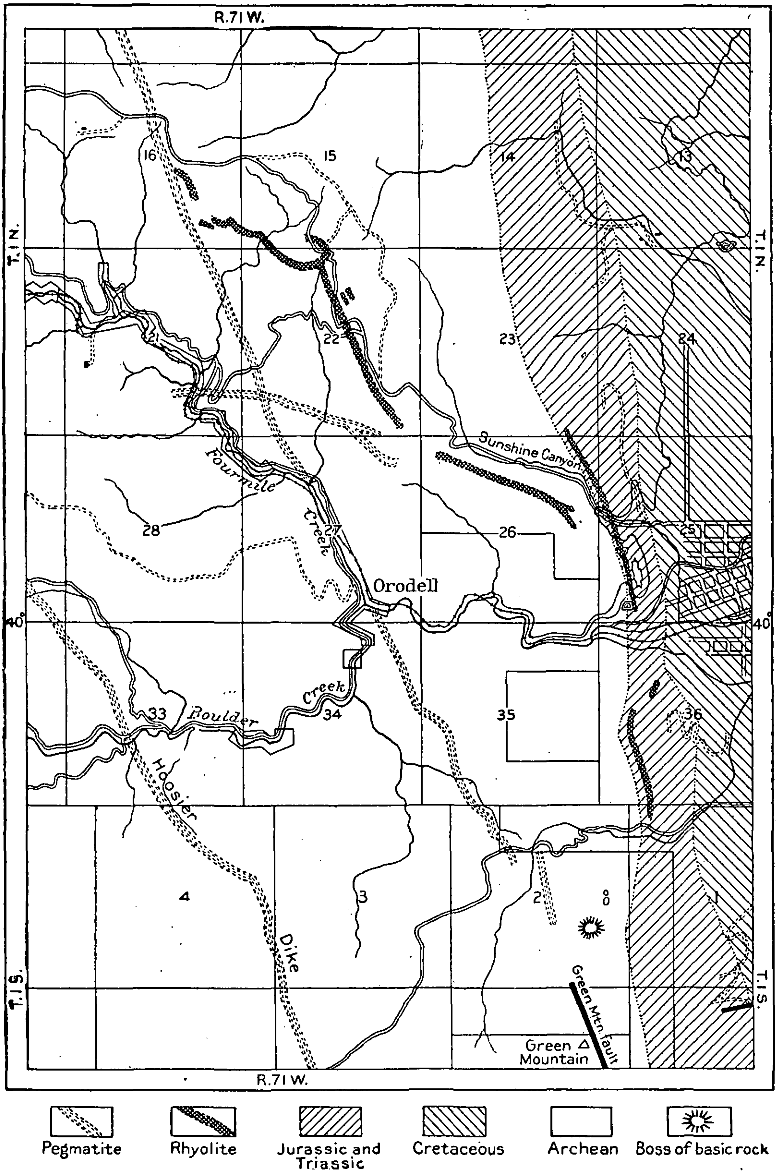

FIG. 2.—Map showing dikes and intrusive sheets west of Boulder. By Hugh F. Watts.

At the north end of Huggins Park is a small offshoot from the main Flagstaff intrusion, or, it may be, merely a dislocated portion of the larger mass involved in the eastward slipping of the red rock. Just below the Huggins Park intrusion is an exposure of the Dakota sandstones and shaly sands, apparently altered by heat. On this account it is presumable that this small intrusion followed a separate fissure which conducted it to a higher horizon than that of the larger sheet on the west.

PLUMELY CANYON SHEET.

A large sheet of rock similar to that at Flagstaff is intruded in the red rock in Plumely Canyon, a western tributary to Lykins Canyon, at the north end of the area mapped. This is fully 30 feet thick and has thoroughly baked the including strata of arkose sandstone, giving them a black color and a siliceous appearance. Minor beds and pockets of shale in the sandstone have been much more affected by the heat than the latter. Pockets of shale are baked and blackened where the including feldspathic sandstone is unchanged.

ALTONA SHEET.

A larger sheet of the same nature, having at places a width of 100 feet, occurs at or near the base of the Lykins, above the Lyons sandstone and below the ocherous shales. The exposure of this sheet begins at a point west of Altona and extends 2 miles to the north without interruption. For much of its length it forms a prominent ridge on the floor of the large longitudinal valley which has been cut out on the Lykins shales.

South of Altona a 20-foot sheet of the same rock is intrusive near the top of the Lykins. The sandy shales have been greatly altered by heat. Their color has changed from red to black, and some of the shales so strongly resemble lavas that they might be mistaken for such if gradations were not apparent. The contacts of this sheet are far from regular, the magma having run out in small branches, sometimes surrounding blocks of the country rock.

All of these sheets are similar in character to the Sunshine dike described above, though varying greatly in details of texture. All are distinctly porphyritic, though the proportion of phenocrysts to the entire mass is subject to much variation. The very fine-textured groundmass is characteristically green or greenish gray, giving color to the whole rock.

INTRUSIVE ROCKS IN THE DAKOTA AND BENTON.

The Dakota contains intrusives at various places in the northern part of the area. In Sixmile Canyon there are three sheets with an average thickness of 10 feet, and the same rock appears at intervals for 2 miles farther north. It appears in sheets at various places in sec. 25, T. 2 N., R. 71 W. On the north side of sec. 36 of the same township it occurs as a boss which has greatly altered the Dakota rocks which it intrudes. The intrusives in the Dakota and those in the Benton, which are very similar, differ little, except in color, from those in the older strata. Those in the Dakota and Benton are a dull gray.

A line of bosses occurs near the base of the Benton shales. The most northerly and largest one is in sec. 25. This irregular mass, together with the dike which runs eastward from it, traverses almost the entire width of the Benton strip, which is nearly one-half mile wide at this place. This fissure crosses one of the most prominent of the échelon folds of the foothills. (See fig. 3, p. 44.) The largest boss is centrally located in a group of such folds.

INTRUSIVE ROCKS IN THE NIOBRARA AND PIERRE.

Near the contact of the Niobrara and the Pierre and within a mile north of Boulder is a line of small volcanic knolls. The igneous rock which forms these knolls may be seen at four places. It occurs at the Colorado Sanitarium, near the mouth of Sunshine Canyon, at the base of the Niobrara. At this place it was thrown out from a small excavation and does not cause any topographic feature. One-fourth of a mile to the north it makes a low knoll 500 feet in diameter extending across the Niobrara and into the Pierre. A second and similar knoll occurs 600 feet farther north, this one being entirely within the Pierre. A little north of the middle of sec. 24, T. 1 N., R. 71 W., is another knoll, similar in every way to the other two.

No sheet connecting these four masses has been found, but as they are ranged along the strike of the strata and are all composed of the same rock, they belong undoubtedly to a common magma, which at this horizon became separated along at least four lines of slight resistance. The rock at this highest horizon contains comparatively few crystals. Large masses of it are nearly white, purely felsitic lava.

DIFFERENCES IN FORM OF INTRUSIONS.

From the Fountain sandstone to the shales of the Pierre the sheets become progressively more irregular in continuity and thickness. The thickness of the sheets is almost uniform throughout the Fountain sandstone, but varies in the Lykins. In the Dakota the intrusive sheets have but limited extent and there is a strong tendency for the igneous masses to be concentrated into bosses. In the Benton such localization is the rule. All the intrusives in this formation appear now as isolated knolls, except in the one instance described above, where a dike runs eastward from the largest of such knolls. In the Niobrara and Pierre all igneous rocks appear as completely isolated and well-spaced knolls with no evidence of connecting sheets. The association of all these igneous rocks with the échelon folds suggests that both the intrusion and the folding occurred during the same process—that is, during the formation of the great foothill monocline.

VALMONT DIKE.

The basic igneous rocks of this area are represented by only one prominent formation—the Valmont dike.[a] This is a great mass of dolerite. Both its occurrence and its petrographic character have been described in detail by Whitman Cross.[b] It has a maximum width of 45 feet and an extreme length of nearly 3 miles, though it is not uninterrupted. From the village of Valmont it extends east by north uninterruptedly 1 mile and as a series of knolls for another mile. For 1 mile west of Valmont it does not appear, but at that distance, in an almost straight line with its course, is a knob of the same rock. The main portion forms a ridge, which rises at Valmont more than 200 feet above Boulder Creek, but which is now being cut away for road material.

This dike is of an even-grained dolerite, divided into large blocks by joints which run parallel and transverse to its length. Within a few inches or a foot of its walls the rock may be divided into thin plates by numerous joints parallel to the bounding surface. In a very narrow zone next to the contact the rock may have a lava-like appearance, but at a distance not greater than a very few inches the characteristic uniform texture of the dike appears.

The stratified rocks containing this dike are (except in case of the isolated knoll to the west) the Fox Hills shales. There is nothing more striking in the whole occurrence than the small degree of alteration which these shales have undergone. Beyond a very little hardening it can not be said that they have been changed at all. In this inference, however, the subsequent weathering is not considered. The vicinity of the contact has doubtless been subject to the work of percolating water. Along the vertical joints of the dike near the contact there have been much weathering and some deposition of calcite.

It is inferred by Cross[c] that this dike "represents a channel through which the basaltic magma rose to the surface;" that this eruption occurred during the Denver epoch; and that strata, since

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[a] One-half mile north of Green Mountain there is, surrounded by the granite, a small isolated mass of a peculiar nearly black igneous rock, with large phenocrysts of several kinds. This knob was located and specimens were collected from it by Mr. Hugh F. Watts, to whom the writer is indebted for information and specimen. The rock is unlike any other known within the area.

[b] Bull. U. S. Geol. Survey No. 150, 1898, p. 261; also Geology of the Denver basin: Mon. U. S. Geol. Survey, vol. 27, 1896, pp. 280 and 298.

[c] Bull. cit., p. 261.

denuded, made the surface of the ground about 2,000 feet higher then than now. The nearly complete uniformity of texture from wall to wall is taken to indicate that the magma cooled at a very uniform rate and that the adjacent shales had been thoroughly heated by long-continued passage of lava.

At Burnt Knoll, 3 miles northeast of Marshall, are rocks which bear a remarkable resemblance to lavas. The zone characterized by this appearance is horizontal and confined to the top of the hill, though much of the material has rolled down and now clothes the sides. Apparent injection among fragments of baked shale is the most common phenomenon, but nothing of undoubted volcanic origin has been found. The coal beneath the hill is nowhere affected by heat. Gradations from the most lava-like appearance to ordinary shale indicate that the phenomena are due to heat alone and not to injection. Doubtless the heat came from the burning of associated coal beds, probably ignited by prairie fires.[a]

STRUCTURE.

FOOTHILL MONOCLINE.

The master structural feature of this region is the great upturn of the strata against the mountain range. The form and magnitude of this fold appear most striking when the Archean surface alone is considered. As shown under the heading "Physiography," the first Archean belt west of the foothills is a dissected plateau 10 to 12 miles wide, which slopes east and abuts against the mountain ridge proper on the west. It is from 6,500 to 7,000 feet above sea level at its eastern edge, where it ends abruptly and is flanked by the Fountain sandstone, which has an average dip of about 50°. The height of this sloping face above the plains is nearly 1,000 feet, but this is a small fraction of the true height of the monocline. Five miles east of the base of the foothills the Archean surface is at least 9,500 feet below the surface or 4,200 feet below the level of the sea. The real face of the granite plateau is therefore about 2 miles high, and this enormous rise is accomplished in 6 miles. These figures represent merely the measured thicknesses of strata outcropping in the first 5 miles from the foothills. They do not take into account the possible thinning or thickening within that distance, nor the probable presence of other beds overlapped by those exposed.

The granite plateau on the west shows no evidence of any deformation since its elevation above base-level. The uplift therefore resulted in the formation of an almost simple monocline not less than 2 miles high and 6 miles wide. But it does not follow that this flexing

[a] See also Eldridge, op. cit., p. 75

was brought about entirely by the mountain-making forces. In fact, the greater part of it was apparently accomplished while the thick formations were being deposited to the east and land continued to the west. When the topmost marine stratum, the Fox Hills, was laid down in the shallow water, the elevation of its surface probably differed little from that of the granite terrane to the west. The same statement would be fairly correct for the lowest stratum of the Fountain sandstone during its deposition, and for any intervening bed. While at any time during the long process of sedimentation the last-laid stratum was approximately horizontal and close to the sea level, the originally (nearly) horizontal granite base was getting constantly lower, and its eastward or seaward dip near shore was correspondingly increased.

It follows from the above that before the present Rocky Mountains were formed, and while the area now included in them was close to the sea level, there had been produced a monoclinal fold whose height was but little less than that which would now appear in the granite surface if the sediments were removed. This conclusion involves no hypothetical premise except the generally accepted continuance of land conditions on the site of the Front Range of the Rocky Mountains.

In determining the height of the monocline it must be remembered that the land surface on the west was constantly being lowered by erosion. Occasional or continuous uplift was necessary in order to furnish the material for the sedimentary formations. The amount of flexing is, therefore, the sum of the subsidence of 9,500 feet on the east and an unknown elevation on the west. This rising on the west might even be equal to the sinking on the east, hence the actual height of the flexure is but partially represented by the 2-mile vertical interval between the exposed surface of the Archean west of the foothills and its buried surface under the plains. The total amount of flexing is equal to the offset that would appear if the denudation west of the hinged shore line had not taken place and the sedimentary formations east of that line were removed.

If the above statements are correct the influence of actual mountain making in increasing the height of this monocline was comparatively small. It is, however, conceivable that an east-west compressive force may have accentuated the fold along the steepest part of its slope, thus tending to narrow the belt of dipping strata, while their dip was at the same time steepened. The slope of the monocline previous to the mountain uplift can not be determined unless the shore line is definitely located, which is probably impossible. No reason appears in this area, however, for departing from the common assumption that the sea did not cover the line which is now the axis of the Front Range and which lies a few miles to the west.

It is not conceivable that mere sinking under an increasing load of sediments should have folded the rocks so sharply or along a belt so narrow as the present monocline; yet the height of the flexure is mainly due to that cause. It is only in association with the last and smaller part of the deformation that lateral compressive force is evident. The process of mountain making gave to the granite plateau west of the foothills a comparatively small relative uplift above the plains.

ÉCHELON FOLDS.

Other definite effects of lateral compression are seen in a special type of folding known as "échelon," which at places accompanies the foothill uplift. Such folding indicates that there was a north-south pressure in addition to the dominant east-west pressure. The resultant stress was in lines a little north of east and south of west, causing folds whose axes diverge slightly from the foothill belt, and trend south by east. Within this area such folds are all small. In general, however, such folds are larger in the younger and easternmost strata. They are largest in the Pierre, become less and less marked to the west, and almost die out by the time the Fountain sandstone is reached. This general rule is not without its exceptions, because the size of such folds is also in a measure dependent on the strength of the strata affected. They are therefore larger and rather more prominent in the weaker Jurassic than in the stronger Dakota above it. Wherever a stratum of some strength is thus folded the end of the canoe-shaped synclinal trough shows a distinct eminence. All the échelon folds are shown on the geologic map (Pl. II).

FOLD NEAR SOUTH BOULDER CANYON.

The échelon fold affecting the lowest strata occurs a mile north of South Boulder Canyon. Here the top of the red rock is offset 1,000 feet to the west on the south side of a small stream as compared with the north side. The younger strata to the east are less and less affected, so that the Dakota is offset but 500 feet and the Niobrara is not folded at all. The location of the fold is significant, being, as it is, at the extremity of the South Boulder fault. The two are but different phases of the same feature and are due to the same act of deformation, only the style of deformation differs.

FOLD SOUTH OF FOURMILE CANYON.

One-half mile south of Fourmile Gulch a mild tendency to this type of folding shows itself in a strong southwest trend of the Dakota hogback, which makes a jog of some 400 feet from its otherwise uniform course. In diminishing degree this fold can be traced north-northwest and south-southeast to the Jurassic and Benton, respectively.

FOLD IN SEC. 25, 6 MILES NORTH OF BOULDER.

A large number of small, well-developed folds of this kind appear in secs. 36 and 25, 6 miles north of Boulder. In the west half of sec. 25 a prominent, bald, rounded hill rises several hundred feet above the crest of the Dakota ridge, which at this place is broad and less distinctly marked than usual, though not lower. Here, for a short distance, the ridge-making rock is not the Dakota, but the strong, purplish sandstone in the Morrison. The rounded hill mentioned is at the end of a canoe-shaped structural trough in this sandstone. (See fig. 3.) East of it, in the same stratum, is a well-delineated anticline, with an axis pointing south by east, thus diverging slightly from the main trend of the outcrop. The exposed edge of this stratum first runs north, turns around the synclinal hill, loops back to the south for a third of a mile, and then turns north again around the anticline. All the beds of the Jurassic and those adjacent are strongly affected in similar manner.

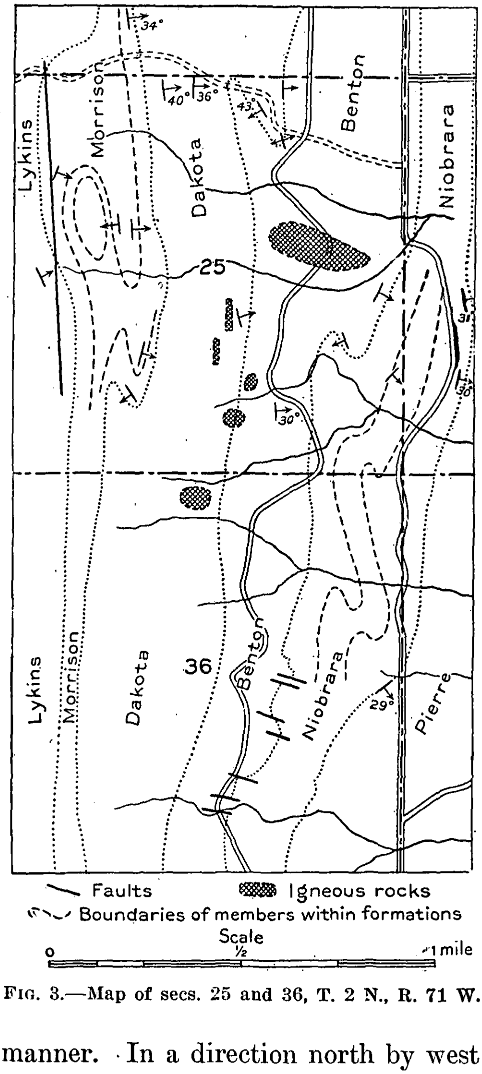

FIG. 3.—Map of secs. 25 and 36, T. 2 N., R. 71 W.

In a direction north by west the fold affects the Fountain sandstone for a number of miles, flattening its eastward dip of nearly 30° to 7° or 8° along the line of the fold. It is largely due to this flattening of dip that the outcrop of the Fountain sandstone is so greatly broadened at the north end of the area mapped. The effect on this formation is also seen in the northeast trend of its eastern boundary, west of Altona.

Near the northern line of sec. 25 the upper beds of the Dakota are distorted by an abrupt fold of the same kind. The outcrop, as traced southward, turns backward to the northwest, but in this instance less than a fourth of a mile. The north-northwest continuation of this fold and the fold above mentioned together produce the flattening in the dip of the Fountain sandstone. The southward continuation of this fold is beautifully revealed in the basal limestone of the Niobrara. The higher, shaly limestones of this series are somewhat folded along the same axis, but seem in the main to have slipped one over another at the place where corresponding folds might have been expected. By such means the site of their folding was shifted nearly a mile to the south. The folds show clearly near the east side of sec. 36.

FOLD IN THE HYGIENE SANDSTONE OPPOSITE SIXMILE GULCH.

Just as the north-northwest continuation of this group of folds in secs. 25 and 36 causes a flattening of the dip of the red rock, its continuation in the opposite direction has like effects in the Hygiene sandstone of the Pierre. If the line of the northwestern continuation be extended in the opposite direction, it crosses the Hygiene sandstone in sec. 6, T. 1 N., R. 70 W. At this point the outcrop of the sandstone deviates from its general northerly course and trends straight northeast, making an offset of an entire mile within the section. (See map, Pl. II, p. 10.) This is one expression of the tendency to échelon folding. Another is seen in the reduced dip, 18°, as compared with 55° on the south and 25° on the north. If the line of these folds is extended still farther south, it passes a little west of the producing oil wells. The significance of this in the structure of the oil field is mentioned below (p. 87).

TABLE MESA FOLD.

Two miles north of Altona all strata younger than the red rock strike approximately northeast for several miles, but to the north again following their usual northward trends. In this deformation no such sharply marked échelon folds were developed in the foothill outcrops as are seen farther south. The deformation represented by this incipient fold is, however, large. The effect of the same stress on the Hygiene sandstone was to make a definite anticline whose western limb dips 18° toward the mountains. The sandstone has been eroded from the crest of this fold for fully 3 miles, while it remains in the canoe-shaped syncline west of it. The edge of the Hygiene sandstone is not everywhere exposed, but if laid bare it would make the long loop indicated on the map, west of

Haystack Mountain. (See map, Pl. II. A detailed description is given on p. 88.) The axis of this anticline, if extended southward, would pass a little east of the producing oil wells. Its significance is discussed below.

FAULTS AND LANDSLIPS.

In the foothills of this area there are three large faults and at least one small one whose directions differ little from the strike. The three large ones which affect the western margin of the Fountain outcrop are shown plainly on the map.

SOUTH BOULDER FAULT.

The fault between the two South Boulder peaks strikes south by east from the vicinity of the peaks, but its southerly extension curves more to the east, and it dies out in the incipient échelon fold mentioned above. The downthrow, more than 2,000 feet, is on the west side, repeating the outcrop of the Fountain sandstone and causing two peaks instead of one. (See fig. 1, p. 12.) The two South Boulder peaks will here be spoken of as outer and inner. The outer is made by the main outcrop of the Fountain sandstone. The inner and higher peak is on the fault block of the same formation. It is half a mile southwest of the outer peak.

The fault can be distinctly seen at a point halfway up the valley of the small stream which runs south from the peaks. Here its hade is to the west. As all other features indicate east-west compression in this region, rather than stretching, it is safe to assume that this is a thrust and not a gravity fault. This implies that the hade was toward the upthrow or east side when the strata were faulted, and that it was rotated to its present position by the further tilting of the strata. If made since the strata attained their present position it must be a normal fault, for the present hade is toward the downthrow side. This would indicate stretching, a supposition which is unsupported.

It is difficult to determine how far this fault extends north of the peaks, because its farther extension is in the granite. The block of red rock is not more than 700 feet deep, being limited below by its stratigraphic base, which dips E. 52°, and by the fault plane, which dips west. (See fig. 1, p. 12.) As the gorge leading west from the outer and more northerly peak is much deeper than this, the fault block terminates here and the red rock is not seen farther north.

GREEN MOUNTAIN FAULT.

Another fault, similar in every respect to the one just described, bears the same relation to Green Mountain as the South Boulder fault does to the inner South Boulder Peak. The Green Mountain fault extends south by east from Green Mountain and dies out in the vicinity of South Boulder Peak. Its extension north of Green Mountain is in the granite and is not apparent. The width of the red rock whose outcrop is thus duplicated west of the main exposure is fully 400 feet; the depth of the block is about the same. The block is terminated by the deep valley just north of Green Mountain. The maximum throw of this fault is probably in Bear Canyon, and is apparently less than that of the South Boulder fault. The granite strip between the duplicated outcrops of the red rock is occupied by streams, as in both the other cases of similar faulting in this area.

FOURMILE FAULT.

A third great strike fault is encountered west of Fourmile Gulch. For 2 miles north of this point it is made evident on the map by the appearance of the red rock in a narrow belt on its west or downthrow side. North of this it extends an unknown distance in the crystalline rock. Its southward continuation runs into the main outcrop of the red rock, south of Fourmile Canyon. The map indicates that at this point a block of red rock is offset to the west. This same block was at first continuous with the isolated fragments to the north, which have subsequently been separated by erosion. The fault has therefore the same general direction and the same relation to the Fountain sandstone as the two faults south of Boulder.

The fault plane itself is not seen, hence the hade is unknown and the depth of the block of sandstone can not be accurately computed. The dip here is but 38°, and the width of the sandstone belt west of the fault is not over 400 feet. If the fault is vertical, the depth of the red-rock block would be but little more than 300 feet. The gorges which cross the fault have cut entirely through the block, and indeed several hundred feet deeper, dividing it into two widely separated parts and isolating both patches from the main outcrop of the Fountain sandstone. Its maximum throw is about 1,100 feet.

FAULT IN SEC. 25, T. 2 N., R. 71 W.

It is significant of the thrust character of these faults that their directions agree with those of the axes of the échelon folds. This relation is emphasized in the case of a small strike fault 6 miles north of Boulder, in the west half of sec. 25. This fault is on the west slope of the prominent bald hill referred to above (p. 44) as formed of a hard Jurassic sandstone and as marking the end of the syncline where the sandstone is characterized by échelon folding. For perhaps half a mile there is a repetition of less than 150 feet of Jurassic strata. This intimate association of fold and fault at once suggests that the two were caused by the same force; and that each supplemented the other in relieving the east-west stress. This would imply a thrust fault, a supposition which is harmonious with all other observations in the district.

DIP FAULTS IN THE FOOTHILLS.

Dip faults in this area are small. In the next section north of Sixmile Canyon the basal Niobrara shows at least eight dip faults, offsetting the line of outcrop from 10 to 150 feet each—sometimes to the east, sometimes to the west. The belt occupied by the interfault blocks is 300 feet wide. (See fig. 3, p. 44.) The close relation with the folds of the locality leaves little doubt that the two types of deformation are due to the same cause and were produced at the same time. Similar repeated faulting, on a very small scale, also occurs in the Niobrara limestone half a mile south of Gregory Creek. Minute faulting and brecciation at places accompanied the crumpling of the "crinkled" sandstone of the Lykins. It was intense for some distance north and south of Fourmile Gulch.

POLE CANYON SLIP FAULT.

The apparent dip fault in Pole Canyon is the most prominent feature of this nature and is also of great interest. Viewed casually, the feature especially noticeable is a jog of 400 feet in the Dakota ridge, which on the north side of the stream is small, and disappears altogether within a few hundred feet. This jog, which would seem to be sufficient evidence of a fault, does not appear in any formations older than the Jurassic. Of the younger formations, the Benton and Niobrara show no natural exposures on the south side of the stream. On the north side the Dakota, Benton, Niobrara, and Pierre appear in regular succession. In excavations under the end of the Dakota ridge, on the south side, the Niobrara has been encountered in its normal position, unfaulted. The Pierre and Benton are also unbroken; the upturned edges of the Dakota and Jurassic have slipped forward over the unmoved higher strata. There are two fault planes here—a vertical one in an east-west position and a horizontal one which is considerably higher than the present bed of the adjacent stream. This structure must be called a "fault," though its structural value is quite different from that of a fault, as the word is generally used. For want of a specific designation it is here referred to as a "slip fault." It grades into the landslip, but where characteristically represented, as it is here, its true nature must be taken into account in mapping. It is characteristic of such faults that they are (1) superficial and (2) younger than the upturning of the rocks in the foothills.

HUGGINS PARK.

A feature intermediate between the slip fault and the more ordinary landslip is seen at the middle of sec. 36, at the foot of Flagstaff Hill, west of Boulder. About 300 feet above the plain a bench or terrace a fourth of a mile wide east and west, and of somewhat greater length north and south, is composed of massive beds of the Fountain red rock. Near the front of the bench these rocks are essentially horizontal, but on the west they curve gently upward and become almost vertical. The higher strata from Jurassic to basal Niobrara, inclusive, come up to this bench on the north and on

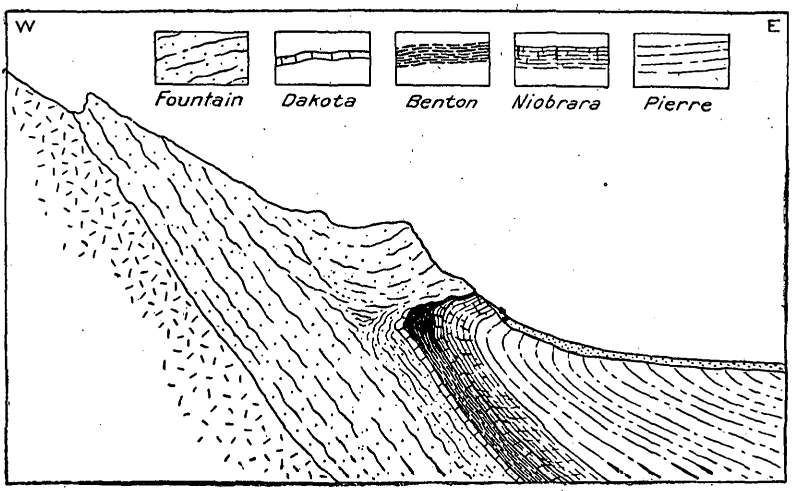

FIG. 4.—Cross section of east slope of Flagstaff Mountain.

the south, and there disappear as if passing beneath the red rock. The bench, known as Huggins Park, is a slide of great dimensions, whose constituent beds are so massive and so unbroken that on the map the red rock is represented as occurring here instead of the higher and younger strata which are covered by the slide. In this case the basal plane, along which slipping has occurred, is in the main a bedding plane, and the phenomenon differs in that respect from the Pole Canyon slip fault.

The recency of this event is shown by a study of the outcrops of the younger strata which were overridden by the red rock in its eastward slipping. The edges of the Dakota, Benton, and Niobrara had been eroded back to a position not differing much from that of the corresponding outcrops which have not been thus covered. When the slip occurred these outcropping edges were dragged forward and overturned. Under the eastward-facing scarp of Huggins Park one of these overturned beds of the upper Niobrara has been found in an almost horizontal position[a] (fig. 4, p. 49).

FOOTHILL OVERTURNS.

Just north of Huggins Park the basal Niobrara and its neighbors are overturned in a manner similar to that just described, though not at the present time covered by the red rock. It is fair to assume that at least a part of these beds were overturned by the original movement and their edges dragged eastward. By a careful examination of the contacts of a dike at the north end of the park, also, Prof. R. D. George has shown clearly that there has been vigorous movement along the planes which bound the dike. The relative motion of the dike rock has been forward (east) with reference to its hanging wall (on its west), and backward with reference to its foot wall. The drawing out of the micas into long streaks plainly indicates this.

As similar overturning is common in the Niobrara of this area, and is sometimes alluded to as "fan structure," implying an origin connected with lateral pressure, the significant features of this occurrence north of Huggins Park are here enumerated. They are as follows: (1) The actual overturn is very superficial, its depth being no greater than the height of the ridge due to the strong stratum of the basal Niobrara above the surface of the neighboring shales, 10 to 20 feet in all. (2) With the exception of this narrow crest there is small difference in dip between the nearly vertical red rock on the west and the slightly overturned Niobrara shales on the east of the basal limestone. (3) The overturn of the limestone increases to the south, where the outcrop swings off to the east toward Huggins Park. (4) The overturn is seen half a mile still farther south, under the red rock in the eastward-facing escarpment of the park.

As pointed out above, this feature resembles fan structure, and it should be so described if interpreted as the result of the profounder processes of mountain making. Recourse to these processes is, however, unnecessary to account for any phenomena within the Niobrara of this area; on the contrary, many of the most pronounced examples of overturn, or fan structure, are clearly the result of mere superficial slipping, aided, no doubt, by frost.

Fan structure occurs most frequently in the Niobrara, but the cause lies in the Benton shale west of the Niobrara outcrop. This shale occupies the steep eastward slope of the Dakota hogback, and its surficial parts may be regarded as having a slow eastward move-

[a] The first recognition of this relation was by Judge Junius Henderson and H. F. Watts. It was first described by Henderson in an article entitled The overturns of the Denver basin: Jour. Geol., vol. 11, 1903, p. 584. Fig. 4, drawn by Watts, is taken from this article.

ment, due to gravity and frost. This movement has involved many landslips, but it has been chiefly effected by creep. The ocular demonstrations of these processes are patches of hummocky landslip topography and superficial overturning of beds. Overturns in the Niobrara may therefore be regarded as due mainly to the eastward creep of its outcropping edges, which were pushed forward by the Benton from the higher slope. In exceptional cases the outcrops have been dragged eastward by landslips.

It is not quite so apparent that the Dakota should have a steeper dip than the Fountain sandstone from causes similar to the ones here defined. It may be shown, however, that the phenomenon is, at some places, a superficial one. The dip of the block affected by slip faulting in Pole Canyon is 20° steeper than the normal dip of the Dakota in that vicinity. Throughout the area the Dakota hogback is in general a high, narrow ridge, rising much higher above the plains on its east side than above the valley on the west. Against the west side, therefore, there is constant pressure of the Morrison and Lykins shales and sands, whose surface has a general eastward slope and thus a tendency to creep eastward, causing pressure against the Dakota ridge. Under these conditions it is difficult to see how the strata of the latter could entirely withstand the tendency to rotation. Where the strata are thickest and the ridge is broadest, and best supported on the east, the dip is least steepened.

An example in the Fountain sandstone further illustrates the shallowness of the zone in which the dips may be affirmed to agree with those at the surface. West of Boulder, and for a short distance north of Sunshine Canyon, the "Red Beds" are vertical. Going north, the dip decreases with comparative abruptness to less than 60°. The strike continues in a uniform direction, and there is no jog in the outcrop. It follows from this that if these diverse surface dips continue to any great depth the Fountain strata are dropped down sharply, and form a deep east-west trough under the city of Boulder—a supposition which is not supported. There has certainly been, since the middle of the Pierre epoch, a great flattening of the Boulder arch, but it is difficult even to conceive of a structural trough in the Fountain sandstone so profound that its dips should be continuous with the present dips of the crags around Sunshine Canyon. It is far more probable that the steep dips of these exposed crags do not continue far beneath the surface.

SLIP OF THE LYKINS IN POLE CANYON.

The direct effect of gravity on foothill topography may be seen at various places along the contact of the Lyons sandstones and the Lykins sandy shales. It is well exemplified in sec. 12, just east of

Green Mountain. (See fig. 5, below.) Here the Lyons sandstone is covered by a long talus slope hundreds of feet high, composed of large blocks derived from the sandstone. The talus slope ends where the Lykins begins. Along this line is a trough, or, more properly, a series of pits, often 20 feet wide and 8 feet deep. Into this irregular trough the lower margin of the talus has fallen. The steeper slope thus made at the foot of the talus has not yet had time to be reduced, and many blocks are in an unstable position. Some have been broken or turned over, and expose fresh surfaces, which contrast with the older weathered or lichen-covered surfaces. Simi-

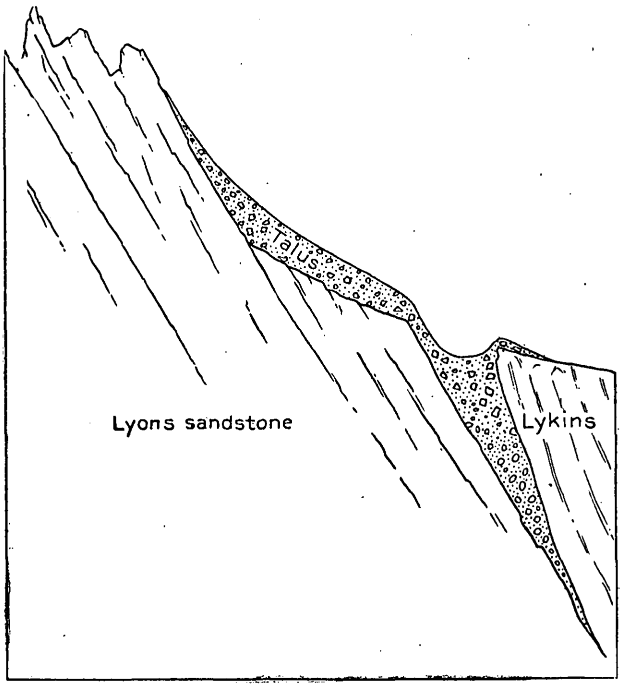

FIG. 5.—Lykins formation in Pole Canyon slipping away from the Lyons sandstone.

lar occurrences are found at various points between Pole and South Boulder canyons.

In explanation of this phenomenon, it is not necessary to assume any other force than gravity. The slope eastward from the contact of the Lyons sandstone and the Lykins is steep and is underlain by shale or sandy shale. At the foot of this steep slope, a fourth of a mile away, a young, deep valley has been cut behind that portion of the Dakota hogback which has been swung forward by slip faulting. (See p. 48.) Similar opportunities for the slipping eastward of the Lykins exist at other points, and are accompanied by the peculiar evidences of slipping described above. The tendency would, of course, be greatly aided by any continuance of the mountain uplift.

FAULTS OF THE PLAINS AREA.

The generally horizontal rocks of the plains are broken by faults much longer than those in the foothills. The throws are, however, very much smaller, rarely exceeding 300 feet. Most of the plains faults within this area converge at Marshall and have their chief interest in connection with coal mining. Any description of them must be little more than a repetition of the excellent account given by Eldridge.[a] They have been traced again in the field and plotted with some detail on the large-scale base map used in this survey. All are far from straight, and their courses are necessarily represented in a generalized way. The actual line of a fault can rarely be seen. Commonly its location is fixed only within several hundred feet by outcropping rocks, whose relations indicate a fault somewhere within the limits named. Fragments of crushed and slickensided rock may define the location more narrowly. In two cases faults can be seen in mines. The faults enumerated in Eldridge's "Marshall subsystem" and two of his "North Boulder faults" are here briefly described under the names given by him.

The main or northern fracture of the Marshall subsystem trends southwest along the northern base of Davidson Mesa to its west end, southwest of which its course is more southerly to beyond the middle of sec. 21, where it is lost. Its northeastern extension also runs in the same direction as its southwest end. It passes half a mile west of Burnt Knoll, northeast along the line of Dry Creek, and is lost. The fault plane, where observed by Eldridge, in a mine now abandoned, dips S. 28° E., at an angle of 45°. As the upthrow is on the southeast side, this is a thrust fault. The maximum throw along its middle course is about 350 feet.

The middle fracture branches off from the main fault near the railroad station at Marshall and follows a northeasterly course, though at its southwestern end the trend is more east than north. Its course is curved similar to that of the northern fault, but the curve is less sharp. The line of the fault crosses the highest part of the mesa near its west end, but farther northeast it follows the foot of the mesa. The fault itself can be seen in a cut of the railroad switch, which encircles the mesa at its western base. The maximum stratigraphic throw of this fault is near its eastern end, and amounts to 180 feet. The downthrow is on the south, so that the fault block on the north has been relatively lifted up between its neighbors.

The southern fracture is approximately parallel to the middle one and distant from it one-fourth to one-third of a mile. It follows a gently sinuous course along the south side of the valley, and south

[a] Mon. U. S. Geol. Survey, vol. 27, 1896, pp. 128–136.

of the Colorado and Southern Railroad, but crosses the valley about the middle of the south side of sec. 15, ascends the mesa to the northeast, and is lost to view in about half a mile. Its southwest end approaches the main or northern fracture near the middle of sec. 21, but here a strong monoclinal fold appears and probably takes the place of the southern fault at its westerly end. The downthrow is on the north and reaches 260 feet. Nearly midway between the middle and southern fractures is another fault of similar direction with downthrow of a few feet on the north.[a]

The block between the middle and southern fractures is cut by the "terminal cross fault," and its west end dropped down about 30 feet. This fault lies a little west of the middle of sec. 15. It trends nearly southeast, but turns more nearly to the south at its southern end, where it seems to cross the southern fracture. It is no doubt the same fault which is encountered in the Gorham mine of the Northern Coal and Coke Company, where the drop on the west side is 10 feet.

The canal fault (so named by Eldridge) is well seen in the deep railroad cut in sec. 13. It runs almost east and west, and has a vertical downthrow on the north of about 50 feet. The massive sandstone on both sides is basal Laramie.

Two of the group of faults appearing on the north side of Boulder Creek lie partly or wholly within the area discussed in this report. No. 1, with upthrow of 180 feet on the east side, brings up the Fox Hills shale in the east halves of secs. 12 and 13 at the eastern edge of the area mapped. The opposing stratum on the west is basal Laramie. No. 2 has 60 feet of upthrow on the east, the opposing strata being Laramie on both sides. All trace of these faults is lost under the alluvium of the valley on the south and also under the surface of Gunbarrel Hill on the north.

GEOLOGIC HISTORY.

PRE-FOUNTAIN TOPOGRAPHY.

The geologic history of the Fountain sandstone is considered with especial reference to the topography of the preexisting land surface. The uneven contact between the Archean and Fountain rocks is understood to represent the subaerial topography of Fountain time as modified by shore erosion during gradual submergence beneath the sea. The principles by which the character of the early topography and of the marine denudation is inferred from the present features can not here be discussed in detail.[b] The observations

[a] The writer's attention was called to this small fault by Mr. H. F. Watts.

[b] See the writer, Effect of cliff erosion on form of contact surfaces: Bull. Geol. Soc. Am., vol. 16, pp. 205-214.

given below, however, point to the conclusion that during submergence the form of the old land surface was much changed by wave erosion.

The Archean-Fountain contact differs from a plane only when broad areas are considered. The undulations of the contact line shown on the map give an exaggerated idea of the unevenness of the Archean surface, but, ignoring the effects of faults, most of the deviations from straightness are due to the irregularities of the present surface.

In the main the proof of the inequalities of the Archean floor is the varying thickness of the red rock. A casual look at the map may be somewhat misleading as to the amount of such variation, for at Boulder, where the band is narrowest, the beds are vertical; toward the north the dip decreases, and where the outcrop is very wide, the dip is but from 7° to 30°. The thickness of the Lyons-Fountain sandstones varies from 500 feet at Boulder to possibly 1,500 feet at Fourmile Canyon and at Bear Canyon, 3 miles south of Boulder. At Lefthand Creek, 3 miles north of Fourmile Canyon, it does not exceed 1,000 feet.

If the eastward tilting due to mountain-making forces were undone and the red rock removed, the exposed Archean surface would show only very smooth, broad undulations. In this area the slopes would not be less than 3 miles long, would have a grade, except at one place, not exceeding 150 feet to the mile, and would be entirely unbroken by valleys. The one exceptional feature of the relief would be a hill, or east-west ridge, at Boulder, rising possibly 1,000 feet above the valleys north and south of it, but having a base 6 miles wide and perfectly smooth slopes. This hill or ridge, however, marks a well-known line of weakness, along which there has been frequent uplifting; it does not, therefore, represent the relief of the floor upon which the Fountain sandstone was laid; it was more probably being elevated during the deposition of the latter, or, rather, it was subsiding less rapidly than the areas north and south. (Compare p. 64.)

The Archean rocks below the Fountain are unweathered. Those which are in immediate contact with the red rock do not differ in this respect from those which occur at a greater distance back in the mountains. In like manner, the felspathic constituents of the stratified rocks are essentially unchanged. The sediments also contain many unweathered rock fragments. The material composing much of the red rock is not unlike the disintegrated granite which now covers many of the steepest hillsides, with this exception, that it has been to some small extent transported by water. Nevertheless, these sediments are in the main but little waterworn and poorly assorted. They are such as should be found near a land which is being actively eroded by streams as well as by waves—that is, where erosion is relatively active as compared with weathering; the more arid the climate the less active need erosion be in order to yield such waste. Such sediments belong to a shore where trituration is not prolonged, and where the bottom subsides so rapidly that the particles are carried downward into quiet water before they have been rounded or broken up.

The above features of form and material suggest that the configuration of the present contact is the result of a considerable change in the topography of the old land. The absence of smaller irregularities on the broad swells that slope 150 feet to the mile and an unweathered rock bed would not both characterize an area subjected to subaerial erosion. If the former land surface was a peneplain its deeply weathered surface could not have supplied the large proportion of feldspar fragments in the red rock, and its slowly flowing streams could not have transported them from the higher land on the west. On the other hand if the surface had its present relief its long slopes would have been cut into sharp hills and valleys. The invading sea, therefore, must have shaved from the surface enough material to obliterate all the relief except the major features, which have been left in a very generalized form.

SHORE EROSION DURING SUBSIDENCE.

The form of the shore line of an advancing sea is indicative of the form of the sea bottom near the shore. This is apparent from the fact that the shore line at any stage of subsidence is the highest contour of the sea bottom and is similar to the other contours, each of which was, in its turn, the shore line. When the submerged surface, therefore, is a plane, whose contour lines are straight, the shifting shore line is known to have been without bays. When the sea bottom is undulating, the shore line of the advancing sea was characterized by bays and headlands.

During the invasion of the Fountain sea, therefore, the shore line was not straight (since the surface of denudation is not a plane), but there has been found no trace of bay heads where filling was in progress. The universal freshness of the underlying granite is evidence that cliff cutting occurred everywhere. The bays that existed did not extend so far inland as to preclude erosion at their heads. While this universal cliff cutting was taking place the surface rocks were being removed from both hills and valleys, though the erosion was greater on the hills than in the valleys. Between headlands 6 or 8 miles apart the water would have been possibly 500 feet deep. These dimensions, which follow from measurements given above, are perfectly consistent with the assumption that the bays were so wide open as to allow wave erosion at their very heads.

The supposition is a long way within the possibilities of shore erosion.

From the above-stated relation of the shore line to the contours of a submerged surface it follows that if a retreating shore line is a sinuous cliff the sea bottom will have a fluted surface. There will be ridges along the lines of retreat of the headlands and furrows where the bay heads receded. If there is suitable offshore slope and rate of subsidence, even the coarse waste may be laid down in beds, which are continuous over these ridges, instead of abutting against them. All these conditions occur along the lower contact of the Fountain sandstone. Fine flow-and-plunge structure is seen where it should be expected—that is, in the thickest part of the formation or within the bays of the Fountain sea.

All the undulations of the Archean floor might be due to gentle crustal folding during Fountain time. This hypothesis also would provide for the continuity of the "Red Beds" over the eminences. It would make unnecessary the assumption that hills stood out as promontories in the advancing sea and that the shore line was crenulated. It does not, however, account so well for the general cross-bedding, and for the flow-and-plunge structure that so plainly characterizes the places which, on account of the greater thickness of the "Red Beds," are regarded as bays. Except in the vicinity of Boulder there is also a lack of collateral evidence of such crustal deformation. The hypothesis of warping during sedimentation might be used to support the theory of a pre-Fountain peneplain, but it has already been pointed out that the character of the Fountain sediments does not admit of the assumption that they were derived from a peneplain. The Boulder arch itself was probably slowly bulging upward while the "Red Beds" were being deposited. The evidence on this point is given under the discussion of the next higher formation. (See p. 61.)

DEPOSITION OF FOUNTAIN FORMATION.

Generally speaking, the local thinning of the red rock is due to thinning of all the beds rather than to a disappearance of a part of them. Except in the vicinity of Boulder the topmost strata of the formation can be traced continuously from point to point along the line of towering crags, which form the most conspicuous feature of the foothills. The Lyons sandstone shows the same continuity at a higher horizon, and the strata at the base of the red rock are almost or quite as continuous as those at the top. If the contact is followed from canyon to canyon over the intervening spurs, the basal ledge of the red rock may frequently be seen for a mile or more. In almost all such cases the continuity of the stratum at the base is noticeable, although this is not quite universal, as there seem to be a few places where the beds at the base abut against a low rise in the granite surface. At such places the contact appears to shift to successively higher beds of the red rock.

DEPOSITION OF LYONS SANDSTONE.

The change which brought about the deposition of the Lyons sandstone was comparatively abrupt. Only a short time after the deposition of rough arkose, the sediments were composed of thoroughly assorted clean-washed quartz sand. The details of structure also changed to a neat cross lamination, producing flags of a uniform thickness and large area. Most of these flags which are now exposed dip east at a smaller angle than the true bedding; that is to say,

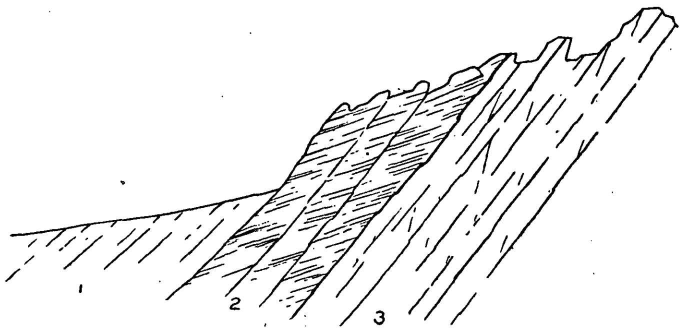

FIG. 6.—Position of cross-bedding of the Lyons sandstone. 1. Lykins formation. 2. Lyons sandstone. 3. Fountain sandstone.

if the true beds were again horizontal the cross-bedding would dip west, or toward the old shore. (See fig. 6.)

BAYS AND BARS.

The nature and peculiar bedding of these sediments indicate that the shore line was indented on the west by a bay, and that this bay was spanned by a bar of clean sand—the formation known as the Lyons sandstone. Most of the sandstone now exposed was deposited on the landward side of the bar and dips toward the land. The area here discussed embraces parts of two such bays, separated by a salient point between Boulder and Gregory creeks. (See fig. 7, p. 60.) In front of this headland the peculiar sediments ascribed to bar building are absent.

Not only are the bar sands absent from this locality, but the headland seems to have been eroded and to have furnished a part of the material for the bars. It can not be stated beyond doubt that there was such erosion, because, at the place concerned, the upper beds of the red rock are poorly exposed. It is certain that just west of

Boulder the red rock is much thinner than it is a short distance to the north or south. From appearances it is probable that this decrease in the thickness of the formation is due in part at least to thinning of the individual beds, but it is not plain that the whole difference can be thus accounted for. In so far as the upper beds fail to cross the arch,[a] it is most consistent with the physical history to assume that they were eroded from the headland which, without doubt, projected at this point when the bars of the Lyons sandstone were being deposited. Cliff erosion on the salient would certainly be expected from the relative position of the headland and bar.

These bays could not have resulted from the continued submergence of an uneven land surface. The headland at Boulder was plainly due to warping resulting from north-south stress. It corresponded in position to the Boulder arch, which has been subjected to repeated upward warping. As the sediments became thinner at this place and as a headland appeared immediately after their deposition, while sedimentation continued to the north and south, the cause of all these phenomena was no doubt crustal deformation.

The conclusion that the Lyons sandstone is the sediment of bars rests finally upon the position of its cross lamination, which in general dips toward the shore. This necessitates either the above-stated hypothesis of bars or that there was land farther east from which sediments were derived. The supposition that there was land farther east is entirely without support. The hypothesis that the sands were laid down in the form of bars is supported by the nature of the sands and by their absence at the most probable headlands, from which, in part, the shore drift should have been derived.

It is to be remarked that the dip of the cross-bedding at Gregory and Boulder canyons, where the formation abuts against the supposed headland, is away from the mountains. The Lyons sandstones exposed at Boulder and Gregory canyons are in immediate contact with the old headland, and therefore represent the seaward side of the bars. From the nature of the contact of a bar with the salient from which it springs, it is the seaward front and not the inside or landward slope of the bar that is tangent to the land. (See fig. 7, p. 60.) Whatever cross-bedding existed on this seaward front must, of necessity, have dipped seaward. Therefore the relative eastward dip of the cross-bedding at these places is in exact accord with the theory of the deposition of these sands in the form of bars.

The supposition that two bays were separated by a salient between Boulder and Gregory creeks rests upon (1) the absence of bar sediments at that point, (2) the probable erosion of the topmost red

[a] See Eldridge, G. H., Geology of the Denver basin: Mon. U. S. Geol. Survey, vol. 27, 1896, p. 110.

rock, (3) the eastward dip of the cross-bedding of the beach sands nearest to this point.

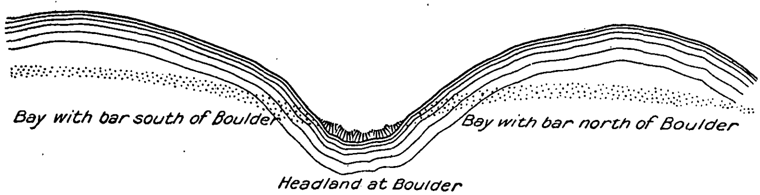

FIG. 7.—Shore line during the deposition of the Lyons sandstone.

From the above reasoning it follows that the Lyons sandstone should be intermittent in its distribution alongshore after the manner of bars. This is true. They should also form a relatively narrow reef-like zone, and, if followed outward from the old land, the direction of dip of the cross lamination should be reversed. Along this line no direct evidence is at hand.

MIGRATION OF BARS.

A bar extending across a bay retreats landward with the recession of the cliff from which it springs. This retreat is accompanied (1) by progressive deposition on the landward side of a series of layers which dip toward the land, and (2) by erosion on the seaward side, which results in the removal of the upper part of layers previously deposited.[a] (See fig. 8.) The first effect is exemplified here in the prevailing dip. The second is beautifully shown wherever there is a good contact between the Lyons sandstone and the next higher formation. The bottom of the Lykins is occasionally exposed as a clearly defined surface against which the clean-cut flags abut at an angle which may reach 36°. (See fig. 6, p. 58.)

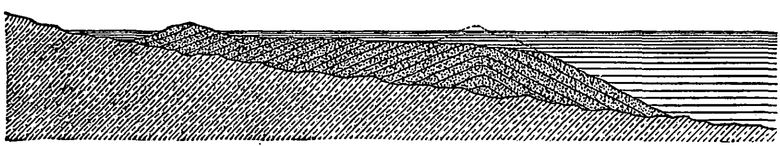

FIG. 8.—Section of a linear embankment retreating landward. The dotted line shows the original position of the crest. (After Gilbert.)

This process of building bars of clean-washed sand, which are shifted gradually landward and truncated, implies a considerable stability of the land with reference to the sea level, though it is not prevented by moderate sinking. In the epoch here considered, not only the well-assorted, clean-washed, creamy sands, but also the shaly sands which follow, indicate quiet conditions and freedom from crustal deformation.

[a] Compare Gilbert, G. K., Lake Bonneville: Mon. U. S. Geol. Survey, vol. 1, 1890, p. 53. The conditions here described are discussed by Gilbert, as exemplified in the mole inclosing Toronto Harbor. Fig. 8 is taken from this discussion, p. 56.

LYKINS SEDIMENTATION.

While the bars of Lyons sands were being truncated sediments could not be deposited on the truncated base unless they were coarser than the sand which had been removed. Later, however, this surface subsided to such a depth that it was buried by a sandy and highly ferruginous mud.

The deposition of the other sediments of the Lykins formation required similar depth, and during this time there was nothing peculiar in the shore conditions. Probably at this time while the sea bottom was depressed so that mud was deposited in places from which sand had been removed, the relief of the land was reduced, and thus the supply of coarse sediment was checked. During much of Lykins time the sea was so deep that ripple marking and cross-bedding did not take place, but toward the close both are apparent.

LYKINS WARPING.

At Twomile Canyon the cross-bedding near the top of the series again indicates deposition on the landward side of a bar. It may be inferred from this that headlands were again being eroded, and this assumption is borne out by the nature of the sediments, which are coarser near the top. The headlands were probably caused in part by a gentle warping, which harmonizes with indications of crustal movement at the close of the Lykins, which may have caused a slight unconformity between the rocks of this epoch and those of the Morrison. The brown sandstone at the top of the Lykins is not of uniform thickness. (See p. 25.) The exceptional abruptness, also, with which at many places the highly ocherous rocks give place to the gray above, at least raises the question whether there might not have been a transitional stage whose record is lost. As pointed out in the description of the stratigraphy, such beds, transitional in color and texture, appear in a number of places.

Uplift of the Boulder arch.—While clear and definite indications of a general unconformity at the top of the Lykins are wanting, there is decisive evidence that the Boulder arch was uplifted and eroded. The "crinkled" sandstone approaches to within a few hundred feet of the south side of Gregory Canyon, maintaining about its usual distance above the Lyons. The same conditions are found on the north side of Boulder Creek, but for more than half a mile north of Gregory there is no trace whatever of the Lykins. The uplift of the fold north of Gregory Creek was almost equal to the combined thicknesses of the Lykins and the Morrison. The former is normally from 600 to 800 feet thick and the latter is not less than 150 feet. Only the topmost beds of the Morrison probably covered the arch and are concealed beneath the talus of red rock.

MORRISON SEDIMENTATION.

The Jurassic in this vicinity is represented by but one formation, the Morrison. The physical history of the period is not well indicated within this area. Fossils have not been found here, but those collected at other places show that the water of the Morrison sea was fresh. On the north and south, therefore, the ocean was shut out by land barriers extending east from the mountains to other land at an unknown distance.[a] At first the Boulder arch stood less than 100 feet above the water, and its height above the sea was gradually reduced by subsidence or by a change of the lake level. The arch was probably covered by the upper beds of the Morrison.

At a distance from the vicinity of the Boulder arch, the clays at the summit of the Jurassic have a nearly but not altogether constant thickness. If present at all between Gregory and Boulder canyons, they are very thin. Erosion is plainly indicated. The fresh-water lake gave way to land. Paleontologic evidence taken from broader areas indicates that this area was land through the whole of Lower Cretaceous time. The relief of this land surface was low. This is inferred not only from the fact that no valleys appear in its present buried surface, but also from the nature of the sediments when it was again submerged.

DAKOTA SEDIMENTATION.

At the beginning of Upper Cretaceous time the sea again covered this region. The first bed of sediments laid down contains much sand, but consists largely of very resistant and generally well-rounded pebbles of quartz, quartzite, jasper, and chert. The selection and separation of such materials from the waste of the previous land surface are consistent with low relief and deep weathering.

These facts are best explained by assuming that these residual pebbles of very resistant minerals were embedded in the surficial deposits of the submerging land. The soil sheet was worked over and assorted by wave action and these large pebbles deposited near shore. An unknown quantity of such deposits, brought down by streams from the land to the west, is doubtless mingled with the material derived from the submerging mantle rock. The finer and much more abundant products of decomposition were necessarily deposited farther seaward. According to this explanation this conglomerate is a shore phase of the lowest Dakota beds.

Mingled with the hard pebbles are occasional fragments of rocks, such as limestone, clay, and feldspathic rocks, that would readily yield to weathering and wear. These may have come in part from

[a] Emmons (op. cit., p. 24) suggests that the Morrison lake may have extended from near the northern boundary of Colorado to the latitude of the Raton Hills.

cliffs that were cut from low hills of the old land surface. They also suggest what they alone would not be sufficient to prove, namely, that the oncoming of the sea was accompanied by some warping and steepening of the land; but of this there is other evidence, as follows:

Before the close of the Jurassic the Boulder arch was covered by sediments, which were not entirely eroded away during the succeeding land epoch, showing that the land must have been very near the sea level. The absence of the lowest Dakota near Boulder, however, shows that just before the Dakota sediments were laid down elsewhere there was a differential subsidence amounting to a renewal of deformation along the old line.

BENTON SEDIMENTATION AND UPLIFT.

As a result of deepening of the sea, decrease in the relief of the land, and gradual removal of the shore, the Dakota sands were followed by the Benton shales, not suddenly, but after some alternation of sediments. The arching was again strongly renewed, this time between Sunshine and Boulder canyons. Erosion cut away the entire Dakota, but there is nothing to show whether the Jurassic was further wasted. The uplift remained above water until very near the close of the Benton epoch. Only the very latest beds of the Benton are continuous over it. The amount of uplifting at this time was therefore approximately equal to the combined thickness of the Dakota and Benton. The average thickness of these formations north and south of Boulder is not less than 700 feet.

NIOBRARA SEDIMENTATION.

The deposition of the Niobrara was not accompanied by noteworthy physical conditions, except those attributable to diminishing sediment, removal of shore, or deepening water. There is no evidence in this area of any disturbance at its close.

PIERRE SEDIMENTATION AND FOLDING.

As a single mass of shale, the Pierre is extraordinary on account of its great extent and thickness. A discussion of the factors adequate to produce these results would not be possible from observations in this small area. It is safe to assume that during Pierre time there was a steadily sinking sea bottom and a steadily rising land that had a relief sufficiently low to allow thorough decomposition. The sinking area on the east and the rising area on the west were necessarily separated by a monoclinal fold of increasing height. It is highly probable that this fold lay along the line of the present foothill belt and that although its dip was more gentle than that of the present great monocline it determined the line along which the forces of mountain making later gave form to the steep monocline which now follows the eastern border of the Archean belt.

The record of changes on the Boulder arch continues legible during a considerable fraction of Pierre time. The arch continued to rise relatively—that is, it sank less rapidly than the adjacent areas. This is shown by the position of the Hygiene sandstone. At Boulder this stratum is separated from the Niobrara by barely 1,000 feet of Pierre shale. Five miles farther north the same shales are 3,000 feet thick, showing a relative rise of the Boulder arch amounting to 2,000 feet during the first half of the Pierre epoch. The record of the latter half of Pierre time is not clear, because there are not enough outcrops to allow satisfactory determinations of thickness over the Boulder arch. The shale-making conditions were not uniform throughout the epoch. The deposit of so thick and continuous a sandy stratum as the Hygiene sandstone probably indicates a temporary dominance of the uplifting forces over subsidence.

FOX HILLS SEDIMENTATION AND LARAMIE UPLIFT.

There were no noteworthy physical changes at the beginning of or during the Fox Hills epoch, except variations similar to those which occasioned the sandy layers in the Pierre. The Laramie indicates a general uplift, both by the coarser character of its sediments and by its beds of coal.

SUMMARY OF HISTORY OF THE BOULDER ARCH.

With the exception of the growing monocline which separated the sinking sea bottom on the east from the rising land on the west, the Boulder arch is the index of all the crustal deformation definitely recognized as occurring in this area before the Rocky Mountains were formed. It is noteworthy that the forces which caused it acted in a north-south direction. In the later deformations east-west forces were completely dominant.

From the evidence given above, the successive rises of this east-west anticline may be summarized as follows: During the Boulder and Lyons epochs there was a rise which may have reached the maximum limit of 1,000 feet. (See p. 55.) The axis of this movement was south of Boulder Creek. At the close of the Lykins there was a further elevation, approximating 850 feet. (See p. 61.) In the interval between Jurassic and Dakota there was a relative elevation whose minimum may be placed at 25 feet. The uplift at this time may have been broad, extending from south of Gregory Creek to a mile north of Sunshine Canyon. At the close of the Dakota the minimum uplift was 700 feet along an axis between Sunshine and Boulder creeks. In the first half of the Pierre epoch the further rise amounted to 2,000 feet.

Maxima are given in some cases, and minima in others, but the sum of all the above amounts, which is 4,575 feet, may be taken as an approximation to the total elevation of this anticline.

An examination of the geologic map shows that there has been a great depression of the Boulder arch since the formation of the Hygiene sandstone. If the strata of the foothills and the plains were now deprived of their eastward dip, the upper beds would show a pronounced east-west syncline on the site of the former anticline. Even in the lower beds little of the former east-west anticline remains. Since the Hygiene sandstone is the youngest formation that gives evidence concerning the age of Boulder arch, the date of this flattening can not be fixed within narrow limits. A similar arch, stretching eastward from Golden, about 17 miles to the south, can be studied in more detail, because of the presence of younger strata. Emmons[a] and Eldridge[b] held that the flattening of the Golden arch may have occurred in Denver time, and perhaps was due in part to the extravasation of basalt along the line of the old anticline. The two arches had almost the same history, and the sites of both are marked by volcanic extrusions. Cross assigns the eruptions to the same epoch. Whatever causal relation exists between the extrusions near Golden and the flattening of the Golden arch may also be assumed to exist between the Valmont dike and the depression of the Boulder arch.

POST-LARAMIE HISTORY.

Post-Laramie history is recorded in the deformations incident to mountain making and in the forms due to erosion. The time of most of the events can not be accurately determined by local evidences.

Topographic features due to erosion are presumably in the main Quaternary. They indicate continuous degradation that has resulted in a series of river terraces. With the exception of the small fragments of the loess sheet (see p. 35) and a few isolated alluvial fans, there are no fluviatile deposits except those left by degrading streams. There is no broad sheet, such as that of the High Plains,[c] implying an epoch of stream aggradation. Everywhere the stratified rocks of this margin of the plains have been neatly pared off by meandering streams. The sheets of gravel which cover the planed surfaces are such as down-cutting streams should be expected to leave.

[a] Mon. U. S. Geol. Survey, vol. 27, p. 50.

[b] Id., p. 100.

[c] Johnson, W. D., The High Plains and their utilization: Twenty-first Ann. Rept. U. S. Geol. Survey, 1901, pp. 651–656.

No features in this area require for their formation streams larger than the present ones. The present Boulder Creek is a degrading stream, with moderate meanders and a broad flood plain sloping toward the stream. Where it reaches the bluffs which front its terraces the river is cutting into the bed rock and planing off a surface on a level with the bottom of its channel. On this planed surface it is depositing a sheet of heavy gravel and finer alluvium, similar both in character and thickness to the sheets which everywhere cover the mesas and other terraces. (For a more explicit comparison see p. 14.) That the streams which caused the present plains topography were degrading their channels is plainly shown by two facts: (1) The débris sheets have a uniformly limited thickness, and (2) the terraces always slope toward the streams to which they were flood plains. This continuity in the cutting by the streams gives to the erosional history of the district a unity which makes subdivision impracticable.

This uniformity of erosional history near the foot of the mountains is in contrast with the more complex history of the plains farther east,[a] where the denuding processes have plainly been interrupted by aggradation one or more times. The obvious inference is that the entire recorded erosional history of this narrow belt must be matched with the last epoch recorded on the plains, which is one of stream degradations.[b]

It is entirely natural that when the character of streams is changed, whether from aggrading to degrading, or the reverse, the belt nearest the mountains should be the first to suffer complete obliteration of the records of former conditions. The rivers may recently have acquired increased cutting power by an uplift on the west that increased their grade, or by an increase of rainfall, or, as Johnson suggests, by a mere cooling of the climate, which would decrease evaporation. In any case the upper course must first be cut down and in this the records of former aggradation will first be erased. If the change of stream habit be the reverse, the prompt burial of features near the mountains is equally well understood. If the climate is moderately arid, as in the area under consideration, there is an additional reason for the prompt erasure of aggradation records near the mountains, as running water is more abundant there, many streams actually losing volume as they proceed.

[a] Johnson, W. D., op. cit., p. 628; also Emmons, S. F., op. cit., p. 255.

[b] As to the geologic data of this epoch Johnson says (op. cit., p. 630): "The beginning of the final and present degradation, during which the smoothness of the Great Plains has been in large part destroyed and their surface lowered, with the exception of the sod-covered plateaus of the central zone, doubtless dates from the opening of that period of climatic oscillations in the Pleistocene which, in the Great Basin region of Utah and Nevada, gave rise to repeated floodings of large areas and the creation of lakes."

ECONOMIC GEOLOGY.

WATER.

SURFACE ZONE.

Ground water in the area under consideration is found at moderate depths. Over the well-drained parts of the plains it is commonly encountered at depths of from 10 to 20 feet. Since the bed rock is in large part relatively impervious shale, the slope of the ground-water surface is very similar to the slope of the ground. One bluff 40 feet high is quite dry at the base, but on the terrace above, less than 200 feet from the bluff, water is found at a depth of 12 feet. The surface shales are everywhere more permeable than the unweathered rock below, and the movement of water in them is freer than at greater depths. In drilling oil wells, therefore, it is found necessary to case off this surface water.

DEEPER ZONE.

Below this superficial zone, which is 25 to 50 feet thick, the shale is so dense and the consequent movement of the water so slow that wells are spoken of as "dry." At irregular intervals within the shales, as deep as the formation has been explored in drilling for oil, are sandier beds of limited lateral extent. In these the movement of the water is more rapid, and after drilling through them it is sometimes necessary to case off the water from these deeper sources. When the character of the water is suitable, these beds might afford supplies for deep wells, but the water is not infrequently slightly saline, and it may be a brine. Flowing wells are not obtained from these sources in the Pierre shales, nor are they expected, on account of the limited lateral extent of the sands and their close texture where unweathered.

FLOWING WELLS.

South of Burnt Knoll, about 6 miles southeast of Boulder, a faint flow of water was obtained from the Laramie at a depth of 80 feet. A similar flow was obtained at Lafayette, 11 miles east of the foothills, at various depths between 400 and 700 feet. It was encountered while drilling for oil.

At the north end of the field the Stuart well, drilled for oil, encountered abundant water in the Morrison formation. At last accounts (April, 1904) the well was still flowing. It is located on the Pierre shales, one-half mile east of the Dakota outcrop (SW. $\frac{1}{4}$ of sec. 5, T. 2 N., R. 70 W.). The dip of the beds at the surface is here 26°. The succession of strata passed through leaves no doubt that the Morrison was encountered at a depth of 1,336 feet. If all the beds passed through dip at an angle of 26° and have the thickness given above, under the heading "Stratigraphy" (pp. 20 et seq.), the Morrison should have been found at a somewhat greater depth than 1,336 feet. Probably at a short distance below the surface the dip is less than at the surface, where it has been steepened by the process described above as tending to produce a fan structure. The water is from a horizon about 60 feet below the top of the Morrison; it is therefore from one of the upper beds, probably from the "Saurian" sandstone. This supposition is supported by the fact that the water comes from yellow sand. Presumably the lower and larger Morrison sandstones, and especially the basal stratum, would yield water still more copiously. This assumption is supported by observations on the small stream flowing east over the Lykins and Morrison outcrops in Lykins Canyon. The channel when examined was dry as far as the outcrop of the Morrison. At this point water appeared within a few yards and there was a flowing stream. No well, however, has reached these lower beds, the Stuart being the only one which is known to have entered the Dakota. The high dip of the strata makes it impracticable to obtain water from even the best beds of the Morrison except within a narrow strip east of the foothills.

WATER IN THE DAKOTA.

Water was obtained in the Stuart well from the Dakota, but not in amount to be compared with that from the Morrison. The relations of the Dakota are not favorable to any great water supply for northern Colorado. The hardness of the formation causes it to outcrop in a single rocky ridge, which quickly sheds the precipitation and is unfavorable to percolation. True, the outcrop is crossed by streams flowing from the mountains, but even this intake must yield a small supply on account of its extremely restricted area. Moreover, the Dakota sandstone is practically sealed below by relatively impervious shales and clays, and therefore can not receive much of the water that penetrates the lower strata which outcrop west of the Dakota hogback. If the Dakota of northern Colorado be compared in these various respects with other well-known water-bearing strata—for example, the Potsdam of central Wisconsin, or even the Dakota sandstone of the Black Hills—its area of intake will be seen to be very small and topographically unfavorable to percolation. The slow inflow into the Stuart well from this formation also indicates that it is denser than the sandstones of the Morrison. The Morrison sandstones, though much thinner than the Dakota, outcrop in a valley, or on the western slope of the great ridge of which the Dakota forms the crest. In either case their edges are generally covered with a sheet of loose waste, favorable to percolation.

BUILDING STONE.

In the matter of building stone the area here described is typical of a much longer stretch of the foothill belt of which it forms a part. Most of the formations yield valuable economic products, the building stone coming mainly from strata not younger than Jurassic.

GRANITE.

Within the area mapped granite has not yet been quarried or even studied with reference to its use as building stone. Apparently, however, the area may furnish granite for architectural purposes of suitable grain, color, strength, and size of block.

THE RED ROCK.

The great mass of the Fountain red rock is not appropriate to building purposes. Locally, however, there are, near its summit, beds of the finest quality of structural stone. One-fourth mile north of Fourmile Canyon a quarry has recently been opened at this horizon to supply material for the new Episcopal Church at Boulder. In contrast with the prevailing arkose character of the Fountain, these exceptional beds are even-grained, quartz sands, containing only here and there minute grains of feldspar. Biotite scales are rather plentiful, and are arranged parallel to the bedding, so that transverse faces show only very minute black lines, which are not sufficiently prominent to indicate the position of the bedding except by very close examination. The stone is of a light pink color, which runs uniform so far as the quarry referred to has been worked. Except in the biotite, all the contained iron is supposably in the peroxide form, and the stone contains nothing to cause a stain upon exposure to the weather. The stone is massive and must be dressed on all sides of the block. Blocks which dress 2 or 3 cubic feet are frequent. The strength has not been tested, but there is no doubt an ample margin beyond the needs for all ordinary building purposes.

LYONS SANDSTONE.

This is by far the most abundant rock of economic importance within the area described, and probably within the foothill belt north of Denver. The name "creamy" sandstone, which is often applied to it, is unfortunate, for it is distinctly pink. It varies somewhat in color, however, and at one extreme it may reach an almost creamy tint, while at the other it may be red. Still, the great mass is so uniform that stone from many quarries might easily be used in one building. The standard color of this stone has more of the creamy and less of the vermilion tint than that of the rock quarried from the Fountain sandstone. It does not develop any discoloration in the wall.

In composition the stone is of the purest even-grained quartz sand, its siliceous cement deriving its color from ferric iron. The cement is so abundant as to make the stone quartzitic, and it is known in the trade as a crystalline sandstone.

The distinguishing feature of the structure of this stone is its delicate lamination and perfect partings in the quarry. Fifty laminations to the inch may sometimes be readily distinguished, but at a distance of a few feet the lines are invisible and the stone has a uniform tint. Occasional stronger lines may make the lamination more prominent.

In the quarry the stone parts perfectly into thicknesses varying from a fraction of an inch to more than a foot. Flagstones of convenient thickness and having as much as 60 or even 80 square feet of surface may be obtained. The flagstone industry has its center at Lyons, about 3 miles north of this area. Near Boulder the thickness of the beds is generally greater, and the stone is commonly quarried for building. The blocks for this purpose may be as thick as 15 inches, but the average is probably not above 8 inches. As the bedding planes are perfectly smooth and parallel, the blocks require dressing on four sides only. Both the convenience and the strength of this stone cause its general use in foundations in the near-by towns and cities. It is also used for the superstructure in some large and handsome buildings. The stone is likewise in common use for sills and curbings. As pointed out on page 24, the bedding planes observed in nearly all quarries of the Lyons sandstone are those of the cross-bedding, having had a dip toward the shore on the west when deposited.

The amount of this stone in northern Colorado is enormous. If its workable thickness in this area averages 50 feet and if quarries be worked 100 feet down the dip of the stratum, each linear mile of the foothill belt would yield 1,000,000 cubic yards of stone.

RED SANDSTONE OF THE LYKINS.

Stone from this series of beds is not quarried in this area. At a few places the Lykins yields a very fine-grained and close-textured red sandstone, easily worked and readily obtained in large blocks.

The same stone occurs abundantly within this area, but, whether from the repeated warping of the Boulder arch or from the diagonal compression resulting in the échelon folds, it is too much fractured to be obtained in large blocks. This is the case at each of the few places where it has been prospected.

WHITE SANDSTONE OF THE JURASSIC.

The chief quarry opened in the lowest Morrison sandstone stratum is known by the name of Doctor Bond. The product of this quarry is a slightly calcareous sandstone of moderate strength, of a gray color, inclining toward yellow rather than blue, and having no lamination or subordinate bedding planes within a 10-foot stratum. It is not always free from iron stains, which may appear in the quarry or may develop after building into the wall. Large dimension stones are readily taken out and easily worked. The bed in which this one quarry is opened has a fairly uniform thickness and character for many miles. It is probable that in the future this stone will be quarried much more extensively.

BUILDING STONES FROM THE CRETACEOUS.

But little stone is quarried from strata younger than Jurassic. The Dakota is very strong, but difficult to work, the blocks generally requiring dressing on all sides. Within this area it need scarcely be taken into account, as it is accompanied by other formations containing such vast stores of more desirable material.

The massive summit sandstone of the Fox Hills is quarried in considerable quantity farther north. It is but little exposed within this area, and where found it is commonly too weak for structural purposes. Beyond the eastern border of the area it is not improbable that this stone will be found locally of fair quality.

The white sandstone of the Laramie can scarcely be called a commercial product. It is present in great quantities and easily taken out and worked in blocks of large dimensions, and a few houses have been built of it. Its strength, however, is small, and it is much stained with iron.

GRINDSTONE.

The white sandstone at the base of the Morrison, which is used for building purposes as described above, is locally used for grindstone and enjoys considerable favor. About a mile north of Altona a quarry, known as the "Grindstone quarry," has been opened by Peter Haldi, of Altona. The few grindstones from this source which are in regular use have been dressed by hand. To all appearances they are doing their work in a highly satisfactory manner. The grain is fairly sharp, the cement is very slightly calcareous, and the stone is easily dressed. Several much-used surfaces seemed to be clogged with the muddy products of the abrasion of the stone itself, but the users maintain that such an occurrence is the result of improper use. The crude methods of quarrying have produced rather small and ill-shaped blocks, but, judging from the same stratum where quarried for building purposes, this does not indicate any fault in the stone itself. Suitable shapes and sizes can no doubt be easily obtained.

LIME.

The production of quicklime is carried on to a limited extent. The stone used is mainly from the basal stratum of the Niobrara. At various places also the limestone lenses of the "crinkled" sandstone in the Lykins have been utilized; occasionally also the beds in the Morrison. The limestone of the Niobrara is highly magnesian[a] and very dense. On account of its density it does not calcine very readily and the large percentage of magnesia makes a "cool" lime.

CLAYS.

OPPORTUNITIES FOR THE BRICK INDUSTRY.

The brick industry at Boulder is already large and there is no necessary limit to its expansion, except the size of the market, the raw material being presumably inexhaustible. It appears, however, that the Pierre shale, which is the chief resource for red brick, is not entirely uniform in its brick-making properties. Yards within the limits of Boulder produce bricks differing in shrinkage, density, and strength. As the surficial aspect of the Pierre shales is highly uniform for long distances, it is very probable that laboratory tests will come into general use in the locating of yards as the industry expands.

Red brick must always constitute the chief product of the clay industry. Three plants, each with a capacity of 20,000 bricks a day, are operating steadily at substantially full capacity. These are all using the Pierre shale and are practically within the city of Boulder. The Benton has not been used. At present all the pits are on mesa edges, the mesa in each case being from 30 to 50 feet higher than the adjacent lowland. While such a situation may be desirable from

[a] An analysis of Niobrara limestone is given by Eldridge, op. cit., p. 67. It shows 18.03 per cent MgO.

the standpoint of moisture conditions, it is mainly a matter of convenience, and must not be understood to be necessary. There is nothing to bar from future use any part of the shales of the Pierre belt as shown on the map.

SHALE SUPPLY.

At each of the three pits the shale is covered with the rough mesa gravel, which at one place has a thickness of 15 feet, and which is removed. Where the mesa gravel is almost absent, the clay resulting from decomposition of the shale may be as thick as 2½ feet, but this is of no significance in the manufacture of brick. Where the mesa gravels are thick, the clay is wanting. The shale is almost free from lime, though some highly calcareous nodules occur, sometimes containing fossils. Occasionally, also, a thin plate of shale is dark and hard with impregnated iron, but the quantity of such is almost negligible.

If the shale is not reduced to clay, it is not to be understood that it has been entirely unaffected by weathering. Its bedding remains perfect and it is apparently unweathered, but where excavation is deep the color is always observed to change from a greenish drab above to something darker (commonly called "black") below. Throughout the belt underlain by the Pierre, though the normal color varies, the surficial zone shows almost the same greenish-drab color. This ends abruptly at a depth of 30 feet, more or less. In the black shale (or "slate") below lamination is less apparent, and large masses break with a conchoidal fracture. Naturally the concretions are not observed within this fresh mass, as they are in the partly weathered zone, from which they roll out upon blasting. The shales of the upper zone have little grit when tried between the teeth.

A partial analysis of the shale from the Austin yard, made by Prof. C. S. Palmer, is given by Mr. Austin, as follows:

Analysis of shale from Austin yard, Boulder.

	Per cent.
SiO_2	60.0
Al_2O_3	18.0
Fe_2O_3	4.75
MgO	2.0

An analysis of a single selected lump (not a mixed sample) of the shale from Mr. Lee's yard, made by Mr. W. B. Stoddard, of Boulder, and furnished by Mr. Lee, is as follows:

Analysis of shale from Lee yard, Boulder.

	Per cent.
SiO_2	63.309
Al_2O_3	14.380
Fe_2O_3	6.270
FeO	.859
CaO	1.810
MgO	2.570
Na_2O	2.190
K_2O	1.280
Loss by drying	2.053
Loss by ignition	5.223
	99.944

PROCESSES OF BRICK MANUFACTURE.

The material is first loosened by blasting. Concretions are thrown out, chiefly to save wear in the crusher. They are said to be harmless in the brick if crushed sufficiently fine. In one of the three pits the black shale below is not reached. In another it is reached at the bottom, but not used. At the Austin works, on the north side of the city of Boulder, it is taken out and used along with the shale of the higher zone. It is harder, drier, and less plastic, and is therefore mixed with the partly weathered material. When thus mixed, no difference in the resulting brick can be detected, and there is no inconvenience in the manufacture. If properly ground, the unweathered black shale may be mixed with the weathered shale in equal parts. The blasting of this fresher shale in the autumn and its weathering or slacking through the winter has been tried, but no notable difference was produced.

The shale is crushed, screened, and pressed dry. Generally the moisture of the bank is sufficient for the pressing process. When the shale is too dry it is moistened in the crusher. No mud bricks are made.

The burning is in up-draft kilns, which generally have permanent walls for two-thirds or three-fourths of the height. One-half to two-thirds ton of local (Marshall or Louisville) coal per 1,000 bricks is used in the burning. Mr. Austin has installed a gas plant, and the project of burning with gas may be said to be on trial.

The shrinkage in both drying and burning of the best and strongest samples tested was but one-sixteenth inch in the height of the brick (4 inches), or less than 3 inches in the height of the kiln. Either by reason of difference in the clay or in the burning, this shrinkage varies at other yards to a maximum of three-sixteenths of an inch per brick, or 7½ inches in a kiln 40 bricks high.

QUALITY OF THE BRICK.

Standard tests made upon the red bricks by Prof. L. Duncan, of the University of Colorado, show an average crushing strength for the best brick equal to 4,100 pounds per square inch.[a] Supported at the ends (supports 6 inches apart) and loaded at the center, the same bricks showed a maximum fiber stress of 498 pounds per square inch. The same bricks absorbed water equal to 11.2 per cent of their weight in fifteen minutes, 11.6 per cent in thirty minutes, and 11.9 per cent in twenty-four hours. The promptness with which these bricks absorbed nearly the whole amount of water which they were capable of containing indicates largeness of the individual pores. The more rapidly water is absorbed, the more rapidly it is lost, and the probability that a sudden freeze should find the pores of these bricks filled with water is very small. This statement does not apply to bricks laid below the water line.[b]

No attempt has been made to make vitrified brick on a commercial scale at the Boulder yards. Experiments have been carried on in this line, and a very good brick resulted, but the shrinkage was great. In two tests it was seven-sixteenths inch and one-half inch in the height of the brick (4 inches).

BRICKS OF LIGHT COLOR.

For several years past small quantities of light brick of a prevailing creamy color have been burned at the Boulder yards from clay brought by wagon from the coal-mining districts to the southeast. The first clay for this purpose was brought from Coal Creek. The largest amount has come from an abandoned coal mine at Marshall, from 3 to 4 feet of the clay being taken from the floor of the mine. More recently a number of samples from near Burnt Knoll have been tested, and encouraging results are reported.

Tests of light bricks from the Marshall clay gave a crushing strength about equal to that of the best red brick (4,090 pounds per square inch), a maximum fiber stress about two-thirds as great as that of red brick (332 pounds per square inch), and absorption slightly greater than that of the red bricks (12.5 per cent in twenty-four hours).

Red brick sell in Boulder at $7 to $9, the last-named price being for facing brick. The common price f. o. b. for shipment is $10

[a] This may be compared with the strength of one of the best-known building stones of the United States, the Bedford limestone of Indiana, which showed, in 17 tests, an average crushing strength of 4,326.7 pounds per square inch.—Twenty-first Ann. Rept. Indiana Dept. Geol. Nat. Resources, p. 317.

[b] See Buckley, E. R., Building and ornamental stones: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 4, 1898, p. 20.

per thousand. Buff brick have not been exported. They sell in Boulder at $20 per thousand.

Just beyond the western border of the area, near Sunshine, is a deposit of kaolin, much of which is to all appearances very pure. Probably the deposit is due to the alteration of feldspars in a pegmatite dike. The clay is white and without grit. Some of it is stony and contains kaolinite crystals. Upon grinding and wetting it becomes thoroughly plastic.

COAL.

A small part of the northern Colorado coal field lies within the area here described. The whole field was carefully studied by Eldridge,[a] who has described the structure, discussed the quality of the coal, and correlated the seams of the different districts. Since the publication of his work, in 1896, several new mines have been opened, but these have revealed no structural relation not known and discussed in Monograph XXVII. The reader will find in that publication substantially all that is known in regard to the geologic relations of the coal.

OIL AND GAS.

SURFACE INDICATIONS.

The development of oil and gas in the Boulder area began in 1901, though their presence was suspected and rumored as early as 1867.[b] The early beliefs were based upon grounds which might now be regarded as far from demonstrative. The subsequent finding of oil must therefore be regarded largely as a piece of good fortune rather than the assured outcome of a safe business venture. The evidence consisted largely in the strongly bituminous odor of the Benton and Niobrara limestones and shales. It was therefore assumed that the strong-smelling rocks were themselves the reservoirs of petroleum, and in the first developments there was no thought of finding oil above these beds. Oil was found several thousand feet higher than these two formations, which have never produced anything of this nature. They have the same characteristic odor near the oil fields and far away. It was reasoned out with equal certainty that the Benton and Pierre shales must produce coal on account of their black color. In fact, it was while prospecting for coal in the Benton that the project of drilling for oil was first conceived.

A second class of surface indications, not found nearer than about 10 miles from Boulder, consists of seepages and "oil springs." The

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[a] Op. cit., p. 345.

[b] A brief historical account of this industry is given by the writer in Bull. U. S. Geol. Survey No. 213, p. 322.

fact that several such, most persistently reported, are on the Archean granite west of the foothill outcrops of stratified rocks shows that

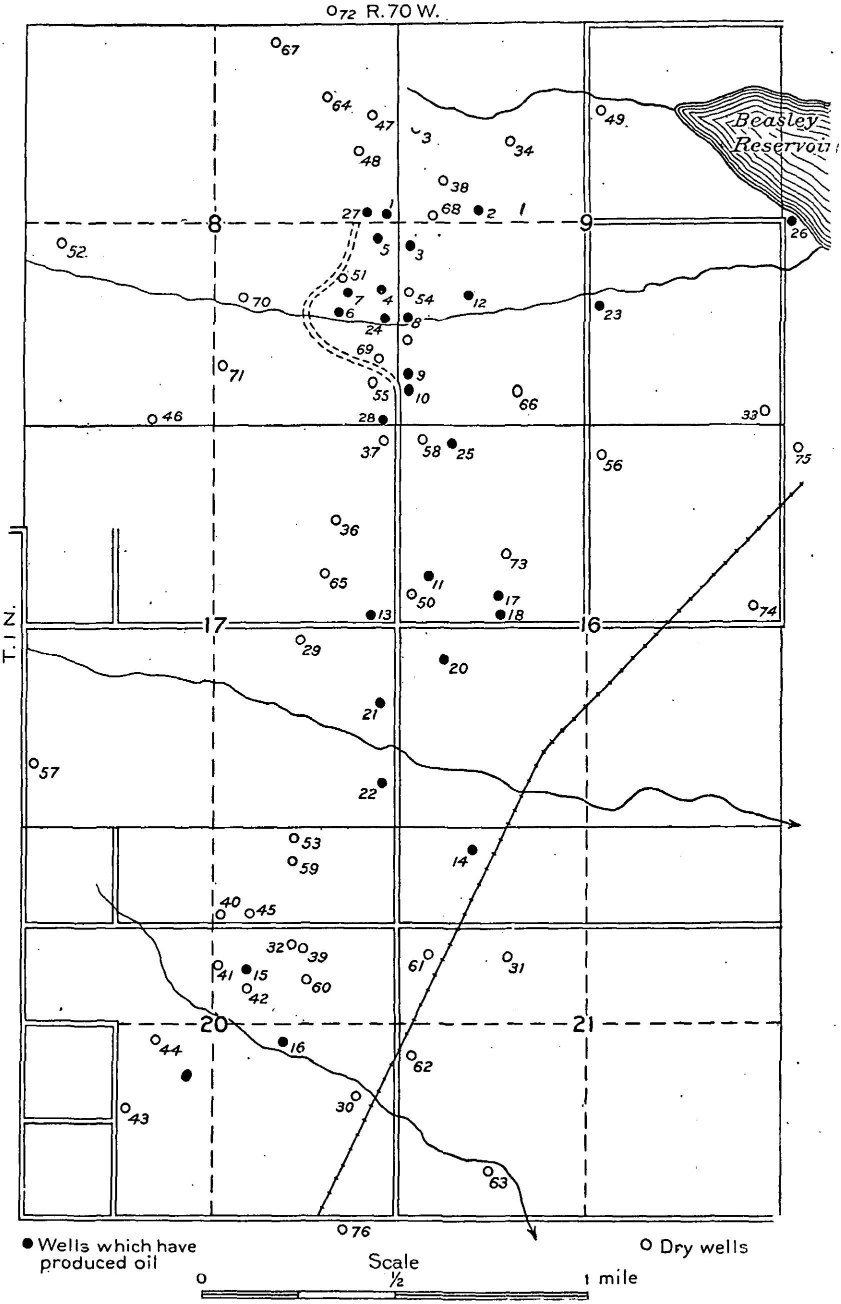

FIG. 9.—Map showing location of oil wells in the productive area.

the distinction between the various kinds of oily substances was poorly made. Some of the springs which issue from the Fountain red rocks are abundantly coated with oily matter at no great distance from the point of issuance, and these springs have been taken very seriously by oil prospectors, but in none of those examined was the odor of petroleum detected. The well-known oil spring on the bank of the Little Thompson, on the Culver ranch, 17 miles north of Boulder, issues from the heavy sandstone member of the Pierre, which has been called in this report the Hygiene sandstone. This is a seepage of petroleum.

OIL-BEARING AREA.

On the evidence of these phenomena, corroborated by the positive behavior of "bobbers,"[a] several wells were drilled. In January, 1901, the McKenzie well, 3 miles northeast of Boulder, struck oil. Since that time there has been more or less drilling from Fort Collins on the north to Golden on the south. Sheet XII of Hayden's atlas has been freely used as "Hayden's oil map," and land underlain by his Colorado group (which includes the Pierre) has been well advertised as lying within "Hayden's oil belt." Development has been successful only within a limited area, the center of which is from 3 to 4 miles northeast of the city of Boulder and a little less than 3 miles east of the foothills. About 100 wells from 300 to over 3,400 feet in depth have been drilled within 5 miles of the McKenzie and about 20 more are scattered over the area between Fort Collins and Golden. Most of the wells (about 70) are within a rectangle 2 miles east and west by 3 miles north and south, comprising secs. 8, 9, 16, 17, 20, and 21, T. 1 N., R. 70 W. of the sixth principal meridian. Within this rectangle are all the producing wells except the Boulder Illuminating, a very small producer in sec. 10 only a few feet from the eastern boundary of the rectangle named, and the Buffalo gas well, which lies 1 mile south of the rectangle.

The following list gives the location of wells, the total depth, and the depth at which oil was found. The accompanying sketch map (fig. 9, p. 77) shows the locations of all wells within the productive area. Some of the dry wells are comparatively shallow; therefore in determining their significance their depths, as shown in the table, should be taken into account.

[a] The exact location of a large proportion of the wells of this field has been fixed by this means. The principle on which the use of the bobber rests is the same as that by which the proper site of a water well is determined by the involuntary turning of a witch-hazel sprout when held in the hand. In two instances, completed derricks have been taken down and removed to distances not exceeding 40 feet, because of the behavior of the bobber after their erection.

Wells in the Boulder district.[a]

WELLS THAT HAVE AT SOME TIME PRODUCED OIL.

No.	Name.	Depth.	Depth to oil.	Location.		
				Section.	Township.	Range.
		Feet.	*Feet.*			
1	Bradford No. 1	2,404	1,810	8	1 N.	70 W.
2	Boulder Valley	2,050 T.	2,010	9	1 N.	70 W.
3	Boulder Valmont No. 2	1,960	1,650	9	1 N.	70 W.
4	Otero No. 1	1,718	1,639	8	1 N.	70 W.
5	Otero No. 3	1,905+	1,807?	8	1 N.	70 W.
6	Otero No. 4			8	1 N.	70 W.
7	Otero No. 5			8	1 N.	70 W.
8	Savanna No. 3	1,763	1,584	9	1 N.	70 W.
9	Savanna No. 4	1,475 T.	1,468	9	1 N.	70 W.
10	Savanna No. 5 (Younglove)	2,005+	1,980 T.	9	1 N.	70 W.
11	Dismuke	2,070+	2,064	16	1 N.	70 W.
12	Orcini			9	1 N.	70 W.
13	McAfee No. 1		2,105 T.	17	1 N.	70 W.
14	McKenzie	2,585 T.	2,537 T.	21	1 N.	70 W.
15	Republic No. 1	961	885	20	1 N.	70 W.
16	Wellington	2,461	2,423	20	1 N.	70 W.
17	Bingham		2,845	16	1 N.	70 W.
18	Arnold	2,820	2,720	16	1 N.	70 W.
20	Wisconsin No. 2	2,900		16	1 N.	70 W.
21	Crawford	2,735 T.	2,683	17	1 N.	70 W.
22	Central	2,621	2,551	17	1 N.	70 W.
23	Two-ten	2,141	2,111	9	1 N.	70 W.
24	Otero No. 2	1,761	1,700	8	1 N.	70 W.
25	St. George			16	1 N.	70 W.
26	Boulder Illuminating	2,700		10	1 N.	70 W.
27	Bradford No. 2	1,720		8	1 N.	70 W.
28	Savanna No. 2	2,300	2,130	8	1 N.	70 W.

DRY OR NEARLY DRY WELLS.

No.	Name.	Depth.	Location.		
			Section.	Township.	Range.
		Feet.			
29	McAfee No. 2	2,700	17	1 N.	70 W.
30	Eagle	2,740	20	1 N.	70 W.
31	Alamo	2,825	21	1 N.	70 W.
32	Great Western	1,600	20	1 N.	70 W.

[a] Numbers in the left-hand column refer to corresponding numbers on the sketch map (fig. 9). Wells not numbered are outside the mapped area. Depths marked T were determined by steel tape measure; most of the others by cable measure.

Wells in the Boulder district—Continued.

DRY OR NEARLY DRY WELLS—Continued.

No.	Name.	Depth.	Location.		
			Section.	Township.	Range.
		Feet.			
33	Planet No. 2	2,025	9	1 N.	70 W.
34	Searchlight No. 2	2,480	9	1 N.	70 W.
35	Home	1,650	9	1 N.	70 W.
36	Hayden No. 1	2,670	17	1 N.	70 W.
37	Hayden No. 2	2,145	17	1 N.	70 W.
38	Phoenix No. 2	2,400	9	1 N.	70 W.
39	North Star	1,160	20	1 N.	70 W.
40	North Bend	787	20	1 N.	70 W.
41	Republic No. 2	1,008	20	1 N.	70 W.
42	Republic No. 3		20	1 N.	70 W.
43	Homestake	1,100	20	1 N.	70 W.
44	Vindicator	1,300	20	1 N.	70 W.
45	Savanna No. 1	700	20	1 N.	70 W.
46	Boulder Petroleum	1,630	8	1 N.	70 W.
47	Pioneer No. 2	2,160	8	1 N.	70 W.
48	St. Julian		8	1 N.	70 W.
49	Canfield		9	1 N.	70 W.
50	Wood	2,525	16	1 N.	70 W.
51	Otero No. 6, now Rathvon No. 2	[a] 3,575	8	1 N.	70 W.
52	Wisconsin No. 1	2,000	8	1 N.	70 W.
53	Cleveland	2,492	20	1 N.	70 W.
54	Savanna No. 6		9	1 N.	70 W.
55	Savanna No. 7		8	1 N.	70 W.
56	McAfee No. 3	2,580	16	1 N.	70 W.
57	Chicago Banner	2,600	17	1 N.	70 W.
58	Langridge	2,500	16	1 N.	70 W.
59	Sale Boulder		20	1 N.	70 W.
60	Me Edma		20	1 N.	70 W.
61	Keystone		21	1 N.	70 W.
62	Blue Jacket		21	1 N.	70 W.
63	Boulder Basin	3,300	21	1 N.	70 W.
64	Independence	2,550	8	1 N.	70 W.
65	Palm		17	1 N.	70 W.
66	Empire No. 2	2,500	9	1 N.	70 W.
67	La Ford	2,700	8	1 N.	70 W.
68	Craig & Bartlett		9	1 N.	70 W.
69	Savanna No. 8		8	1 N.	70 W.
70	Rathvon No. 1		8	1 N.	70 W.

[a] Drilling deeper.

Wells in the Boulder district—Continued.

DRY OR NEARLY DRY WELLS—Continued.

No.	Name.	Depth.	Location.		
			Section.	Township.	Range.
		Feet.			
71	Hayden No. 3		8	1 N.	70 W.
72	Citizens No. 2	1,850	5	1 N.	70 W.
73	Empire No. 1		16	1 N.	70 W.
74	Anderson	2,684	16	1 N.	70 W.
75	Peoria	2,300	15	1N.	70 W.
76	Phoenix No. 1		29	1 N.	70 W.
(a)	Citizens No. 1	2,500	25	1 N.	71 W.
(a)	Maxwell No. 1		24	1 N.	71 W.
(a)	Maxwell No. 2	2,268 T.	24	1 N.	71 W.
(a)	Pioneer No. 1	2,700+	29	2 N.	70 W.
(a)	King	2,870	22	1 N.	70 W.
(a)	Lafayette, Colo	2,325		1 N.	70 W.
(a)	Planet No. 1	700		1 N.	70 W.
(a)	Searchlight No. 1	1,185		1 N.	70 W.
(a)	Monarch	1,500	27	1 N.	70 W.
(a)	Moore	1,500	23	1 N.	70 W.
(a)	Balkan	1,000	29	1 N.	70 W.
(a)	Boulder Valmont No. 1	2,740	22	1 N.	70 W.
(a)	Rose Crude	2,500	29	1 N.	70 W.
(a)	Jasper		10	1 N.	70 W.
(a)	Aurora	3,006	10	1 N.	70 W.
(a)	Amazon		15	1 N.	70 W.
(a)	Carnahan	3,105	18	1 N.	69 W.
(a)	Hoover		35	1 N.	70 W.
(a)	Martin		5	1 S.	70 W.
(a)	Manhattan	3,216	14	1 N.	70 W.
(a)	Olean	2,995	30	3 N.	69 W.
(a)	Hygiene	2,993	36	3 N.	70 W.
(a)	Gardiner	2,300 ?	2	2 N.	70 W.
(a)	Phenomenal	2,150	6	1 S.	70 W.
(a)	Thomas	3,055	19	2 N.	69 W.
(a)	Silver Lake (Stuart well)	1,396	5	2 N.	70 W.
(a)	Sternberg		33	1 N.	70 W.
(a)	Pioneer No. 3		34	1 N.	70 W.
(a)	Prince No. 1		27	2 N.	69 W.
(a)	Prince No. 2		27	2 N.	69 W.
(a)	Buffalo (gas well)	1,800	29	1 N.	70 W.

[a] Wells not numbered are outside the area of sketch map (fig. 9).

The Savanna No. 9, in sec. 9, has reached at the present writing (October, 1904) a depth of 1,840 feet, where a good showing of oil has been encountered.

The Rathvon No. 2 (No. 51 on the map, fig. 9), already the deepest well in the field, is being drilled deeper.

DRILLING IN THE PIERRE.

With few exceptions, the wells thus far put down have been drilled entirely in the Pierre. The exceptions are among the scattered wells to the east, which are on the very similar Fox Hills, or even on the Laramie, but these also traverse the Pierre for the greater part of their depths.

Drilling in this formation is comparatively easy and rapid. It is not uncommon to make 100 feet a day at considerable depths, and this is sometimes done without change of bits. On the other hand, slow progress is made in some beds. The average expense of drilling a well under contract with responsible parties is, at the present time, about $1.65 per foot for the first 2,000 feet. Below that depth the cost is greater. Under such contracts the owner of the well furnishes casing.

Surface water is usually encountered at a depth of about 15 feet and may be found in the first 100 or even the first 200 feet. Below this the wells are commonly "dry" or the seepage into the wells from the dense shales is so slow as to be of no significance in drilling. In isolated cases deep water-bearing strata are encountered, and such water is sometimes salt. At Lafayette, 11 miles east of the foothills, a well that was drilled for oil yielded a vigorous flow of water from several horizons between 400 and 700 feet deep. The oil from another well is mixed with about 10 per cent of salt water, which comes from just below the oil, and a slight admixture of salt water is found in at least one other well.

Many wells are cased only to the depth of the surface water. Others require 1,000 or even 2,000 feet of casing. In general, deep casing is not for the purpose of shutting off water so much as to avoid caving, which is common though not general. It has necessitated the abandonment of several wells.

REPORTS RECEIVED FROM WELL DRILLERS.

By far the most common material reported as passed through is shale or "slate," occasionally varied as "clay" or "soapstone." Sand or "sand rock" is often reported. If it shows oil it is often called "the oil sand," with no particular reference to correlation with the sands of other wells. These sands are described on pages 31–33.

Their composition is generally far from that which the name would suggest. They range from sand to clay, vary in thickness up to a maximum of over 100 feet, have a limited lateral extent, pass by gradations into the normal shale of the Pierre, and occur at any depth. One well may pass through five or six such beds, while another near by may penetrate nothing but shale to a depth of 2,000 feet. In drilling, the sandy beds are distinguished from the shales by their greater hardness, by the more rapid wear of the tools (the driller's chief criterion), and by the smaller amount of suspended matter in the water of the bailer. The washed-out samples commonly appear upon close examination as a collection of gritty shale granules, whose edges have been rounded under the drill. The better grades show an admixture of quartz grains, and exceptional beds are pure sand.

"Streaks" and "shells" are other terms used to indicate more than usual hardness at certain horizons. In the outcrops of these shales may frequently be detected hard beds a few inches or even several feet in thickness. They are either very calcareous or stained with iron oxide, or both, and owe their superior hardness to concentration of these substances. Such induration may affect the entire bed equally or may be concentrated into ellipsoidal concretions, which may be more or less separated, so that there are all gradations between the continuous hard plate and the isolated concretions. The word "shell" is suggestive of the concretions, as the word "streak" is of the plates, but in the reports the two words may be taken to be synonymous and alike indefinite. The comminuted fragments of these hard masses are not easily suspended in the water of the bailer, and probably for this reason, as well as on account of their superior hardness, are not infrequently reported as sand. On the other hand many of the so-called hard streaks are siliceous. The reports of "lime rock" are probably sometimes to be traced to the same occurrences, though, as seen on page 31, there are some true limestone beds in the Pierre.

OIL-BEARING STRATA.

The beds from which the oil is obtained are the highly variable sands or sandstones, described above as varying between clay shale and silica sand. Such beds may be met with at any depth, but there is no depth at which such rock is certain to be found. Reports might indicate that it is slightly more abundant at a depth approaching 2,000 feet, but this may be due to the sharper lookout for sand as the well gets deeper. Not all of these strata contain oil or gas; some of the most porous sands give no indication of either.

While the thickness of such beds may be anything up to 100 feet or more, oil or gas may be obtained from only a part of their thickness. Such strata are plainly not so homogeneous as would appear from the bailings and, except locally, are far from being porous sandstones. Except in an oil well they would probably not be called sands at all. It is not uncommon to drill many feet into such strata and then strike a showing of oil or gas with no attendant change in the texture of the rock that can be detected in the bailings.

These small reservoirs of oil or gas seem mutually independent, being separated by the impervious shales. This isolation is well illustrated by the occurrence of deep veins of water in some wells and the absence of water from near-by sands in the same well or in adjacent wells. This mutual isolation of the several pockets is not accompanied by any great diversity in the character of the oils. With but few exceptions there is approximate uniformity, as shown by standard physical tests. Considering the striking uniformity of the great body of shales, this general likeness in the character of the oils is to be expected. Thus far there is but one authenticated instance in which the pumping of a new well has influenced the production of an older well. In this case the two wells are less than 200 feet apart. Curiously enough, these two wells found oil at depths differing almost 500 feet.

SHOOTING OF WELLS.

All but one of the wells which were pumped previous to the close of 1902 were shot. In 1903 this practice was less general. The amount of nitroglycerin used in these shots has varied from 10 to 140 quarts. Dynamite charges have been as large as 500 pounds, 70 per cent nitroglycerin. The effects of these shots have not been uniformly favorable. The beneficial effects in a few of the best wells have doubtless been responsible for most of the later attempts. More recently a number of wells have begun pumping without being shot. The fact that the flow of some wells has decreased since the shooting will lead to greater caution, and it is to be hoped that it will lead to a more careful study of the nature and thicknesses of the strata passed through.

The beneficial or harmful effects of a shot must depend largely upon the texture of the stratum yielding the oil, for it seems to be true that some shales are compacted rather than shattered by the explosion. Supposably for this reason, shooting is not practiced in the Florence field, which, of all the older oil districts, the Boulder field most resembles. Owing to the difference in texture of the various beds yielding oil in the Boulder field, it is but reasonable to expect that the same shot which would prove beneficial to one well would be ruinous to another. On this account, if on no other, the texture and composition of the oil strata should be carefully studied by methods far more discriminating than the superficial ones first used in this field. It is but just to the companies and contractors now remaining on the ground to say that there has been much improvement in the character of well records.

A second reason for injurious effects from shooting lies in uncertainty about the exact depth of the sand which it is intended to shatter. Measurements of depths by steel tape are now becoming more common. In most of the earlier wells the depths of all formations are known only by cable measurement. It is not uncommon that the stated depths of important sands are thus liable to errors of 25 to 50 feet.

The possible injuries from a shot at the wrong place may be readily seen from the following consideration. If a porous rock is saturated with oil under pressure and is pierced by the drill, the oil is pressed upward in the hole solely because it has no outlet in any other direction, being surrounded (as in this field), or at least overlain, by impervious rocks. If this well is shot in such a way as to rupture the impervious rocks that surround the oil sand, the oil may leave the sand by other openings besides the well and may thus be dissipated in other porous beds and the well may be ruined.

Such an injurious effect may be produced even by shooting at the proper depth if the charge employed be too heavy. In one instance a well was shot at 740 feet with 500 pounds of dynamite, 60 per cent nitroglycerin. The formation above the sand was a uniform dense shale. A good quality of sandstone was blown from the hole in large chunks, one of which weighed 14 pounds. The shale was ruptured to the surface. Open cracks an inch or more wide extended for some rods from the well. It may be presumed that cracks also reached a considerable depth below the sand which was to be shattered. The well, of course, yielded no oil.

It can not be too carefully borne in mind that the one object in shooting is to shatter the rock which carries the oil and that only. With this object in view, it is plain that intelligent and discriminating shooting must depend upon the answers to the following questions: Is the oil stratum of such a texture that it will be shattered rather than compacted? What is the exact depth of its top (and bottom if drilled through)? How much of a shot will the overlying rocks bear without giving other outlets to the oil? This last question is one of great importance in this field. It is needless to say that such questions can be answered only by a carefully kept log and close study of samples, not only of oil sands but of all strata, in order to properly forecast their behavior under the influence of a shot.

Wells which were shot previous to June, 1903.

Name.	Charge of nitro-glycerin.	Depth of shot, in feet.	Effect.
	Quarts.		
McKenzie	140	2,530-2,587	No change.
Savanna No. 1	40		Abandoned after shot.
Savanna No. 2	100	2,115	Intended to shoot at 2,100; abandoned after shot.
Savanna No. 3	50	1,579-1,600	Reduced production from 10 barrels to 5 barrels.
Savanna No. 3 (second shot).	100	1,579-1,600	Produced about 7 barrels after second shot.
Otero No. 1	60	1,649-1,673	Not pumped before; a good producer.
Otero No. 2	10	1,724-1,761	Not pumped.
Otero No. 2 (second shot).	60	1,724-1,761	Little oil before; not pumped; a fair producer afterwards.
Otero No. 3	[a] 10	1,600-1,900	Shot four times; little oil.
Otero No. 3 (fifth shot).	60	1,807-1,837	Produced 3 or 4 barrels.
Bradford No. 1	100		Produced 4 or 5 barrels.
Bradford No. 2	30	1,650	Went on drilling.
Bradford No. 2 (second shot).	15	1,720	Very small producer.
Boulder Illuminating.	100		Not pumped before; a very small producer.
Crawford	100	2,682-2,734	Fair well before; ruined.
Boulder Valley	80	2,021	Increased production from 6 barrels to 15 barrels.
Hayden No. 1		2,005	Shot with 500 pounds dynamite, 70 per cent; no effect.
Do	80	Same depth.	Never pumped.
Central	100	2,600	A little oil; soon abandoned.
Two-ten	120	2,111-2,141	Not pumped before; small producer afterwards.
Hayden No. 2	40	2,135	Never pumped.
Anderson	40	2,670	Do.
Wisconsin No. 2	40	2,035	Small producer; drilled deeper and abandoned.
Boulder-Peoria	80		Never pumped.
Independence	60	1,100	Do.
Boulder-Valmont No. 2.	60	1,650	Drilled deeper.
Boulder-Valmont No. 2 (second shot).	60	1,947	A fair producer.
Dismuke	60	2,064	Not pumped before; a small producer afterwards.

[a] For each shot.

Wells which were shot previous to June, 1903—Continued.

Name.	Charge of nitro-glycerin.	Depth of shot, in feet.	Effect.
	Quarts.		
Buffalo	40	1,600	No oil; did not affect gas production.
Republic No. 1	24	965	Little or no change.
Republic No. 3			Shot with 100 pounds dynamite; no change; dry hole.
North Bend		740	Shot with 500 pounds dynamite, 60 per cent; hole ruined.

STRUCTURE OF THE OIL FIELD.

From all observations previous to the preliminary report made by the writer in January, 1903,[a] there appeared to be no law governing the distribution of oil in the Pierre shales. Small bodies of oil have been found in various parts of Colorado and neighboring States, but their structural relations, so far as known, afforded only vague explanations of their presence, and left the prospector with the impression that oil might or might not be found at almost any place in the Pierre.

The want of any known evidence of anticlinal arches suggested the inference that such structures were unnecessary to form receptacles for oil and gas in so dense a rock as the Pierre shales. The idea of some connection with folds was, however, not given up, and renewed efforts were made to induce companies and drillers to preserve samples and careful records, with a view to determining the exact position of the strata. During the summer of 1903 a detailed structural study was made of an area of 150 square miles, of which the oil field occupies the center.

It is a noteworthy fact that, with the exception of two very small producers, all the wells which have thus far produced oil are in a very narrow north-south belt. It is now known that this belt follows a monoclinal fold, the wells being near the top, and therefore in similar structural position to those of Ohio described by Orton as occurring on "arrested anticlines." The two very small producing wells, referred to above as located outside the narrow belt, are the Two-ten, one-half mile east, and the Boulder Illuminating, 1 mile east. It will be seen below (p. 92) that these wells occupy very significant positions with respect to another fold.

The monocline on which the wells are located is almost in line with an incipient échelon fold to the north-northwest, which affects the

[a] The Boulder, Colo., oil field: Bull. U. S. Geol. Survey No. 213, 1903, p. 322.

foothill belt after the characteristic manner of such folds in this region. (See p. 43; also map, Pl. II.) For the present purpose it is best seen in the prominent offset in the outcropping edge of the Hygiene sandstone in sec. 6. The axis of this fold points east of south. In the outcrop of the same sandstone, but 5 miles farther northeast, a well-developed fold of similar character branches off, with an axis trending almost due south. Both these folds are described below. The monocline which determines the present line of producing wells is the southward continuation of the western and smaller one of the two flexures, but it is affected both in degree of flexure and in the direction of its axis by the stronger fold to the east.

It may be confidently affirmed that whatever may be the nature of the occurrence of oils elsewhere in the Pierre, there is nothing thus far known in the field at Boulder to offer encouragement to prospectors, except in intimate relation with folds. The essential features of this particular flexure should, then, be determined with care. Such a study may afford a basis for inference as to the probable oil-bearing or barren character of other similar structures occurring throughout a distance of 50 miles along the front of the range.

The form and location of these folds are best made clear by tracing the outcrop of the Hygiene sandstone (see p. 31), which made possible the discovery of the folds. Near Boulder the stratum is thin and weak and is separated from the Niobrara on the west by not more than 1,000 feet of shales. Seven miles north of Boulder it is 250 feet thick, and the Pierre shales below it have thickened to nearly 3,000 feet. As the dip has also greatly decreased within the same space, the sandstone outcrop has been carried nearly 2 miles to the east.

Stated more definitely, the outcrop forms a prominent cuesta (a ridge of abrupt scarp slope and long, gentle dip slope) running from the southwest corner to the northeast corner of sec. 6, T. 1 N., R. 70 W. This northeastward strike in sec. 6—an exception to the prevailing trend, which is almost north—is the surface expression of a mild tendency to échelon folding. It belongs to the same flexure as the monocline of the oil field, and its more prominent northwestward extension has been described on page 44. From the northeast corner of sec. 6 the outcrop extends north by east through the west side of sec. 32, T. 2 N. For nearly a mile north of this, in the vicinity of Lefthand Creek, the ridge is lost, but it reappears in the west half of sec. 20, running almost north. On the north side of this section the outcrop disappears under Table Mesa. If the mesa is crossed in a northeasterly direction, its northern side is reached in the middle of sec. 9. At this point the sharp crags of this sandstone are seen, forming a bold, bare ridge running far away to the northeast (N. 27° E.).

If the mantle rock were removed from the mesa it is believed that the outcropping sandstone ledge would be seen to describe a great loop (see map, Pl. II) instead of cutting straight across from the point where it disappears under the southwest side to where it reappears on the northeast. The reasons for assuming such a structure will appear in a description of the outcrops.

As noted above, the strike for the last mile or two on the southwest side of Table Mesa is nearly north. Similarly on the northeast side, the ledge which approaches the plateau with a strike of S. 27° W. turns, just before its disappearance, to a direction differing only 8° from due south. The two outcrops, therefore, on the northeast and southwest sides would, if prolonged in straight lines, miss each other by about a mile.

There is a second outcropping ledge of sandstone on the south side of Table Mesa, a little more than a mile east of the one mentioned above, and about one-half mile west of Haystack Mountain. The sandstone of this eastern outcrop also forms a low ridge, and is to all appearances identical with that of the more westerly exposure. It shows the same succession of beds—a strong ledge of sandstone and a second horizon, a few hundred feet higher, marked by great calcareous concretions. (See p. 32.) The strike here is N. 35° W., and the dip is 10° to the northeast.

This low ridge abuts, as do those of the other outcrops, against the steep mesa scarp. It is believed that this line of outcrop is directly continuous with that which approaches Table Mesa from the northeast; that it represents the eastern limb of an anticlinal fold whose crest has been eroded away; that if the soil cover could be removed and the edge of the Hygiene sandstone everywhere exposed it would be found again dipping west on the western limb of this anticline a quarter to a half mile west of the eastern exposure; that the loop would be seen as represented in fig. 9, the outcrop crossing Table Mesa with a southerly trend from the middle of sec. 9, passing in a southeasterly course past Haystack Mountain, looping perhaps a mile to the south, then turning back to the north for 3 miles or more, then turning sharply around once more to the south along the course first described.

The structure here described is inferred mainly from dips, all of which within the area concerned agree with the features described. Although the Hygiene sandstone shows no good outcrop on the western limb of the anticline, westward dips as high as 18° are plainly seen within the sandy shales on the south side of Lefthand Creek near the line between secs. 28 and 29. At the north end of the canoe-shaped synclinal trough southward dips are found, according perfectly with the assumed structure. These may be seen along the high, level ditch skirting the northwest side of Table Mesa.[a]

Such an anticlinal fold as the one just described must die out gradually at the end. (See fig. 10.) If the axis be traced southward, the dip of the western limb should become less and less steep. At a certain point the westward dip will become zero; there will be a structural bench, as it were, interrupting the general eastward dip. This bench will be horizontal, except for a southward

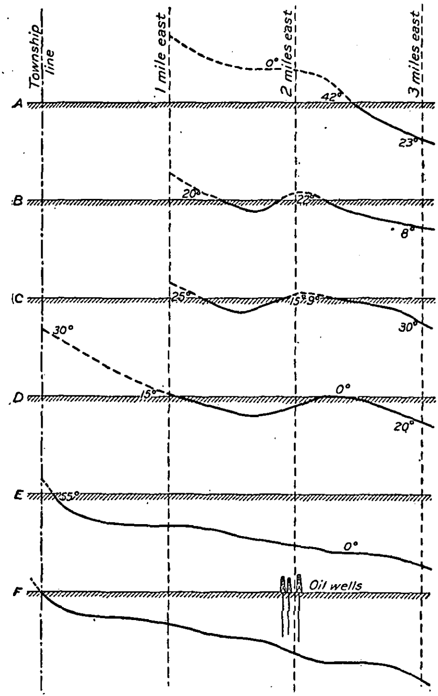

FIG. 10.—Cross sections showing the folding of the Hygiene sandstone. The straight horizontal lines represent the surface of the ground. The solid curve indicates the present position of the stratum, and the dotted curve indicates the position of the stratum before erosion. A, 10 miles north of the fortieth parallel, which is 1 mile south of Boulder; B, 9 miles north; C, 8 miles north; D, 6½ miles north; E, 5 miles north; F, 4 miles north.

inclination. Still farther south the whole will again dip toward the east, but in line with the axis of the anticline the dip will be smaller than either east or west of that line.

In the north side of sec. 9, T. 1 N., northwest of the Beasley reservoir, the only dip is one to the south, as is made apparent on the map

[a] This structure was first described by the writer in a paper entitled Structure of the Boulder oil field: Bull. U. S. Geol. Survey No. 225, 1904, p. 383. Since that publication and since the above paragraphs were written Messrs. S. F. Rathvon and William Rathvon, oil operators, have had eight holes dug to ascertain the dip of the shales in sec. 33, T. 2 N., R. 70 W., and secs. 4 and 9, T. 1 N., and to verify the structure as described above. The results have fully confirmed the statements made here.

by the outcropping of two arenaceous beds, the lines of outcrop having an east-west direction. This is on the axis of the larger fold. At this place the axes of the two folds (see p. 88) are in proximity, and the eastern and stronger fold uplifts the east side of the feebler western fold, making a horizontal bench out of what would otherwise be only a partial flattening of the general eastward dip. The result is seen on a line passing south through secs. 8, 17, and 20, along which the shales have no eastward dip. This belt is, however, narrow—a small fraction of a mile—and in short distances both east and west of it decided eastward dips appear.

Immediately east of this bench, perhaps on an average one-fourth of a mile, the producing wells are found. Their linear arrangement is all the more striking if the line be extended south to include the Buffalo gas well in the southeast corner of sec. 29. The position of the oil-producing strip is in exact accord with that of oil-producing belts of Ohio, where the conditions of occurrence have been made so well known by the very complete discussion of Orton.[a] The possible finding of other pools remote from such a structure need not be discussed here. They may or may not be found in structures differing from the one to which they are here related. It can only be said that the example of the already developed portion of this field offers no warrant for prospecting where these structural features are absent.

It may safely be assumed that the one significant feature in the structure of the oil field is the decided arrest of the general eastward dip. The peculiar relation of the two folds whose effects at this place unite to produce the result is not in itself taken to be significant, except in so far as it explains the occurrence or location of the one valuable feature. Further, it must not be assumed that this or any similar flexure will necessarily be oil-bearing throughout its whole length. Even very small transverse folds affecting the axis are sufficient to break up the deposit into so-called "pools." The intermittence of good oil territory along the line thus far developed, from secs. 8 and 9 on the north to the Buffalo gas well on the south, is already known. It can not therefore be assumed that one or two dry holes indicate that a line marked by the above-described structure is entirely barren.

SUGGESTIONS AS TO FURTHER DEVELOPMENT.

If, then, the promise of future developments in this oil field be limited to a relationship with folds, it is highly important to exam-

[a] The Trenton limestone as a source of petroleum and inflammable gas: Eighth Ann. Rept. U. S. Geol. Survey, pt. 2, 1889.

ine similar occurrences beyond the limits already developed. In the discussion, however, it must always be taken into account that the beds capable of containing deposits are small and of uncertain lateral extent. At the outset the further extension of the immediate group of productive wells demands attention. The axis of the fainter of the two folds, whose combined effects produce the monocline in and south of sec. 8, runs northward from the present developed field, but the very few exposures along this northern portion have not shown dips less than 6° or 7°, and therefore no close approach to the structure described above as occurring farther south, in the vicinity of the successful wells.

The stronger fold to the east completely neutralizes the general eastward dip as far south as sec. 4, while farther north it has a westward-dipping limb. The axis of this fold runs north by a little west through sec. 4, T. 1 N., R. 70 W., and secs. 33 and 28 of T. 2 N. The axis of this fold has not been tested by the drill. At its southern extremity, however, where the strata begin to dip strongly southward (10° or 15°), is the Two-ten well, and one-half mile farther east is the Boulder Illuminating. Both of these wells are small producers (about 2 barrels a day from each well), but the finding of oil, even in small quantities, in this relation to the fold is significant. From a structural standpoint it may be expected that if larger quantities of oil are present they will be found nearer the axis of this fold rather than farther away.

Sheet No. XII of Hayden's Atlas of Colorado shows with considerable detail a series of large échelon folds, but those described above are, in general, too small to appear on that map. The salient curve in the Dakota, however, shown on the Hayden map north of Lefthand Creek, must be correlated with the long loop in the Hygiene sandstone described above. If this latter formation were drawn on the Hayden map, the loop in question would be three-fourths of an inch long. A fair idea of the relative sizes of such folds may be had by comparing the effects of each on the same formation, as, for example, on the Dakota.

The question of stores of oil in the larger folds naturally suggests itself, in view of the known relation of oil to the smaller. It is to be remembered, however, that in the Appalachian region it is not the great anticlines which have conserved the hydrocarbons. Here, as there, the greater deformations may prove to have made poor reservoirs, probably by the opening of cracks. Nor, indeed, has it yet been shown that the larger of the small folds in the Boulder field is an oil reservoir. If the future proves otherwise, there will be a strong presumption in favor of restricting the search for oil to folds of the smaller order. If the large folds shown on the Hayden map are to prove oil-bearing, it will probably be in their remote ends, where the fold is dying out on the plains.

A condition of this nature has been put to the test in one instance. A fine fold of this kind, north and east of Lyons, flattens out in the vicinity of Hygiene (about 12 miles north and 5 miles east from Boulder). Here, in a line transverse to the axis, three wells were drilled to depths approximating 3,000 feet. They were not without showings of oil, but a better showing was obtained 4 miles farther down its axis to the southeast, where the fold has flattened greatly and was probably never considered a factor. Oil from a depth of about 600 feet has also accumulated in an abandoned water well, a mile north of Hygiene. This is also on or near the axis of the fold.

If the larger folds fail to yield oil, the one remaining hope (probably more promising from the start) lies in the smaller folds. For reasons given above, these, in so far as they affect the Pierre shales, are betrayed only by the most obscure outcrops. Yet it is in this formation, at a distance of a few miles from the harder rocks of the foothills, that folds must be found if they are to serve as guides in prospecting for oil.

Herein lies the large significance of the similar though often very small flexures which affect the stronger and well-exposed strata of the foothills from Morrison to Niobrara, inclusive. In these stronger rocks they may be very small, the looping back generally being less than a quarter of a mile; but the same stress will be found to have produced larger results in the weaker Pierre. Therefore, if the Pierre shales are to be prospected in this region of échelon folding, much time will be saved by making a preliminary examination of the stronger strata. Where the Hygiene sandstone is exposed, it is the natural index of structure and the best. Where it does not outcrop, the basal Niobrara limestone is the nearest criterion.

In these suggestions no account is taken of the possibility of folds running strictly parallel to the foothill outcrops. This is of course possible, especially south of Boulder, where the échelon type is not prevalent. The lines of procedure suggested above are only those which have been derived from the known structure of the already developed field. They are not intended to exclude consideration of structures not yet exemplified.

The Maxwell gas well, less than 2 miles north of Boulder and a little more than half a mile from the Pierre-Niobrara contact, may seem an exception to all that has been said above regarding the location of oil and, by inference, of the closely associated gas. It might therefore be thought of as putting the generalization to a severe test. Near-by outcrops are too few and unsatisfactory to fix the structure with any definiteness, but it is a remarkable fact that this well lies south-southeast from an incipient échelon fold which affects the boundaries of all outcrops from the Lykins to the Benton. (See p. 43.) The axis of this fold would seem to pass a little west of the Maxwell well.

SOURCES OF THE OIL.

The strata containing the original substances from which the oil of the Boulder field has been derived are not determined with exactness. Much of the Pierre is black with disseminated carbonaceous matter. The Niobrara below is bituminous, yielding a strong odor, especially from its more fossiliferous beds. The same is true of the Benton, whose shales are characteristically dark, and whose bituminous odor is at least as well marked as that of the Niobrara. The Dakota bears oil in Wyoming, and an asphaltic substance oozes from its cracks at various places from Wyoming to southwestern Colorado. Even the Morrison beds contain some oil, as seen near the Florence field.

The strata thus enumerated have a combined thickness of from 5,000 to 6,000 feet below the horizon of the lowest oil reached in the Boulder field. The Benton and Niobrara are doubtless richer in organic matter than any higher strata and surely far richer than anything below. While these considerations are favorable to the beds below the Pierre as the ultimate sources of the oil, others favor a source not far from the horizon at which the oil is found. Neither hypothesis is established and neither can yet be abandoned.

The great density of the Pierre shales must make them a serious barrier to the passage of any form of matter. It is significant that the same dense shale which forms the so-called "cap rock," and is therefore considered impervious to oil or gas, also underlies the oil, and must therefore have been traversed by the hydrocarbons for thousands of feet if the ultimate source of these substances was in the Benton and Niobrara. It is also noteworthy that some of the purest white friable silica sand found in deep wells has contained no oil. Such sands must have been quickly discovered by the rising hydrocarbons working their way upward from great depths through the scanty pores of the shale. Both the general density of the shales and the absence of the oil from certain friable sands favor a hypothesis which locates the original source of the oil at horizons not very far from those at which it is now found. In this case it is safe to say that the tilting of the beds has given opportunity for the segregation of their fluids according to their several specific gravities. Theory would require that the oil should be found just about where the present wells are located; that is, on the slope below the horizontal bench. The summit of the monoclinal slope, or edge of the structural terrace, should be the approximate western limit of gas, or of oil, if there be little gas present. This is because fluids lighter than water, after rising through an inclined porous stratum to this line, could find no higher place to go.

A similar segregation might occur in beds whose dips are not interrupted by a horizontal bench. If oil, in mounting to higher levels through such porous beds, finds them gradually changed to dense shales, there must result an accumulation along the upper margin of the porous portion, regardless of folds and interrupted dips. It is not improbable that small accumulations of this kind exist in the Pierre shales and may in the future be found. The chance that such may exist is independent of the original source of the hydrocarbons. It matters little whether this was near the horizon of the oil-bearing strata or thousands of feet below.

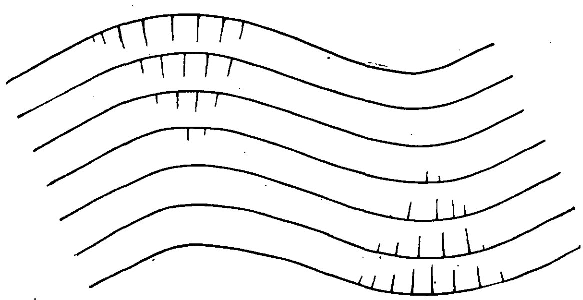

FIG. 11.—Hypothetical cracking in the formation of the oil-field monocline.

The suggestion of a deep source for the original constituents of the oil, based on the bituminous character of the Benton and Niobrara beds, is so strong that any plausible explanation of its rise through the Pierre shales deserves consideration. While in general highly dense, it is not certain that the Pierre shales directly below the known oil deposits are unfractured. If affected by fracture they may not be so impervious as would be inferred from a study of samples. The folding along this belt may have had more significance than the making of suitable closed reservoirs in which to hold the oil. At the foot of such a monoclinal offset as has been described, the lower strata might well be expected to be stretched and those above compressed. (See fig. 11.) At the top of the monocline, the reverse is true; the upper beds should be stretched and those below compressed. If such folding, therefore, is to result in greater permeability of the lower beds along any belt, it must be along the foot of the monoclinal slope. From all observations in this field, this tendency to fissuring in the deeper beds might well be the chief significance of the monocline. It has been pointed out above that the axis of the oil-producing belt so far as explored is a full quarter of a mile east of the north-south line along which the shales are horizontal. The dip of the shales through which the producing wells are drilled approaches 20°. Assuming the folds of the lower strata to be similar to those above, and remembering that no reservoirs of gas have been found, which might be expected to crowd the oil down the slope, this situation of the oil deposits does not favor the analogy of the anticlinal reservoir. It seems to suggest that the foot of the monoclinal slope may be quite as important in relation to the accumulation of oil as is its top.

There are here, therefore, two possible ways in which folding may have affected these oil deposits: (1) It may have provided suitably constructed reservoirs; (2) it may have made the deep rocks sufficiently permeable to allow the ascent of hydrocarbons from the lower formations whose constitution makes them the most plausible sources. If the deeper origin be assigned to the oil, then the second consideration is more urgent in this field than the first, though the two are quite consistent. The second consideration provides for communication (otherwise seemingly impossible) with the most bituminous beds of the region. It also localizes the upward movement of the hydrocarbons along lines of fracture, thus accounting for the absence of oil and gas in some of the most porous sands. It also harmonizes well with the situation of oils far down the monoclinal slope. Finally, such a structure in a mass of shales containing occasional sandy beds would result in accumulation at very diverse depths. Fractures leading up from below would here strike and there miss sands of limited lateral extent, just as the wells reaching down from the surface have done.

The stretching and possible fracture of the deeper beds at the foot of a monoclinal slope are, of course, not open to observation. The corresponding process in the upper beds at the top of the slope has left the marks which were to be expected in this field. A considerable amount of fracturing is evidenced by calcite vein filling. In the SE. ¼ sec. 6, T. 1 N., R. 70 W., where there is the incipient échelon fold that has been described (map, Pl. II), the north side of the mesa shows broad exposures of the bare shales. The weathering and erosion of these has left the surface strewn with chunks of calcite which occupied the crevices of the shale. These veins are often several inches wide. Similar evidence is seen just west of the oil wells, where the horizontal position of the shales gives way to the eastward dip.

It is not intended to suggest that the lower beds at the foot of the monoclinal slope could be affected by open fissures. The necessary depth to which permeability, resulting from deformation, must be extended in order to reach the Niobrara and Benton is even now well above half a mile, and it may have been one or two thousand feet more at the time the folding took place (assuming subsequent denudation to that amount). At such a depth it is not to be expected that crevices in shale will open wide; indeed, the plausibility of the entire supposition here sketched depends upon the possibility of any fracture at all. However, inasmuch as the shale, when perfectly fresh, is a fairly strong rock, it seems at least probable that deformation within the zone concerned would be by fracture rather than by flowage. Still the connection between oil accumulation and permeability caused by folding can not yet be affirmed. Some questions remain to be answered before this supposition can be made a working hypothesis.

PHYSICAL PROPERTIES.

In physical tests the products of the different wells show a noteworthy resemblance, despite the diverse depths from which they are derived. There are minor differences in color, but in general the oil is a light amber and has a paraffin base and an agreeable odor. Gravity tests range from 42° to 44.6° Beaumé. In all flash tests reported the oil has flashed below 60° F., and the exact temperature of the point was therefore not recorded. The proportions of the more valuable products of refinement, notably that of kerosene, are very large. The current price of the crude oil, $1.10 per barrel, is the best indication of its quality from a commercial point of view. It is said by Oliphant to be the best oil west of Mississippi River.[a]

PRODUCTION OF OIL AND GAS.

As stated above (p. 77), there are nearly 70 wells in the productive area, though this number includes some very shallow holes. Twenty-eight have pumped oil at some time. Twelve of the 28 were abandoned before October, 1904, and a few others were not at that time pumped with any regularity.

The oil production amounted to 11,000 barrels in 1902 and 39,000 barrels in 1903. While a very substantial gain is thus indicated when the output is stated by years, the monthly production at the close of 1903 was smaller than at the beginning of the year. The average daily production for 1904 did not exceed 70 barrels.

[a] Mineral Resources U. S. for 1902, U. S. Geol. Survey, 1904, p. 562.

One gas well, the Buffalo, in the southeast corner of sec. 29, and therefore in the same north-south line with the oil wells, but farther south, has yielded considerable quantities of gas for several years. The gas is piped to Boulder and was at first used in connection with the manufactured gas. Since September, 1903, no gas has been manufactured, and the quantity of gas used from the well has been gradually increased. The rate of consumption has at times been nearly 3,000,000 feet per month. It is probable that the present rate of consumption could not with safety be greatly increased, but no diminution of the capacity of the well has yet been observed. Its quality is very satisfactory.

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