The Occurrence of Ground Water in the United States

With a Discussion of Principles

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 489

The Occurrence of Ground Water in the United States

With a Discussion of Principles

By OSCAR EDWARD MEINZER

GEOLOGICAL WATER-SUPPLY PAPER 489

Reprint, 1959
(Original plates not available)

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1923

UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C. - Price $3 (paper cover)

CONTENTS.

ILLUSTRATIONS.

THE OCCURRENCE OF GROUND WATER IN THE UNITED STATES

WITH A DISCUSSION OF PRINCIPLES.

By Oscar Edward Meinzer.

INTRODUCTION.

The writer has planned and partly prepared a series of six papers on ground water in the United States. These papers are to deal with (1) occurrence, (2) origin, discharge, and quantity, (3) movement and head, (4) quality, (5) recovery and use, and (6) ground-water provinces. The present paper is the first of the series.

The writer is indebted to many colaborers for assistance in preparing this paper, especially to the following members of the United States Geological Survey: M. R. Campbell, who read the entire paper; E. W. Shaw, C. E. Van Orstrand, A. F. Melcher, and C. K. Wentworth, who examined Chapter I; W. C. Alden, who examined Chapters II and IV with special reference to their statements regarding glacial geology; E. S. Larsen, who examined a part of Chapter II; G. W. Stose, who examined Chapter III; T. W. Stanton, who examined Chapter IV; L. W. Stephenson, who examined the parts of Chapter IV that relate to the Coastal Plain; C. W. Cooke, who furnished many unpublished data on the geology of the Coastal Plain; Miss M. G. Wilmarth, who gave valuable help in compiling the geologic sections; D. G. Thompson and Miss Norah E. Dowell, who furnished original data on the mechanical composition and porosity of various sedimentary materials; B. H. Lane, who made valuable criticisms of the text; and Martin Solem, who had charge of the preparation of the illustrations.

CHAPTER I. PRINCIPLES OF OCCURRENCE.

ROCKS AS RECEPTACLES OF WATER.

The rocks that form the crust of the earth are in few places, if anywhere, solid throughout. They contain numerous open spaces, called voids or interstices, and these spaces are the receptacles that hold the water that is found below the surface of the land and is recovered in part through springs and wells. There are many kinds of rocks, and they differ greatly in the number, size, shape, and arrangement of their interstices and hence in their properties as containers of water. The occurrence of water in the rocks of any region is therefore determined by the character, distribution, and structure of the rocks it contains—that is, by the geology of the region. Most rocks have numerous interstices of very small size, but some are characterized by a few large openings, such as joints or caverns. In most rocks the interstices are connected, so that the water can move through the rocks by percolating from one interstice to another; but in some rocks the interstices are largely isolated, and there is little opportunity for the water to percolate. The interstices are generally irregular in shape, but different types of irregularities are characteristic of different kinds of rocks. The differences in rocks with respect to their interstices result from the differences in the minerals of which they are composed and from the great diversity of geologic processes by which they were produced or later modified.

POROSITY OF ROCKS.

DEFINITION OF TERM.[1]

The porosity of a rock is its property of containing interstices. Some authors have used the term to refer only to minute interstices, which they call pores, but in comparison with the size of the earth itself even the largest openings are no more than pores, and the term "porosity" is much more useful if it is made to apply to all openings, instead of only to openings having an arbitrary limit of size. Porosity is expressed quantitatively as the percentage of the total volume of the rock that is occupied by interstices or that is not occupied by solid rock material. A rock is said to be saturated when all its interstices are filled with water. In a saturated rock the porosity is practically the percentage of the total volume of the rock that is occupied by water.

[1] See Gregory, H. E., and others, Military geology and topography, p. 114, New Haven, Yale Univ. Press, 1918 (chapter on water supply prepared chiefly by O. E. Meinzer).

CONDITIONS CONTROLLING POROSITY.

The porosity of a sedimentary deposit depends chiefly on (1) the shape and arrangement of its constituent particles, (2) the degree of assortment of its particles, (3) the cementation and compacting to which it has been subjected since its deposition, (4) the removal of mineral matter through solution by percolating waters, and (5) the fracturing of the rock, resulting in joints and other openings. Well-sorted deposits of uncemented gravel, sand, or silt have a high porosity, regardless of whether they consist of large or small grains. If, however, the material is poorly sorted small particles occupy the spaces between the larger ones, still smaller ones occupy the spaces between these small particles, and so on, with the result that the porosity is greatly reduced (fig. 1, A and B). Boulder clay, which is an

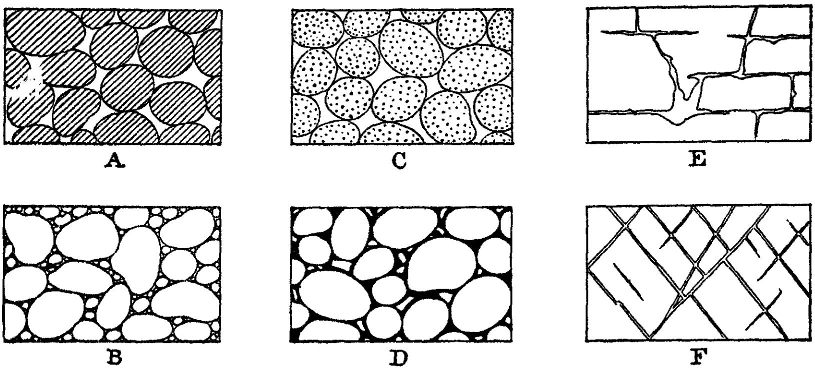


FIGURE 1.—Diagram showing several types of rock interstices and the relation of rock texture to porosity, A, Well-sorted sedimentary deposit having high porosity; B, poorly sorted sedimentary deposit having low porosity; C, well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; D, well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; E, rock rendered porous by solution; F, rock rendered porous by fracturing.

unassorted mixture of glacial drift containing particles of great variety in size, may have a very low porosity, whereas outwash gravel and sand, derived from the same source but assorted by running water, may be highly porous. Well-sorted uncemented gravel may be composed of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity (fig. 1, C). Well-sorted porous gravel, sand, or silt may gradually have its interstices filled with mineral matter deposited out of solution from percolating waters, and under extreme conditions it may become a practically impervious conglomerate or quartzite of very low porosity (fig. 1, D). On the other hand, relatively soluble rock, such as limestone, though originally dense, may become cavernous as a result of the removal of part of its substance through the solvent action of percolating water (fig. 1, E). Furthermore hard, brittle rock, such as limestone, hard sandstone, or most igneous and metamorphic rocks, may acquire large interstices through fracturing that results from shrinkage or deformation of the rocks or through other agencies (fig. 1, F). Solution channels and fractures may be large and of great practical importance, but they are rarely abundant enough to give an otherwise dense rock a high porosity.

POROSITY OF GRANULAR DEPOSITS.

RELATION OF POROSITY TO ARRANGEMENT OF GRAINS.

The most common type of water-bearing materials consists of deposits composed of fragments of rock that were more or less rounded by wear before they were deposited. In such deposits the water exists in the irregular spaces that remain between these fragments or grains. To investigate the water-bearing characteristics of such material Slichter[2] first made a theoretical study of the most simple case—an "ideal soil" consisting of spherical grains of equal size.

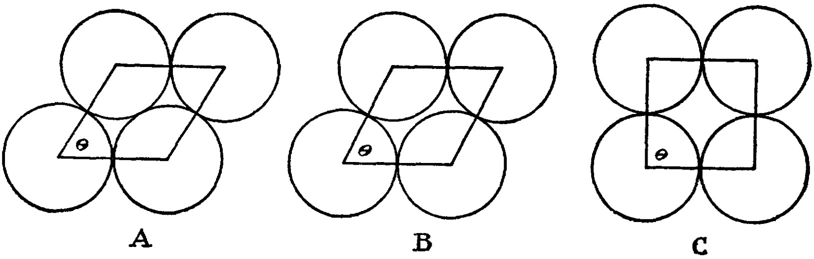


FIGURE 2.—Sections of four contiguous spheres of equal size. A, Most compact arrangement; B, less compact arrangement; C, least compact arrangement.

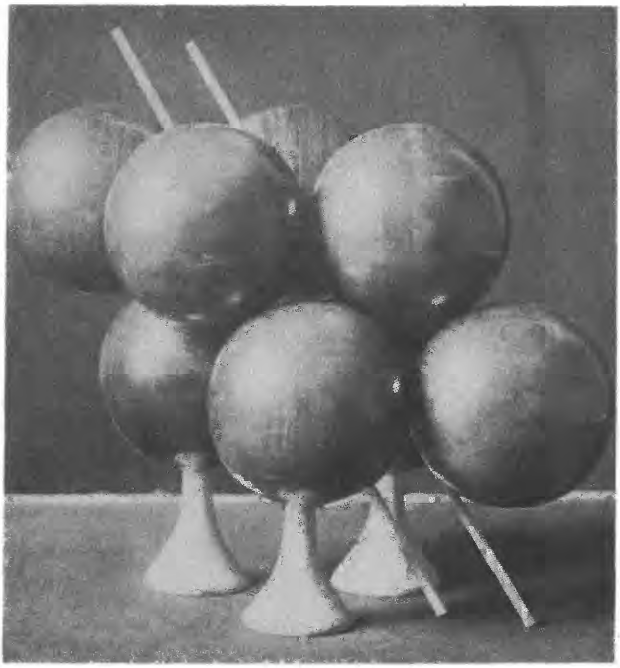
He described the conditions with these simple assumptions, as follows:

In order to study the nature of the pores, we may separate out from the mass of the soil eight contiguous grains in such manner that the lines joining their centers form an equilateral parallelopiped or rhombohedron, as represented in Plate I, *A*,[3] in which the white rods mark the position and direction of two of the pores. By studying the properties of the pores of this rhombohedron we may arrive at the properties to be assigned to the pores of the entire mass of soil, since this rhombohedron constitutes the element of volume, or the unit element, which, if repeated, will give the entire mass of soil.

If the grains of soil are arranged in the most compact manner possible, each grain will touch surrounding grains at twelve points, and the element of volume will be a rhombohedron having face angles equal to 60° and 120° (fig. 2, A). If the grains are not arranged in the most compact manner the rhombohedron will have its face angles greater than 60° (fig. 2, B), and each sphere will touch other spheres in but six points but will nearly touch in six other points. The most open arrangement of the soil grains which is possible with the grains in contact is had when the rhombohedron is a cube (fig. 2, C).

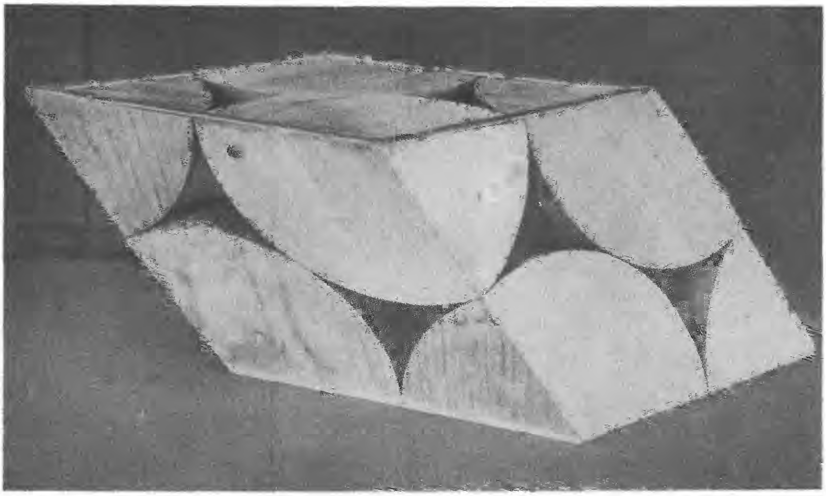
[2] Slichter, C. S., Theoretical investigation of the motion of ground water: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, pp. 305-328, 1899.

[3] The numbers of the illustrations cited have been changed to conform to those of the present paper.—O. E. M.



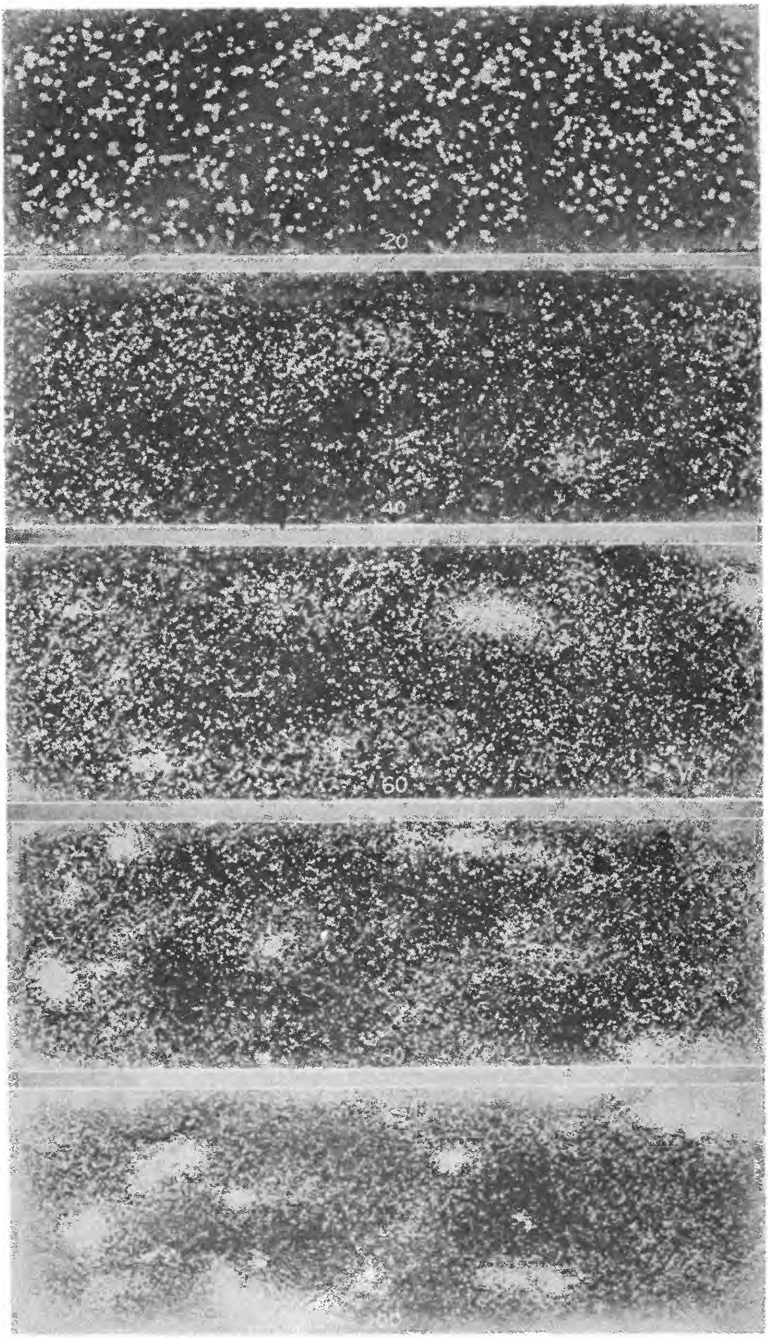
A. UNIT ELEMENT OF A GROUP OF SPHERES ARRANGED IN THE MOST COMPACT MANNER POSSIBLE.

Face angles 60° and 120°.



B. UNIT RHOMBOHEDRON FORMED BY PASSING PLANES THROUGH THE CENTERS OF EIGHT CONTIGUOUS SPHERES IN THE MOST COMPACT ARRANGEMENT OF A GROUP OF SPHERES.

497781 O–59–2



SANDS USED IN KING'S EXPERIMENT OF WATER-YIELDING CAPACITIES.
Natural size.

Plate I, *B*, shows the rhombohedron formed by joining the centers of the spheres of Plate I, *A*.

If we imagine a soil made up of particles arranged so that the lines joining their centers form cubes, the percentage of open space to the whole space, or the so-called porosity, can be found by dividing (1) the difference between the volume of a sphere and the volume of the circumscribed cube by (2) the volume of the circumscribed cube, which gives a porosity of 47.64 per cent. If the particles are arranged as compactly as possible, as in Plate I, *A*, the percentage of pore space can be found by dividing (1) the difference between the volume of a sphere and the volume of a rhombohedron whose acute face angles are 60° and whose edges equal the diameter of the sphere by (2) the volume of this rhombohedron, which gives a porosity of 25.95 per cent. This fact is shown nicely by considering that the pieces of eight different spheres which make the rhombohedron of Plate I, *B*, can be placed together so as to make a perfect sphere. It is plain that the eight pieces would make a complete sphere even if the face angle θ had not the value 60° but had any other value up to 90°. If we measure the porosity of a soil composed of grains of nearly uniform size, we shall find a large variation in the results, depending largely upon the manner in which the soil was packed; but usually the porosity will lie within these limits.

The pores through such an ideal soil are capillary tubes of approximately triangular cross section. The pore enlarges slightly in area as it follows the surfaces of the spherical soil grains and then diminishes again to its former value.

RELATION OF POROSITY TO SIZE OF GRAINS.

It will be noted that the size of the grains does not enter into Slichter's calculations. If other conditions are the same, a material will have the same porosity whether it consists of large or small grains. Thus, although there is wide range in the porosity of each of the four principal types of granular deposits—gravel, sand, silt, and clay—there is probably no great difference in the average porosity of the different groups. On the whole, silt and clay are about as porous as sand and gravel. N.B. recent work in soils, clay xtalography, clay chemistry, & clay compaction; wide variability in clay porosity!

RELATION OF POROSITY TO SHAPE OF GRAINS.

Natural sedimentary deposits differ from the "ideal soil" investigated by Slichter in being made up of grains that are not perfect spheres and that are not all of the same size. The shapes of the grains differ considerably, according to the character of the minerals of which they are composed and the shapes of the original fragments; also according to the kind and amount of breaking up and wear they received before they were deposited. Irregularity in shape results in a larger possible range in porosity. To some extent the irregularities tend to counteract one another, but it is believed that the porosity of many deposits is increased by the irregular, angular shapes of its constituent particles.

habit, cleavage, etc.

RELATION OF POROSITY TO DEGREE OF ASSORTMENT.

Variety in size of grain, or the degree of assortment, is of fundamental importance with respect to the porosity of a deposit. A deposit composed of large grains of uniform size has a high porosity, and a deposit composed of small grains of uniform size has an equally high porosity; but a deposit composed of a mixture of grains of these two sizes has a much lower porosity. If small grains are added to a deposit of large grains the small grains will occupy the interstices between the large ones, thereby reducing the amount of void space (fig. 1, A and B). If in the opening between the spheres shown in figure 1, A, a small sphere is placed, this small sphere will occupy space that would otherwise have been empty or occupied by water—that is, it will reduce the porosity to the extent of its own volume. If large grains are added to a deposit of small grains, they will fill with solid rock the spaces which they occupy and which would otherwise be occupied by an aggregation of the small grains with their intervening interstices. Those interstices will thus be replaced by solid rock, and the porosity will be correspondingly reduced. This is illustrated in figure 3, in which *a* represents a deposit of nearly uniform grains and *b* represents the same deposit with the addition of a large grain or rock (*R*) that contains no interstices. Obviously, the large rock has displaced a number of interstices and reduced the porosity of the deposit.

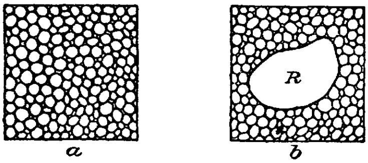


FIGURE 3.—Diagrams showing reduction in porosity caused by addition of a large grain (*R*) to an aggregation of small grains.

The amount of variation in size of grain, or the degree of assortment of a deposit, can be quantitatively expressed by means of a mechanical analysis in which are given the proportions of the sample that consist of grains of specified sizes. The mechanical analyses of eight samples examined by Hazen[4] are given in the following table and are graphically represented in figure 4.

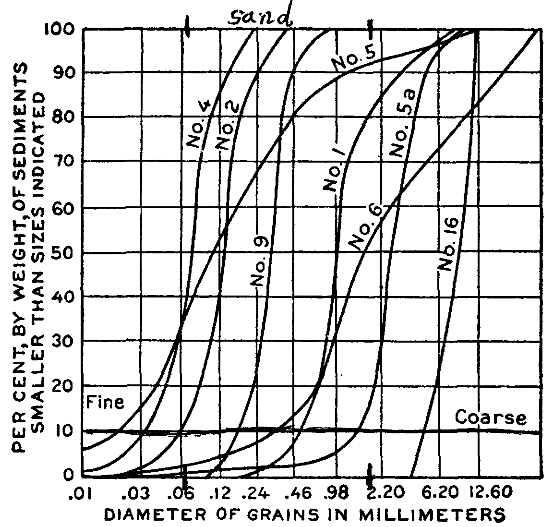


FIGURE 4.—Diagram showing mechanical composition of materials used in experiments by Hazen. The lines representing diameters of the particles are spaced according to the logarithms of these diameters.

[4] Hazen, Allen, Experiments upon the purification of sewage and water at the Lawrence experiment station: Massachusetts State Board of Health Twenty-third Ann. Rept., for 1891, pp. 429-431, 1892.

should use % volume not % weight in Fig 4.

Mechanical composition of materials used in experiments by Hazen.

Diameter of grains (millimeters).	Per cent of total sample by weight.							
	No. 5.	No. 4.	No. 2.	No. 9.	No. 6.	No. 1.	No. 5a.	No. 16.
Less than 12.6	99	....	....	....	83	100	100	98
Less than 6.2	96	....	....	....	73	97	95	27
Less than 2.2	92	....	....	....	57	85	31	0
Less than 0.98	89	....	....	100	32	53	4	....
Less than 0.46	80	....	100	91	13	7	2	....
Less than 0.24	67	100	90	26	7	1.5	1.5	....
Less than 0.12	51	85	43	3	4	0	1.0	....
Less than 0.06	33	35	10	0	2	....	.5	....
Less than 0.03	16	10	2	....	.5	....	0	....
Less than 0.01 (organic)	6	1	0	....	0	....	....	....
Effective size of grain in millimeters[a]	.02	.03	.06	.17	.35	.48	1.40	5.00
Uniformity coefficient	9.0	2.3	2.3	2.0	7.8	2.4	2.4	1.8
Porosity (per cent by volume)	36	44	42	42	32	40	....	45

[a] The effective size of grain, as defined by Hazen, is the diameter of a grain of such size that 10 per cent of the sample (by weight) consists of smaller grains and 90 per cent of larger grains.

In order to have a simple quantitative expression of the degree of uniformity in size, an arbitrary quantity is used—the uniformity coefficient. This is the ratio of the diameter of a grain that has 60 per cent (by weight) of the sample finer than itself to the diameter of a grain that has 10 per cent finer than itself. This coefficient can be obtained from a mechanical analysis such as those given above, or it can conveniently be obtained from a curve representing a mechanical analysis, such as those shown in figure 4. In explanation of the uniformity coefficient and its relation to the graphic representation of mechanical analyses, as in figure 4, Hazen makes the following statements:

For study and comparison the results have been plotted and are shown in the accompanying diagram [fig. 4], the height of a curve at any point showing the per cent of material finer than the size indicated at the bottom of the diagram. The lines representing the diameters are spaced according to the logarithms of the diameters of the particles, as in this way materials of corresponding uniformity in the range of sizes of their particles give equally steep curves, regardless of the absolute sizes of the particles, thus greatly facilitating a comparison of different materials. This scale also shows adequately every grade of material from 0.01 to 10 millimeters in a small space, and without unduly extending any portion of the scale. * * * If all the grains of a sand were absolutely of the same size, the uniformity coefficient would be 1; with most comparatively even-grained sands the coefficient ranges from 2 to 3; with No. 6 and No. 5, the figures are about 8 and 9, respectively; and some extremely uneven sands have coefficients as high as 20 or 30; but the data in regard to the action of such materials is as yet limited.

In regard to the relation of the uniformity coefficient to the porosity, Hazen[5] makes the following statement:

The amount of open space depends upon the shape and uniformity in size of the particles of sand and is independent of their absolute size. The materials which have the sharpest rise on the diagram [fig. 4], indicating the greatest uniformity in

[5] Op. cit., p. 432.

size, have the greatest open space, while the sands having a more gradual rise pack more closely; the finer particles occupy the spaces between the larger stones, greatly reducing the open space.

Obviously, the uniformity coefficient is an index to the porosity. The larger this coefficient the smaller the porosity. The relation for the samples whose mechanical analyses are given in the preceding table is shown in figure 5.

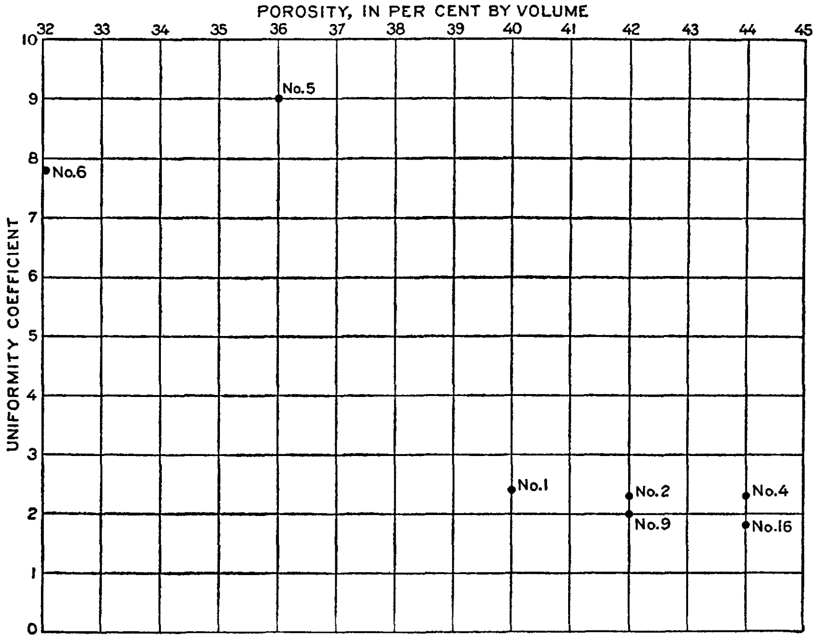


FIGURE 5.—Diagram showing relation between the porosity and the uniformity coefficients of materials used in experiments by Hazen.

DATA ON POROSITY.

The porosity of different materials ranges from only a small fraction of 1 per cent to more than 50 per cent. Much of the newly deposited material of the Mississippi Delta has a porosity of 80 to 90 per cent.[6] A porosity of more than 40 per cent, however, is rare except in soils and in recent deposits that have not had time to settle. A porosity of less than 5 per cent may be regarded as a small porosity; one between 5 and 20 per cent as a medium porosity; and one greater than 20 per cent as a large porosity.

As already shown an aggregate of perfect spheres of solid matter of equal size has a porosity between 25.95 and 47.64 per cent. As a matter of fact, well-sorted, uncemented sedimentary deposits com-

[6] Shaw, E. W., unpublished communication. See also Sorby, H. C., On the application of quantitative methods to the study of the structure and history of rocks: Geol. Soc. London Quart. Jour., vol. 64, p. 214, 1908.

monly range between these two extremes, but sedimentary deposits that are poorly sorted or considerably cemented have a much lower porosity. Most soils, however, although being far from uniform in size of grain, have a high porosity, more than 50 per cent being common. Lying at the surface, they are not compacted, and by cultivation and other processes they are kept in an especially open condition. They are composed largely of particles which consist of aggregates of smaller particles, as shown in figure 1, C. Sedimentary deposits that have become so thoroughly cemented or otherwise altered that the original spaces between the grains have been entirely filled and rocks that were originally compact, such as granite, may have very little space that is unoccupied by solid mineral matter. Fractures and solution channels, even if they are of considerable size, are generally spaced too far apart to give any high percentage of void space. The following statement by Fuller,[7] based on the work of Ellis,[8] is instructive in this respect:

Recent investigations in Connecticut, made by E. E. Ellis for the United States Geological Survey, have shown that in the ordinary granites and gneisses of the region the water occurs largely in the vertical joints, which have an average spacing of between 3 and 7 feet at the surface. At depths of more than 50 feet the spacing is greater, owing to the dying out of subordinate joints. At still greater depths there appear to be very few water-bearing joints, 250 feet being the depth fixed as a limit beyond which it is not advisable to go for water. Of the horizontal joints, almost all are confined to the upper few feet of the rock, being generally above the water table. Mr. Ellis finds that while the joints may be half an inch or more in width at the surface, they rapidly narrow with depth, and that the common width in the upper 200 or 300 feet is 0.01 inch.

In a rock cut by three sets of fractures, each set with fractures spaced 5 feet apart, if the average thickness of the void space in each fracture is 0.01 inch, the total void space represented by the fractures is only one-twentieth of 1 per cent of the total volume of the rock. In some compact rocks at considerable depths the porosity represented by fractures is probably even less, but in many compact rocks near the surface it is much greater, chiefly because the openings represented by the fractures are much larger.

There is so much variation in the porosity of even rocks of the same kind that specific data are of little general value. The following table, compiled by Fuller,[9] gives data on the porosity of numerous rocks and soils of different kinds. Additional data are given under "Water-yielding capacity" (pp. 53-63).

---

[7] Fuller, M. L., Amount of free water in the earth's crust: U. S. Geol. Survey Water-Supply Paper 160, pp. 69-70, 1906.

[8] See Gregory, H. E., Underground water resources of Connecticut, with a study of the occurrence of water in crystalline rocks, by E. E. Ellis: U. S. Geol. Survey Water-Supply Paper 232, 1909.

[9] Fuller, M. L., op. cit., p. 61.

Porosity of various rocks and soils.

[Compiled by M. L. Fuller.]

Rock.	Authority.	Number of tests.	Porosity (per cent by volume).		
			Minimum.	Maximum.	Average or mean.
Granite, schist, and gneiss	Buckley[a]	14	0.02	0.56	0.16
Do	Merrill[b]	22	.37	1.85	1.2
Gabbro	do	1			.84
Diabase	do	2	.90	1.13	1.01
Obsidian	Delesse[c]	1			.52
Sandstone	Buckley[a]	16	4.81	28.28	15.89
Do	Merrill[b]		3.46	22.8	10.22
Quartzite	do	1			.8
Do	Geikie[d]				.21
Slate and shale	Delesse[c]	2	.49	7.55	3.95
Limestone, marble, and dolomite.	Buckley[a]	11	.53	13.36	4.85
Chalk	Geikie[d]				53
Oolite	Merrill[b]	8	3.28	12.44	7.18
Gypsum	Geikie[d]		1.32	3.96	2.64
Sand (uniform)	King[e]	Many.	26	47	35
Sand (mixture)	do	Many.	35	40	38
Clay	do	Many.	44	47	45
Do	Geikie[d]				53
Soils	U. S. Department of Agriculture.	Many.	45	65	55

[a] Buckley, E. R., Building and ornamental stones [of Wisconsin]: Wisconsin Geol. Survey Bull. 4, pp. 400–403, 1898.

[b] Merrill, G. P., Stones for building and decoration, Appendix.

[c] Delesse, Achille, Recherches sur l'eau dans l'intérieur de la terre: Soc. géol. France Bull., 2d ser., vol. 19, p. 64, 1862.

[d] Geikie, Archibald, Textbook of geology, 4th ed., vol. 1, p. 410, 1903.

[e] King, F. H., Principles and conditions of the movements of ground water: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, pp. 209–215, 1898.

The following table gives the porosity of 85 gas and oil bearing sandstones and associated rocks tested by A. F. Melcher for the United States Geological Survey:[10]

Porosity of gas and oil bearing sandstones and associated rocks.[a]

Material.[b]	Number of samples tested.	Porosity (per cent by volume).		
		Minimum.	Maximum.	Average.
Gas-bearing sands from Mexia-Groesbeck gas field, Limestone County, Tex	8	10.7	37.7	24.4
Gas and oil bearing sands from Developers Oil & Gas Co., Petrolia, Tex	4	18.5	26.6	22.9
Oil sands and associated rocks from Butler and Zelienople quadrangles, Pennsylvania	8	4.5	22.2	10.1
Oil and gas bearing sands and associated rocks from Ohio	18	4.7	18.4	12.3
Oil and gas bearing sands and associated rocks from Wyoming and Montana	10	3.4	29.3	17.1
Oil and gas bearing sands and associated rocks from Dawes, W. Va.	9	4.8	21.7	15.5
Sands from Bartlesville, Okla.	4	16.1	17.7	16.7
Gas-bearing sands and associated rocks from Shreveport, La.	21	9.2	37.7	22.7
Medina sand from Niagara, N. Y., and Bradford oil-bearing sand from Custer City, Pa.	2	7.9	17.8	12.8
All samples	84	3.4	37.7	17.5

[a] The methods used for determining porosity are described on pages 13–15.

[b] The "sands" tested are coherent sandstones.

[10] Melcher, A. F., Determination of pore space of oil and gas sands: Mining and Metallurgy, No. 160, sec. 5, April, 1920.

The following table gives the results of field tests, made by the writer, of glacial materials in Pomperaug Valley, Conn., consisting of boulder clay, outwash deposits, and lake beds. The samples were not entirely dry, the fine-grained material perhaps containing enough moisture to make an appreciable difference in the results. Materials were obtained in as nearly their original condition as possible, and the tests were made by adding water to the samples. In the results for boulder clay corrections are made for pebbles and boulders that were too large to be included in the samples examined.

Field tests of porosity of glacial materials in Pomperaug Valley, Conn.

Type of deposit.	Material.	Porosity (per cent by volume).
Stream deposits	Fine sand of uniform grain	48.0
Glacial outwash	Medium to fine sand of uniform grain	37.6
Do	Loose mixture, chiefly fine sand and silt	36.0
Do	Coarse sand with gravel	33.6
Do	Coarse clean grit or fine gravel	28.0
Do	Gravelly silt	26.4
Do	Sand and gravel, including a few large pebbles	25.2
Do	Gravel with a matrix of sand	20.0
Do	Silt and clay	18.0
Till or boulder clay	Sandy and gravelly	21
Do	Stony	16
Do	Gravelly	14.0
Do		13.5
Do		12
Do		11.5
Lake deposit	Silt	36.0

METHODS OF DETERMINING POROSITY.

Several methods have been used to determine the porosity of rocks and soils. These methods differ in the time they require and in the accuracy of the results they produce. Some are adapted only for testing coherent rocks, others only for testing incoherent materials; still others can be used with either coherent or incoherent samples. The different methods are interrelated in various ways but can for convenience of discussion be designated as follows: (1) Measuring the quantity of water required to saturate a known volume of the dry material, (2) comparing the volume of a sample with the aggregate volume of its constituent grains, (3) comparing the specific gravity of a sample with the weighted average of the known specific gravities of its constituent materials, (4) comparing the specific gravity of a dry sample with that of a saturated sample of the same material, (5) obtaining the uniformity coefficient and estimating the porosity on the basis of the observed relation between porosity and uniformity coefficient, and (6) producing a partial vacuum in a vessel that contains a dry sample and observing the change in air pressure when this vessel is connected with another that contains air under atmospheric pressure, the volume of each vessel and of the sample being known.

If the specific gravity of water is taken as unity, the following equations express porosity, in percentage, according to the first four methods:

$$P = 100\left(\frac{W}{V}\right) = 100\left(\frac{V-v}{V}\right) = 100\left(\frac{S-a}{S}\right) = 100\left(b-a\right).$$

Where P = porosity (by volume).
W = volume of water required to saturate the sample of rock or soil when it is dry.
V = volume of the sample.
v = aggregate volume of the solid particles that comprise the sample.
S = weighted average of the specific gravities of the minerals that constitute the rock or soil.
a = specific gravity of the dry sample.
b = specific gravity of the saturated sample.

The volume of a sample of incoherent material as it exists in its natural condition (V) should, if possible, be determined at the time the sample is taken. In the laboratory this sample or any measured part of it can be used to determine other quantities. If the volume of the sample is not determined in the field it can be measured in the laboratory with any convenient calibrated vessel, but considerable error is likely to result because of the difficulty of giving it the same compactness as it had in the field. The volume of a sample of coherent rock (V) can be obtained by coating the sample with paraffin to make it waterproof (see p. 14) and then weighing it in air and in water. Its loss of weight in water is the weight of the volume of water it displaced.

The aggregate volume of the solid particles that comprise the sample (v) can be determined by measuring or weighing the quantity of water that they displace.

The weighted average of the specific gravities of the minerals (S) can be determined either by ascertaining the proportions in which the different minerals, with their different known specific gravities, occur in the sample, or by determining how much water is displaced by a weighed quantity of the solid particles that constitute the sample. If there is only one abundant mineral, as in a quartz sand or sandstone, or if the constituent minerals have practically the same specific gravity, the problem is relatively simple. Generally, no great error is involved if the specific gravity (S) is assumed to be 2.65.

The specific gravity of a dry sample of coherent rock (a) can be obtained by coating the sample with paraffin and then weighing it in air and in water. The specific gravity of the sample is its weight in air divided by its loss of weight in water. The specific gravity of a dry sample of incoherent material (a) can be obtained by weighing a measured volume of the material and dividing this weight by the weight of an equal volume of water.

The specific gravity of a saturated sample (b) is equal to the weight of the saturated sample divided by the weight of an equal volume of water. The determination of this value involves saturation of the sample and determination of its volume.

Difficulties are encountered in completely saturating either coherent or incoherent materials. As the process of saturation is involved in determining W and b and also, in a sense, in determining v and S by the second procedure mentioned, these difficulties apply to most of the methods for determining porosity. They are largely, though not entirely, due to air that remains imprisoned in the interstices. In the following table are given the results of tests on seven samples of building stone to determine the degree of saturation attained by various methods. These instructive tests were made by Hirschwald,[11] and the table is quoted from a paper by Melcher.[12]

Water absorbed by porous rocks under specified conditions, in percentages of the quantity absorbed under pressures of 50 to 150 atmospheres.

No. of sample.	By method of quick immersion.	By method of gradual immersion.	By method of gradual immersion in vacuum.
17	45.9	52.2	61.1
16	47.6	49.7	96.1
1	53.0	61.3	85.5
18	53.3	54.6	99.5
2	60.9	63.0	99.4
11	71.3	81.2	81.5
4	72.6	77.2	81.0

The following suggestions are made by Hazen:[13]

The specific gravity of the solid particles (S) is obtained by putting a weighed quantity of the thoroughly dry material into a narrow-necked graduated flask of distilled water, taking great care that no air bubbles are inclosed, and weighing the displaced water. Very accurate results may be obtained in this way. The specific gravity of the material (a) is obtained by weighing a known volume packed as it is actually used, or as nearly so as possible. As the material is usually moist, it should either be dried before weighing or else a moisture determination made and a correction applied. * * * The results obtained by measuring the quantity of water which can be put into a given volume (w) when introduced from below are invariably too low, because the water is drawn ahead by capillarity, and air bubbles are inclosed and remain, often causing serious errors.

The methods at present used by the United States Geological Survey for determining the porosity of sandstones are those developed by Melcher.[14] They are concisely described by him as follows:

The method selected is based on the principle that the volume of the fragment of the sand [sandstone] minus the volume of its individual grains equals the volume of

[11] Hirschwald, Julius, Die Prüfung der Natürlichen Bausteine auf ihre Wetterbeständigkeit, Berlin, W. Ernst und Sohn, 1908.

[12] Melcher, A. F., Determination of pore space of oil and gas sands: Mining and Metallurgy, No. 160, April, 1920.

[13] Hazen, Allen, Some physical properties of sands and gravels, with special reference to their use in filtration: Massachusetts State Board of Health Twenty-fourth Ann. Rept., for 1892, p. 550, 1893.

[14] Melcher, A. F., op. cit., pp. 2-9.

the pore space. The volume of the pore space divided by the volume of the fragment gives the per cent pore space by volume.

Dipping samples in paraffin.—Sometimes the texture of the samples is so loose that it is difficult to keep the grains of sand from rubbing off while handling them; other fragments are firmer and more compact. It was because of this looseness of texture and the small size of some of the samples that the method of dipping in paraffin [15] was adopted. After the surface of a sample was thoroughly cleaned of foreign material with an assay brush and loose particles brushed off, it was broken into two parts; one part was used for finding the volume of the fragment and the other was used for finding the volume of the individual grains making up the fragment.

The pieces that were to be used for finding the volume of the fragment were weighed and then dipped into paraffin heated to a temperature a little above its melting point. The layer of paraffin around the sample was then examined for air bubbles and pinholes. If any were found, they were removed by remelting the paraffin at that point with the end of a hot wire.

The fragments are best dipped by holding them with the fingers. First, the half of the sample opposite the fingers is dipped; then the sample is turned around and the other half is dipped. The samples should never remain in the melted paraffin longer than two or three seconds, and very small samples or very porous ones should be immersed for shorter periods. Bubbles should not be permitted to come out of the samples, as they usually indicate that the paraffin is beginning to enter the pores. If there is any doubt about the paraffin entering the pores of the sample, the specimen may be broken, after it is weighed in distilled water, and examined with a hand lens or microscope, depending on the size of the pores. It will be found that, after a little practice, if the samples are cold, there will not be much difficulty in dipping them so that the paraffin will not enter the pores, as the paraffin almost immediately hardens when it comes into contact with the cold surface of the sand. When the paraffin cools, the sample with its coating is weighed to determine the weight of the paraffin.

Determining volume of fragment.—The sample with the coating of paraffin is suspended in distilled water by a No. 30 B. & S. gage platinum wire and weighed; a fine wire is used so that the error due to surface tension will be as small as possible. The water should have been boiled and its temperature taken to one-tenth of a degree at the time of the weighing. The sample is then removed from the water, dried by pressing the surface against bibulous paper or a smooth towel, and weighed in air. This weighing is made to see whether the sample absorbed any water. If any appreciable quantity of water is absorbed, a correction can be made to the weight of water displaced from the difference between the last weighing and the former weighing of the sample plus the paraffin in air.

From the weight of the water displaced, its temperature and density, the volume of the sample plus the volume of the paraffin can be obtained. The tables by P. Chappuis [16] on the change of density with the temperature of pure water free from air were used. From a previous determination of the density of paraffin, which in this case is 0.906, and the weight of the paraffin covering the sample, its volume can be obtained. Subtracting this volume from the total volume of the sample, plus the volume of the paraffin, gives the volume of the fragment of stone used.

Determining volume of individual grains.—The second part of the sample is weighed and crushed in an agate crucible into its separate particles, or, in the case of a very fine sand, until it will pass through a 100-mesh sieve. It is again weighed and thor-

[15] Julius Hirschwald (Die Prüfung der Natürlichen Bausteine auf ihre Wetterbeständigkeit, Berlin, W. Ernst und Sohn, 1908) describes a method of dipping the specimens in paraffin, which he used to determine the specific gravity of building stones.

[16] Bur. internat. poids et mesures Trav. et mém., 1907, p. 13; U. S. Bur. Standards Circ. 19, 5th ed., table 27.

oughly dried in an electric oven, or better in the Steiger toluene bath[17] at from 100° to 150° C. for 30 minutes to 1 hour; a lower temperature is used when there is danger of driving off an appreciable quantity of combined water. It is then placed in a desiccator to cool. After the particles have cooled, the sample is weighed and exposed to the air to take up moisture. After the particles have reached a constant weight, or nearly so, they are again weighed to correct for hygroscopic water. The particles of sand are then transferred to the pycnometer, using glazed paper. [A pycnometer is a bottle whose capacity for water under specified conditions is accurately determined.] The pycnometer plus the sample is weighed to correct for the loss in transfer. The pycnometers used are of the type designed by John Johnston and L. H. Adams,[18] of the Carnegie Institution.

The device of G. E. Moore,[19] slightly modified by Day and Allen,[20] was used for the evacuation of the air from the ground particles.

After the pycnometer is nearly filled with boiled distilled water, the aspirator is removed and the pycnometer is placed in a constant-temperature thermostat regulated to 0.1° C. The filling of the pycnometer is completed from distilled water taken from another vessel in the thermostat. The pycnometer is then removed from the thermostat and weighed after its outside surface has been dried with a towel. From a previous calibration of the pycnometer, which gives the weight of the water necessary to fill the pycnometer, the weight of water that the crushed sample displaced is found. The volume of the ground particles in the pycnometer is found from the weight of water displaced and the table of densities of water at the temperature of the thermostat.

By proportion, the total volume of grains in the fragment dipped in paraffin is determined. Then the volume of the fragment dipped in paraffin minus the volume of its grains is equal to the volume of the pore space. This volume divided by the volume of the fragment gives the per cent pore space by volume.

Determining pore space of very small samples.—In case the sample is too small to break into two parts, the whole sample can be dipped into paraffin and the paraffin burned off, if the grains of the sample are of sufficiently pure quartz not to be appreciably changed in volume or weight by the burning. In many cases the paraffin can easily be shaved and brushed off with a knife and assay brush, and a new weighing made to determine the loss of weight of particles brushed off. In case there is oil in the fragment that is crushed, the oil is either burned out by placing the crushed sample in a platinum crucible or it is dissolved by a solvent, as petroleum ether or carbon tetrachloride. * * *

For very accurate determination of pore space it is necessary to add a correction to some of the weighings for buoyancy of the air. * * * Pore space determinations can be made of chunk samples that weigh 0.1 ounce with an error of less than ± 1 per cent. The pore space of a chunk sample weighing 0.05 ounce, the grains of which will pass through a No. 20 mesh sieve, can be determined with sufficient accuracy for commercial use.

If the material is incoherent the volume of the sample as it occurs in nature should be determined in the field, and this sample or a measured part of it can then be used to determine the aggregate volume of the solid particles by means of a pycnometer, as described by Melcher.

[17] U. S. Geol. Survey Bull. 422, pp. 75–76, 1910.
[18] Am. Chem. Soc. Jour., vol. 34, p. 566, 1912.
[19] Am. Jour. Sci., 3d ser., vol. 3, p. 41, 1872.
[20] Carnegie Inst. Washington Pub. 31; U. S. Geol. Survey Bull. 422, pp. 48–50, 1910.

The following method is suggested by Hazen[21] for making rough estimates of the porosity of incoherent material from the uniformity coefficient (p. 7). It may be of use in estimating the porosity of materials whose mechanical analyses only are known.

A rough estimate of the open space can be made from the uniformity coefficient. Sharp-grained materials having uniformity coefficients below 2 have nearly 45 per cent open space as ordinarily packed; and sands having coefficients below 3, as they occur in the banks or artificially settled in water, will usually have 40 per cent open space. With more mixed materials the closeness of the packing increases until, with a uniformity coefficient of 6 to 8, only 30 per cent open space is obtained, and with extremely high coefficients almost no open space is left. With round-grained water-worn sands the open space has been observed to be from 2 to 5 per cent less than for corresponding sharp-grained sands.

The sixth method of determining porosity, mentioned on page 11, has recently been devised by Washburn and Bunting.[22] In this method air or some other gas is used to fill the interstices, and the volume of the interstitial space is determined by observing changes in the gas pressure. Although the method is very simple in principle, it had apparently not been suggested prior to its use by Washburn and Bunting. Its great advantage over methods that involve saturation with water consists in the more accurate results which it gives, especially for materials that have small and poorly connected interstices. This advantage is due to the perfect expansibility and low viscosity of gases. The essential features of the method can be described as follows:

An air-tight vessel, B, is joined by a capillary tube to a second air-tight vessel, A. There is a stopcock on each vessel and in the tube that connects the two vessels. There is also a manometer connected with vessel A. A dry sample of known volume of the material to be tested is placed in vessel A. Most of the air in vessel A is then pumped out, and the pressure of the remaining air is observed. The air in vessel B is at the atmospheric pressure. The stopcock in the connecting tube is then opened, and the resulting pressure is observed. After each operation the apparatus must be allowed to stand, preferably in a constant-temperature bath, until temperature equilibrium is attained. For most materials air can be satisfactorily used, but for some hydrogen or helium is required. The following equations can readily be deduced:

$$(p_1-p_3)\,v_1=(p_3-p_2)\left[v_2-\left(\frac{100-P}{100}\right)v_3\right]$$

and therefore

$$P=100\left[\frac{(p_1-p_3)\,v_1}{(p_3-p_2)\,v_3}-\frac{v_2-v_3}{v_3}\right]$$

Where P = porosity, in percentage by volume,
p_1 = initial pressure in vessel B,
= atmospheric pressure,
p_2 = initial pressure in vessel A,
p_3 = pressure in both vessels after the stopcock between them has been opened,

[21] Op. cit., pp. 550-551.

[22] Washburn, E. W., and Bunting, E. N., Porosity; VI, Determination of porosity by the method of gas expansion: Am. Ceramic Soc. Jour., vol. 5, pp. 113-129, 1922.

v_1 = volume of vessel B,
v_2 = volume of vessel A,
v_3 = volume of sample.

METHODS OF MAKING MECHANICAL ANALYSES OF GRANULAR MATERIALS.

A mechanical analysis of granular material consists in separating into groups the grains of different sizes and determining what percentage, by weight, each group constitutes. (See pp. 6–7 and figs. 4 and 38.[23]) According to standard methods used by the United States Bureau of Soils,[24] which has made thousands of mechanical analyses of soils, the following arbitrary limiting diameters, in millimeters, have been adopted:

Fine gravel, 2 to 1.
Coarse sand, 1 to 0.5.
Medium sand, 0.5 to 0.25.
Fine sand, 0.25 to 0.1.
Very fine sand, 0.1 to 0.05.
Silt, 0.05 to 0.005.
Clay, less than 0.005.

How small the grains here dealt with actually are is suggested by Plate II, in which sand grains of several sizes are shown without magnification or reduction.

In making a mechanical analysis the grains are first separated by mixing the material with water and working it with a rubber-tipped pestle or agitating it a long time in a shaking device. According to the original methods, the mixture is then allowed to stand in a beaker until all grains larger than 0.05 millimeter in diameter have settled to the bottom, when the liquid still containing grains smaller than 0.05 millimeter is poured off into another beaker. New water is added to the residue, and the process is repeated until the separation between the grains that are larger than 0.05 millimeter and those that are smaller is fairly complete. The smaller grains are then separated by the same process into those larger and those smaller than 0.005 millimeter. The residue consisting of grains larger than 0.05 millimeter is dried and separated into the various grades given in the table by means of sieves of different sizes of mesh. More recently the use of the centrifuge has been introduced to expedite the separation of the finer grades out of suspension in water, the centrifugal force applied being many times as great as the force of gravity. Various other apparatus has been devised for expediting and improving the analyses.

[23] For diagrams showing numerous mechanical analyses of sandstone formations in the United States, see Dake, C. L., The problem of the St. Peter sandstone: Missouri School of Mines and Metallurgy Bull., August, 1921.

[24] Mechanical analysis of soils: U. S. Dept. Agr. Bur. Soils Bull. 4, 1896. Briggs, L. J., Martin, F. O., and Pearce, J. R., The centrifugal method of mechanical soil analysis: U. S. Dept. Agr. Bur. Soils. Bull. 24, 1904. Fletcher, C. C., and Bryan, H., Modification of the method of mechanical soil analysis: U. S. Dept. Agr. Bur. Soils Bull. 84, 1912.

A method devised by Oden[25] for studying the mechanical composition of deep-sea deposits consists in observing the rate at which the material settles out of suspension in water, without attempting the more laborious task of separating the grains into groups according to size.

A rapid method of making mechanical analyses of the very fine particles of clay (those less than 0.003 millimeter in diameter) has recently been described by Schurecht.[26] It is essentially the same as Oden's method except that the rate of sedimentation is determined by ascertaining the change in specific gravity of the mixture from time to time instead of actually weighing the sediments deposited. The specific gravity is determined by weighing a plummet in air and in the mixture.

A method used by Mitscherlich[27] is to estimate the total surface area of the grains in a unit quantity of the material by determining its hygroscopic power. (See pp. 88–94.) The following comment on this method is made by Oden:[28]

> Apart from the serious objections which can be raised against the theoretical side of Mitscherlich's method, it is obvious that a determination of the surface is by no means sufficient if we want to define a deposit. For example, a sample consisting of coarse sand intermingled with some high-colloidal clay may have the same total surface area as a loamy deposit consisting of more uniform particles of intermediate size, yet it will in most other respects differ profoundly from the latter, so that there are no reasons for classing them together.

FORCES CONTROLLING WATER IN ROCKS.

The two principal forces that control the water in the rocks are gravity and molecular attraction. Gravity is the force that causes the water to percolate from the surface deep into the earth and thence to percolate laterally for long distances. It is the principal force that causes the water to seep out of the earth in low places, to flow from springs, or to enter wells, and to issue from flowing wells. This force acts in a system of rocks with interstices very much as it does in a system of waterworks with standpipe, mains, and service connections.

In rocks having only large openings, comparable to the mains and service pipes of a system of waterworks, gravity is the controlling force, and the ordinary laws of hydraulics apply without much modification. But many rocks have very small interstices, and in these another force becomes very effective. This is the force of molecular attraction—the attraction of the walls of the interstices for the ad-

---

[25] Oden, Sven, On the size of the particles in deep-sea deposits: Royal Soc. Edinburgh Proc., vol. 36, pp. 219–239, 1917.

[26] Schurecht, H. G., Sedimentation as a means of classifying extremely fine clay particles: Am. Ceramic Soc. Jour., vol. 4, p. 812, 1921.

[27] Mitscherlich, E. A., Bodenkunde, p. 56, Berlin, 1905.

[28] Op. cit., p. 220.

jacent molecules of water and the attraction of the molecules of water for one another. The relative importance of this force is the most significant fact in the behavior of water in rocks; it is the condition which makes the hydraulics of this water a distinctive subject.

MOLECULAR ATTRACTION OF WATER IN ROCKS.

The molecules or minute unit parts of most substances have an attraction for one another and also for molecules of other kinds. The attraction between molecules of the same kind, as for example between adjacent molecules of quartz or between adjacent molecules of water, is called "cohesion"; the attraction between molecules of different kinds, as between a quartz molecule and an adjacent water molecule, is called "adhesion." The molecular attraction of many substances is very great. Thus the cohesion that holds together the different parts of a mineral such as quartz makes it firm and strong. The cohesion of liquid water is much less than that of solid rock but is sufficient to affect very greatly the behavior of the water in the interstices of the rocks.

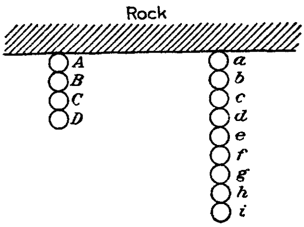


FIGURE 6.—Diagram showing how water is held by the molecular attraction of rocks. The circles represent water molecules that cling to one another and to the overhanging rock surface. The weight of the molecules produces a downward pull that tends to overcome the molecular attraction.

The force of adhesion may be as strong as that of cohesion. Thus, the particles of different minerals in a crystalline rock hold tenaciously to one another, and the cement of an indurated sandstone holds so firmly to the grains of sand that the rock makes a strong building stone.

Molecular attraction, however, acts at only very short distances, and consequently if a rock is once fractured it is impossible to press the two parts close enough together to enable the molecules on the opposite sides of the fracture to attract each other.

If a piece of rock is dipped into water and then taken out it remains wet—that is, a film of water adheres to the rock surface and is not detached by the pull of gravity. The water molecules nearest the rock surface are held firmly by the molecular attraction of the rock, while those a little farther away are held less firmly by their cohesion to the water molecules that adhere to the rock. In figure 6 the conditions, as they are understood, are diagrammatically represented in very simple form. The actual interrelation of all molecular forces is of course much more complex. For purposes of illustration it may be assumed that the water molecule *A* adheres firmly to the rock and that the water molecules *A*, *B*, *C*, and *D* are held together only by cohesion. If the cohesion between *A* and *B* is strong enough to support the weight of three molecules then *B*, *C*, and *D* will be

497781 O-59-3

held against the pull of gravity. The molecules *a* to *i* form a similar chain. The molecule *a* may be assumed to adhere so firmly to the rock that it can not be torn away by the weight of all the other molecules. However, if the other water molecules are beyond the range of attraction of the rock and the cohesion between adjacent water molecules is only strong enough to support the weight of three of these molecules, the chain will be broken and some of the molecules will fall away. The adhering molecules, such as *A* and *a*, together with those held by cohesion, such as *B, C, D, b, c, d,* form the film of water that gives the rock a wet surface. As a matter of fact, the force of molecular attraction is believed to extend through several times the space occupied by one molecule, and the force of cohesion is much greater than is assumed for this illustration.

If the rock is not solid throughout but is ramified by interstices the walls of the interstices will retain a film of water similar to that held by the outside surface of the rock.

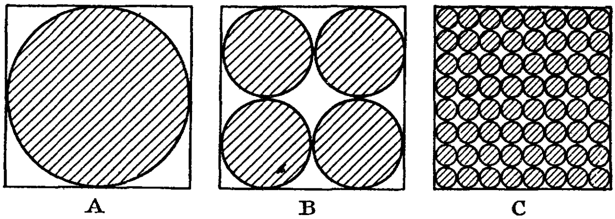


FIGURE 7.—Diagram showing relation between the size of the interstices in a rock and their aggregate surface. In a given volume of rock having a given porosity and containing interstices of the same shape the total interstitial surface varies inversely with the size of the interstices.

In a rock of a given porosity the aggregate surface of the interstices varies inversely with their size. This can be conveniently illustrated by granular deposits, in which the surface of a spherical grain varies as the square of its diameter but the volume it occupies varies about as the cube of its diameter. Figure 7 shows sections of two samples of gravel and one sample of sand consisting of spherical pebbles or grains of three different sizes, the pebbles in A being 1 inch in diameter, those in B half an inch in diameter, and those in C much smaller. A half-inch sphere has one-fourth as large a surface as a 1-inch sphere, yet a cubic inch will hold eight of these smaller spheres but only one of the larger spheres. Therefore, a given volume of half-inch gravel has about twice as much surface for holding water as an equal volume of 1-inch gravel. Likewise, it can be shown that if the spheres are very small, as they are in silt or clay, their aggregate surface will be very great and the influence of molecular attraction will be correspondingly great. This relation is also shown in figure 8. The water films, *a*, have the same thickness in the interstices of the two rock specimens, A and B, but they occupy a much larger proportion of the small interstices than of the large one, illustrating the fact that the force of molecular attraction has more influence over the water in a rock having small interstices than over the water in a rock having large interstices.

It can readily be shown, by applying the rule that the surface of a sphere is equal to 3.1416 times the square of its diameter, that the total interstitial surface of a cubic foot of sand composed of grains 1 millimeter in diameter is about 1,000 square feet, that of a cubic foot of sand composed of grains 0.02 millimeter in diameter is about 50,000 square feet, or more than 1 acre, and that of a cubic foot of material composed of grains only 0.001 millimeter in diameter is about 1,000,000 square feet, or more than 20 acres. From experiments made with the flow of air through various soils King[29] calculated the

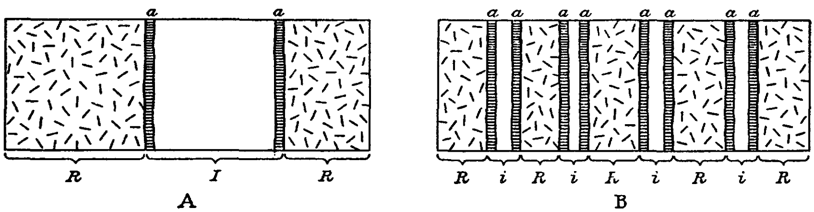


FIGURE 8.—Diagram showing relation between size of interstices and quantity of water controlled by molecular attraction. *R*, Solid rock; *I*, large interstice; *i*, small interstices; *a*, films of water held by attraction of rock walls. With a given porosity and a given shape of interstices the total interstitial surface and hence also the total quantity of water controlled by molecular attraction varies inversely with the size of interstices.

aggregate surface of a cubic foot of ordinary loam soils to be about 1 acre and that of a cubic foot of fine clay soils to be about 4 acres.

These figures give some conception of the vast areas of interstitial surface that are involved in fine-grained material and of the great influence that may be exerted upon water by the attraction of this surface, even though it acts through only a small range. The quantity of water held by a wet surface of a few square feet may be very small, but the quantity held by an entire acre is considerable even though the film of water adhering to this surface is very thin.

SURFACE TENSION.

If a pencil or glass rod is dipped in water and then taken out, a droplet of water can be seen clinging to the lower end of the pencil or rod in just the same form and manner as if it were held in an elastic membrane. In similar fashion water clings to the particles of

[29] King F. H., A textbook of the physics of agriculture, p. 124, Madison, Wis., 1900.

solid matter that constitute a rock or soil, as is illustrated in figure 9. This membrane is produced by the force of cohesion in the water which causes the phenomenon called surface tension. Surface tension is explained in all textbooks on physics and is discussed very clearly and simply with reference to the occurrence of water in rocks and soils by Briggs,[30] from whom the following is quoted:

In a suspended drop of water the particles in the interior of the liquid are attracted equally in all directions by the other particles of the liquid. The resultant attraction on any particle in the interior is therefore zero, and it is free to move through the liquid. A particle on the surface of the drop, on the contrary, is not attracted equally on all sides, since the molecules of the gas surrounding the drop exert less attraction upon the particle than is exerted by the particles of the liquid. The resultant attraction is therefore inward, along a line perpendicular to the surface of the liquid at that point. Now, the equations representing the behavior of the drop under the action of these forces are identical with those obtained if we imagine the drop inclosed in a water-tight membrane having a uniform tension. The action of the drop is therefore the same as if this imaginary membrane actually existed, and what we call surface tension is the tension that this ideal membrane would have to possess in order to produce the observed phenomena. This ideal membrane differs from all material membranes in that its tension does not change when the surface is increased. When the surface is extended, particles which were formerly in the interior are brought to the surface, so that the number of particles per unit of area of the surface always remains the same.

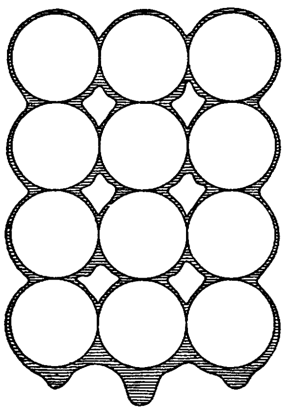


FIGURE 9.—Diagram showing how a liquid clings to solid particles against the pull of gravity. Drawn from a photograph by Briggs in which oil and rubber balls about 1 inch in diameter were used to illustrate the principle involved.

CAPILLARITY.[31]

If a piece of glass or rock is partly immersed in water, the water will as a rule be pulled slightly upward where it comes into contact with the glass or rock, forming what is called a meniscus. (See fig. 10.) If a glass tube of very small diameter is held upright with one end immersed in water, the water will as a rule be drawn upward in the tube, filling it completely up to a certain level. If a rock that is ramified by a system of small interstices is partly immersed in water the water will be drawn up in these interstices just as it is in the glass tube. A capillary tube is one of hair size, and in such a tube water rises perceptibly. The phenomenon of water rising in capillary tubes is called "capillary action" or "capillarity." Capillary interstices in rocks and soils are small enough to draw water upward a perceptible distance. The upward pull of a cylindrical tube is proportional to its

[30] Briggs, L. J., The mechanics of soil moisture: U. S. Dept. Agr. Bur. Soils Bull. 10, 1897.

[31] For a thorough discussion of this subject see the article by J. C. Maxwell on "Capillary action" in the Encyclopedia Britannica. The subject is also discussed in all textbooks of physics.

circumference where the glass comes into contact with the free surface of the water. It is therefore also proportional to its diameter. The downward pull caused by the weight of the elevated water is proportional to the square of the diameter. Inasmuch as the upward pull varies as the diameter and the downward pull varies as the square of the diameter, it follows that under given conditions the height to which water is lifted by capillarity in a cylindrical tube is inversely proportional to the diameter of the tube. For example, water will rise twice as high in a tube 0.1 millimeter in diameter as in a similar tube 0.2 millimeter in diameter and ten times as high as in a similar tube 1 millimeter in diameter (fig. 10).

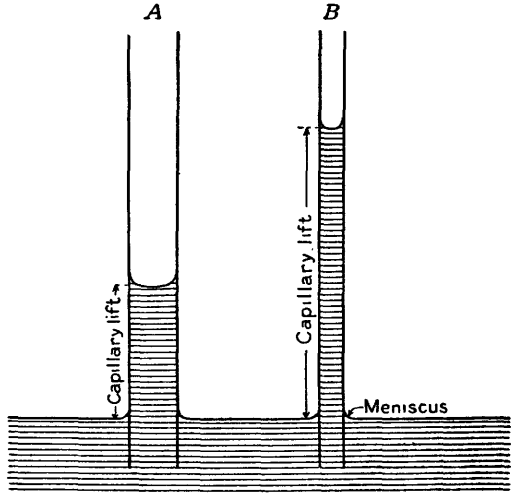


FIGURE 10.—Diagram showing inverse relation between size of tube and capillary lift.

It can be mathematically demonstrated that the height of a column of water that can be held in a capillary tube is determined by the size of the tube at the meniscus—that is, the size at the top of the column of water where the free surface of the water comes into contact with the tube—and that the size and shape of the tube farther down makes no difference. This fact has also been demonstrated by experiments of Biglow and Hunter.[32] It is illustrated in figure 11. It is of great importance with reference to capillarity in the interstices of the rocks, because the capillary tubes formed by these interstices are invariably irregular in shape and size.

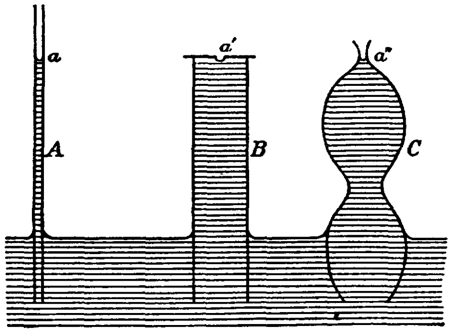


FIGURE 11.—Diagram illustrating the fact that the height to which water can be held by capillarity is independent of the shape and size of the tube below the level where the free surface of the water comes into contact with the tube. *A*, Cylindrical capillary tube; *B*, large tube covered by a plate with orifice, *a′*, of same diameter as diameter of tube *A*; *C*, tube of irregular size and shape which at *a″* has same diameter as tube *A*. If tubes *B* and *C* are immersed and then lifted they will hold their water up to the openings *a′* and *a″* until these openings reach the level of *a*, but as soon as they are lifted higher the water will drop to a much lower level.

[32] Biglow, S. L., and Hunter, F. W., The function of the walls in capillary phenomena: Jour. Physical Chemistry, vol. 15, pp. 367–380, 1911.

The water in a capillary tube is held up not only by the attraction of the walls of the tube for the water but by this attraction acting through the cohesion of the water, whereby the influence of the attraction of the walls is extended far beyond the range of molecular forces. The walls of the tube hold, as it were, to the elastic membrane formed by the surface tension. Hence the height to which water can be held by capillarity is proportional to the surface tension of the water, which determines the strength of the surface membrane. The surface tension of water decreases somewhat with increase in temperature. The surface tension of most salt solutions is higher than that of pure water, and the surface tension generally increases with the concentration.[33] Hence the capillary rise is greater for cold water than for warm water and generally greater for highly mineralized water than for pure water, although there is a compensating effect in the fact that the specific gravity, and hence the resultant downward pull per unit of height, is greater for cold water than for warm water and greater for mineralized water than for pure water.

It has been seen that the height at which water is held in a capillary tube varies with the size of the tube and with the surface tension of the water. According to some investigators it also varies with the kind of material of which the tube is made; according to others the material of the tube makes no difference. Quincke[34] believed that water rose to different heights in tubes of different kinds of glass. Volkmann[35] subjected this conclusion to an exceedingly careful investigation and decided that the nature of the glass made no difference. Apparently the first investigators to make direct measurements of the capillary range in tubes other than glass were Bigelow and Hunter, cited above, who used tubes of the type of *B* in figure 11, the tubes themselves being glass and only the covering plates with the apertures (*a′*) being of other materials. They stated their conclusions as follows:

> We have demonstrated that the capillary ascension of water is different in tubes of different substances. We consider it probable that the capillary ascension of liquids is primarily a measure of the adhesion between the liquid and the substance of the wall.

It is well known that water will not rise as high in a dirty tube as in a clean tube, but this may be due to grease or oil from the walls of the tube spreading over the water and thereby decreasing its surface tension rather than to any difference in the walls to which

---

[33] Briggs, L. J., The mechanics of soil moisture: U. S. Dept. Agr. Bur. Soils Bull. 10, pp. 20-21, 1897.

[34] Quincke, G., Ueber die Messung der Oberflächenspannung des Wassers und Quecksilbers in Capillarröhren: Weidmann's Annalen der Physik und Chemie, vol. 52, pp. 1-22, 1894.

[35] Volkmann, P., Ueber die Messung der Oberflächenspannung des Wassers in Capillarröhren aus verschiedenen Gläsern: Weidmann's Annalen der Physik und Chemie, vol. 53, pp. 633-663, 1894.

the water adheres. On this point Becker[36] makes the following statement:

In any attempt to apply the principle of capillarity to geology, it must be borne in mind that uncontaminated surfaces in porous rocks must be very exceptional.

Mathematically stated, the upward pull of a liquid in a cylindrical capillary tube is 3.1416 $dT \cos \alpha$; the downward pull is 0.7854 $d^2 h \varrho g$, where d = diameter of the tube, in centimeters.

T = surface tension, in dynes (per centimeter).
α = angle of contact between the liquid and the walls of the tube.
h = capillary rise, in centimeters.
ϱ = density of the liquid.
g = gravity, in dynes (per cubic centimeter).

These two forces are equal to each other. Therefore, $h = \frac{4\, T \cos \alpha}{d \varrho g}$

For water in a clean glass tube the constants in this equation have the following values:[37]

T = 75.6 at 0° C. and 72.1 at 25° C.
α = nearly 0.
$\cos \alpha$ = about 1.
ϱ = about 1.
g = 980.

For a tube having a diameter of 1 millimeter, or 0.1 centimeter, the value of h for water at a temperature of 0° C. is about as follows:

$$h = \frac{4T}{dg} = \frac{4 \times 75.6}{0.1 \times 980} = 3.09 \text{ centimeters} = 30.9 \text{ millimeters.}$$

These and similar calculations indicate that in a clean glass tube 1 millimeter in diameter pure water will rise by capillarity to a height of about 30.9 millimeters if the water has a temperature of 0° C. or to a height of about 29.4 millimeters if it has a temperature of 25° C. This is about 1.2 inches. If the glass is not clean the angle of contact may be large and the capillary rise correspondingly small.

The water in an ordinary capillary tube, except that very near the walls, can be forced through the tube simply by overcoming the relatively feeble force of the cohesion of the water. The weight of the column of water in the tube is itself sufficient to cause it to move if the column extends higher than the capillary range. If, however, the tube is so small that the molecular attraction of its walls extends to its center, all the water in the tube is under the direct control of the powerful molecular attraction of its walls and can not be moved except by overcoming this attraction. As the pressure exerted upon

[36] Becker, G. F., unpublished manuscript.
[37] Smithsonian physical tables, p. 173, 1920.

the water in the rock formations is, as a rule, not great enough to overcome this attraction, the water in the interstices of such minute size is believed to be practically imprisoned.

CLASSIFICATION OF INTERSTICES WITH RESPECT TO MOLECULAR ATTRACTION.

From the preceding discussion it is obvious that the interstices of the rocks can be divided, with respect to their size in relation to the range of molecular forces, into three classes—supercapillary interstices, capillary interstices, and subcapillary interstices.[38]

Supercapillary interstices are so large that water will not be perceptibly lifted or held up in them by molecular attraction except in the meniscus. There is, however, no mathematical limit to the size of openings in which capillarity is exhibited; moreover, the capillary range differs with differences in the temperature and mineralization of the water, with differences in the cleanness of the rock surfaces, and, according to some authorities, with differences in the kinds of minerals that form these surfaces.

Supercapillary interstices also differ from the smaller ones in being of sufficient size for water moving through them to form eddies and cross currents. This distinction is also indefinite, especially because of the great variety in the shape of interstices and because the tendency to form eddies and cross currents increases with the velocity of the water. Moreover, it does not have any causal relation to the criterion of capillary rise. Daniell[39] states that the maximum size of a capillary tube, according to the law of flow of water, is about one-fiftieth inch, or about 0.5 millimeter. This is a lower limit than is obtained from the law of capillary rise, because, according to the formula on page 25, water will rise by capillarity nearly 2½ inches in a clean glass tube of this size. As water generally moves very slowly through rocks having small interstices, it may also be a low limit as based on the law of flow. At best it is only a rough approximation.

Subcapillary interstices are theoretically so small that the attraction of the molecules of their walls extends through the entire space occupied by them. The water in these interstices is supposed to be so firmly held by the force of adhesion that it can not be moved except by forces that greatly exceed the pressures usually found in subsurface waters. According to Van Hise, the maximum size of subcapillary interstices is a diameter of 0.0002 millimeter for circular openings and 0.0001 millimeter for sheet openings.[40] These conclusions are

---

[38] Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Survey Mon. 47, pp. 134–146, 1904.

[39] Daniell, Alfred, A text-book of the principles of physics, 2d ed., p. 293, London, Macmillan & Co., 1885. Van Hise (op. cit., pp. 134–146), quoting from Daniell, gives the maximum diameter of circular capillary tubes as 0.508 millimeter and the maximum width of capillary sheet openings as 0.254 millimeter. This statement has given an impression of mathematical accuracy that apparently does not exist, for 0.508 millimeter is merely one-fiftieth inch carried out to three decimal places.

[40] Van Hise, C. R., op. cit., pp. 134–146.

based on the work of Quincke, who made experiments to determine the greatest distance at which the effect of molecular forces is sensible and found for various substances distances about the twenty-thousandth part (0.00005) of a millimeter.[41] More recent investigators,[42] working with thin films of soap, oil, or other substances, have obtained smaller values. Wells,[43] confirming the work of Perrin, gives 0.0000044 millimeter as the thickness of the black spot of a soap film, which he regards as a "bimolecular" layer. It should be said, however, that it is not clear just how all these results from thin films are to be interpreted with respect to the range of molecular attraction. It is not improbable that molecular attraction produces practical impermeability in interstices that are considerably larger than the values obtained in these investigations. It should be recognized that subcapillary interstices are so minute that they are beyond the range of ordinary observations and that statements in regard to their size or the behavior of water in them are largely a matter of conjecture. How very small these openings are can be appreciated to some extent by the fact that, according to Atterberg,[44] grains 0.002 millimeter in diameter, or ten times the diameter of the largest subcapillary tubes according to Van Hise, show pronounced Brownian movements when suspended in water. This means that the colloidal stage of fineness is reached at this size, and, according to the kinetic theory of heat, it means that the particles are so small that they are bounced about by the rapidly moving molecules with which they collide.

---

[41] Quincke, G. H., Über die Entfernung in welcher die Molekularkräfte der Capillarität noch wirksam sind: Poggendorf's Annalen der Physik und Chemie, vol. 137, pp. 402-414, 1869. See article "Capillary action" in Encyclopedia Britannica.

[42] Plateau, Statique des liquides, vol. 1, p. 210.

Reinold, A. W., and Rücker, A. W., On the electrical resistance of thin liquid films: Roy. Soc. Philos. Trans., vol. 172, pp. 447–489, 1881.

See also articles on the same subject by Reinold and Rücker in Roy. Soc. Philos. Trans., vol. 174, p. 645, 1883; vol. 184, pp. 505–529, 1893.

Drude, P., Über die Reflexion und Brechung ebener Lichtwellen beim Durchgang durch eine mit Oberflächenschichten behaftete planparallele Platte: Weidemann's Annalen, vol. 43, pp. 126–157, 1891; Über die Grösse der Wirkungssphäre der Molecularkräfte und die Constitution von Lamellen der Plateauschen Glycerin-Seifen-Lösung: Idem, pp. 158–176.

Rayleigh (Lord), Measurements of the amount of oil necessary in order to check the motions of camphor upon water: Roy. Soc. Proc., vol. 47, pp. 364–367, 1890.

Johonnott, E. S., Thickness of the black spot in liquid films: Philos. Mag., 5th ser., vol. 47, pp. 501–522, 1899.

Bakker, G., Zur Theorie der gekrümmten Kapillarschicht: Zeitschr. physikal. Chemie, vol. 80, p. 129, 1912. See Washburne, C. W., The capillary concentration of gas and oil: Am. Inst. Min. Eng. Trans., vol. 50, pp. 851–852, 1914.

Perrin, Jean, La stratification des lames liquides: Annales de physique, 9th ser., vol. 10, pp. 160–184, 1918.

Wells, P. V., L'épaisseur des lames stratifiées: Annales de physique, 9th ser., vol. 16, pp. 69–110, 1921. Additional references to recent papers are given in the paper by Wells.

[43] Op. cit., p. 109.

[44] Atterberg, Albert, Die rationelle Klassifikation der Sande und Kiese: Chem. Zeitung, vol. 29, pt. 1, p. 196, 1905.

PERMEABILITY OF ROCKS.

The hydraulic permeability or perviousness of a rock is its capacity for transmitting water under pressure. If the pressure on the water in a permeable rock is the same in all directions static equilibrium exists and there is no tendency for the water to move, but if there is a resultant pressure in any direction the water will move in that direction. The permeability of a rock is measured by the rate at which it will transmit water through a given cross section under a given difference of pressure per unit of distance. Many rocks have a structure that makes their permeability greater in one direction than in another.

Rocks that will not transmit water may be said to be impermeable. Impermeability is, however, a relative term. A rock may not transmit water under a slight pressure, whereas it may transmit some water under a great pressure. Thus, steel is ordinarily impermeable to air, but according to experiments by Bridgeman[45] air can be forced through massive steel walls by about 60,000 atmospheres of pressure. It seems to be true also that a rock in which water is not moved by a given hydrostatic or hydraulic pressure may permit the migration of water caused by molecular forces. A good deal of confusion and controversy as to the impermeability of rocks could perhaps be avoided by recognizing a difference between absolute and hydraulic impermeability and by using the term "hydraulic impermeability" only with reference to a specified differential pressure or pressure gradient.

Some rocks, such as certain dense clays and shales, are apparently impermeable to water under the differential pressures usually found in the water in the rocks—that is, they will apparently transmit no water under these ordinary pressures, and wells ending in them remain entirely empty even though the clays or shales are saturated. An impermeable rock may be devoid of interstices, may contain only isolated interstices, or may have very minute communicating interstices. Most rocks are more or less permeable to water under the pressures ordinarily found in rocks reached in drilling, but they differ greatly in their degree of permeability, according to the number and size of their interstices and the extent to which these interstices open into one another. A clayey silt, with only minute pores, may transmit water very slowly, but a coarse clean gravel or a cavernous limestone with large openings that communicate freely with one another will transmit water very readily.

Permeable rocks may be impenetrable by water under pressure because their interstices are filled with gas or with petroleum or some

[45] Bridgeman, T. W., Experiments on the effects of extremely high pressure: Compressed Air Mag., vol. 26, pp. 10223–10225, Sept. 9, 1921. See Sci. Abstracts, Jan. 31, 1922.

other liquid that has no avenue of escape. Permeable rocks under these conditions are inert with respect to water in somewhat the same sense as impermeable rocks are inert with respect to water. If means of escape for the gas or petroleum are provided by wells sunk into the gas-bearing or oil-bearing formation, water may enter the rocks previously occupied by the gas or oil.

The permeability of rocks and the movement of water through rocks will be more fully discussed in a paper on the movement and head of ground water, now in preparation.

ZONE OF SATURATION.

The permeable rocks that lie below a certain level are generally saturated with water under hydrostatic pressure. Their interstices are filled with water. These saturated rocks are said to be in the "zone of saturation." The water that enters from the surface into the rocks of the earth is drawn down by gravity to the zone of saturation except as it is held by the molecular attraction of the walls of the interstices through which it passes in its descent. The permeable rocks that lie above the zone of saturation may be said to be in the "zone of aeration" (a new term that has been proposed by the writer). Some of the capillary and subcapillary interstices in this zone are also filled with water, but the water is held in them by molecular attraction and not by hydrostatic pressure.

Impermeable rocks may be found within the zone of saturation, within the zone of aeration, or between these two zones, but they are in a sense not functional parts of either zone. They may contain minute interstices or larger isolated interstices that are filled with water, but these interstices will remain filled regardless of whether they are in the zone of saturation or far above it. If impermeable rocks lie between the two zones they are rather arbitrarily classed as being in the zone of aeration. Oil-bearing and gas-bearing rocks generally lie deep within the zone of saturation.

In most places there is only one zone of saturation, but in certain localities the water may be hindered in its downward course by an impermeable or nearly impermeable bed to such an extent that it forms an upper zone of saturation, or perched water body, which is not associated with the lower zone of saturation.

Water that saturates soil or subsoil immediately after a rain or before the deeper frost has disappeared in the spring forms a temporary perched water body. Water percolating downward from the surface to a zone of saturation may be regarded as passing through the zone of aeration.

The zone of saturation and the zone of aeration can be illustrated very simply, as shown in figure 12, by means of a pitcher filled with fine gravel, which is, however, too coarse to be appreciably affected by capillarity, with enough water added to saturate the gravel up to a certain level. The relations of impermeable rocks and of perched water bodies to these zones can be illustrated, as shown in the figure, by means of a mass of some impermeable material at the water level and a tumbler containing a little water buried upright in the gravel at a higher level. The same principles are illustrated in figures 26 and 27, on page 79.

WATER TABLE.

The upper surface of the zone of saturation in ordinary permeable soil or rock is called the "water table." Where the upper surface is formed by impermeable rock the water table is absent. If a well is

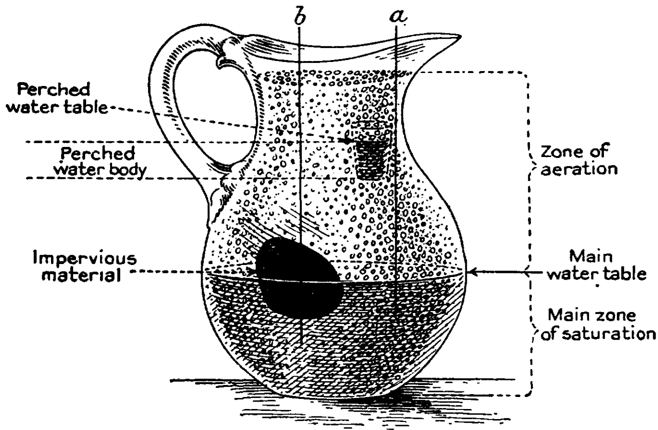


FIGURE 12.—Simple device to illustrate zone of saturation, water table, and perched water body.

sunk it remains empty until it enters a saturated permeable bed—that is, until it enters the zone of saturation as defined on page 29. Then water flows into the well. If the rock through which the well passes is all permeable the first water that is struck will stand in the well at about the level of the top of the zone of saturation—that is, at about the level of the water table. If the rock overlying the bed in which the first water is struck is impermeable the water is generally under pressure that will raise it in the well to some point above the level at which it was struck. In such a place there is no water table.

If in figure 12 a tube of larger than capillary size is sunk into the zone of saturation, as at *a*, it will form a tiny well in which water will stand at the level of the water table. If a tube is sunk through the impermeable material, as at *b*, it will receive no water until it reaches the bottom of this material and enters the saturated gravel. Then water will suddenly come in and rise some distance in the tube. The surface at which water is struck in this second well is functionally very different from the water table, where water is encountered in the first well. In this simple case the water rises in the second well about to the level of the water table in the surrounding permeable material, but where the impermeable bed is extensive there may be no definite relation between the water level in the well and the elevation of the water table elsewhere.

The water table is not a level surface but has irregularities comparable with and related to those of the land surface, although it is less rugged. It does not remain in a stationary position but fluctuates up and down. The irregularities are due chiefly to local differences in gain and loss of water, and the fluctuations are due to variations from time to time in gain or loss.[46]

The subject of water levels will be more fully discussed in a paper on the movement and head of ground water now in preparation.

CAPILLARY FRINGE.

In fine-grained material the earth is invariably moist for a distance of several feet above the water table. This condition is due to capillarity. Small communicating interstices form irregular capillary

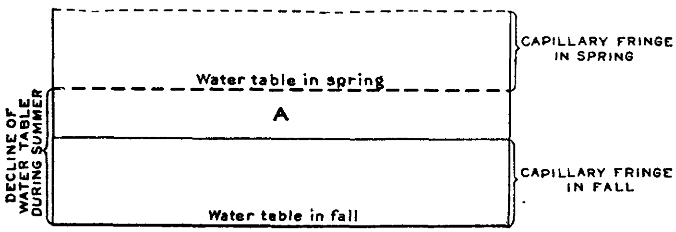


FIGURE 13.—Diagram showing relation of capillary fringe to water table and illustrating water-yielding capacity. The water-yielding capacity of the body A is the volume of water that drains out of it when, owing to the decline of the water table, it passes from the zone of saturation to a position above the capillary fringe.

tubes through which water is drawn up by molecular attraction, acting against gravity, and is held in this suspended position at a height above the water table where the two opposing forces are in equilibrium. This moist belt above the water table may be called the "capillary fringe." It is generally recognized by well diggers and borers, who interpret it correctly as a prophecy of available water. Its water content and wet appearance are likely to increase downward, for in that direction progressively larger interstices are filled with water. However, not until the water table is reached does water enter the well. The relation of the capillary fringe to the water table is shown in figure 13.

As a general rule, the thickness of the capillary fringe varies inversely with the size of the interstices. The fringe is relatively thick

[46] Veatch, A. C., Fluctuations of the water level in wells, with special reference to Long Island, N. Y.: U. S. Geol. Survey Water-Supply Paper 155, 1906.

in rock or soil that has small interstices, such as silt or clay loam, and relatively thin in substances that have larger interstices, such as coarse sand. It has been observed to be about 8 feet thick in various fine-grained loamy and silty materials, but it is much thinner in sand, and it practically disappears in clean gravel.

In the following tables are given the results of two series of experiments on the capillary rise of water in sorted sediments of specified

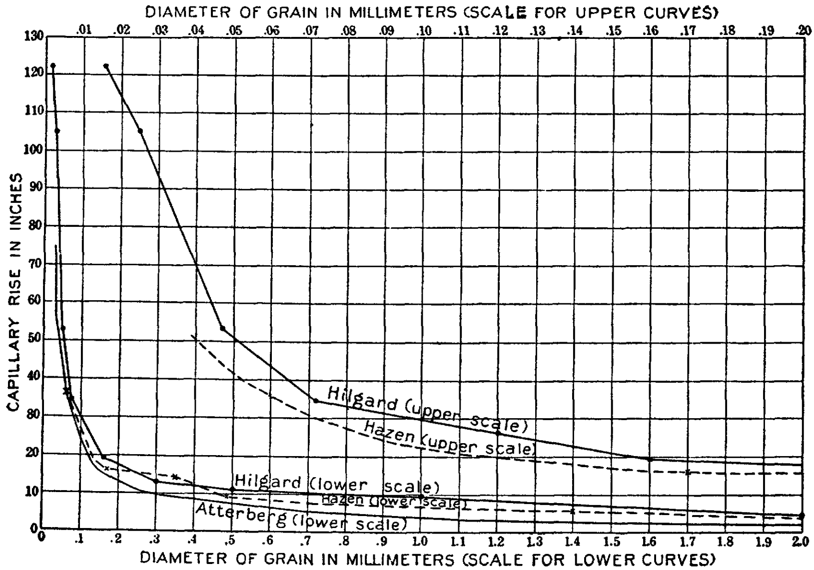


FIGURE 14.—Diagram showing relation of capillary rise of water in granular materials to size of grain, according to experiments by Hazen, Atterberg, and Hilgard.

sizes. One series of experiments was made by Albert Atterberg and the other by E. W. Hilgard. The maximum rise for the different sizes in each series of experiments is graphically shown in figure 14, but the Atterberg data are given in such form that the curve based on them is necessarily only approximate.

Capillary rise of water in sorted sands and silts, according to Atterberg.[a]

Diameter of grain (millimeters).	Rise in 24 hours (meters).	Rise in 48 hours (meters).	Maximum rise.		Period required to attain maximum rise (days).
			Meters.	Inches.	
5 to 2	0.22		0.025	1.0	3
2 to 1	.054	0.060	.065	2.6	4
1 to 0.5	.115	.123	.131	5.2	4
0.5 to 0.2	.214	.230	.246	9.7	8
0.2 to 0.1	.376	.396	.428	16.9	8
0.1 to 0.05	.530	.576	1.055	41.5	72
0.05 to 00.2	1.153	1.360	[b]1.860	[b]73.2	[b]53
0.02 to 0.01	.485	.922			
0.01 to 0.005	.285				
0.005 to 0.002	.143				
0.002 to 0.001	.055				

[a] Atterberg, Albert, Die rationelle Klassifikation der Sande und Kiese: Chem. Zeitung, vol. 29, pt. 1, p. 196, 1905.
[b] Rise incomplete; was estimated to have an ultimate rise of about 2 meters.

Capillary rise of water in soil sediments, according to Hilgard.[a]

Diameter of grain (millimeters).	Maximum rise (inches).	Period required to attain maximum rise (days).	Diameter of grain (millimeters).	Maximum rise (inches).	Period required to attain maximum rise (days).
2	4½	80	0.072	34¾	144
1	9½	100	0.047	53¼	160
0.5	11	138	0.025	105	300
0.3	13	188	0.016	122	475
0.16	19¼	171	Clay	60½	350
0.12	26¼	158	Sandy loam	52	144

[a] Hilgard, E. W., Soils, p. 206, New York, Macmillan Co., 1906. (Reprinted by permission.)

There is fairly close agreement between these two sets of results, obtained independently of each other and doubtless with sediments of different origin. The lower values of Atterberg are in part due to the much shorter periods of rise allowed in his experiments.

Hazen[47] states that "the height to which water will be held to such an extent as to prevent the circulation of air can be roughly estimated" by the formula $h=\frac{1.5}{d^2}$, in which h is the height of capillary rise, in millimeters, and d is the effective size of grain, in millimeters. The effective size of grain of imperfectly assorted material is defined by Hazen[48] as the diameter of a grain of such size that 10 per cent of the material, by weight, consists of smaller grains and 90 per cent of larger grains. Hazen states that "the data from which the constant 1.5 in the above formula was calculated are very inadequate, and consequently the formula may require modification with more extended observations." This formula has no comparable relation to the data given by Atterberg and Hilgard, as it applies to different conditions expressed by the phrase "to such an extent as to prevent the circulation of air." This difference can best be appreciated by reference to figure 15 (p. 53), on the data of which the formula is in part based, by using the values indicated in the third column of the following table. The extreme capillary rise indicated in figure 15 seems to be more nearly as indicated in the fourth column.

Capillary rise of water in materials tested by Allen Hazen.

[See figs. 4 and 15.]

No. of sample.	Effective size of grain (millimeters).	Height to which water will be held to such an extent as to prevent the circulation of air (inches).	Maximum capillary rise, estimated from curves in figure 15 (inches).
5	0.02	60	
4	.03	24	56(?)
2	.06	10	36
9	.17	1	16
6	.35		14
1	.48		9
5a	1.40		6
16	5.00		1

[47] Hazen, Allen, Some physical properties of sands and gravels: Massachusetts State Board of Health Twenty-fourth Ann. Rept., for 1892, p. 551, 1893.

[48] Idem, p. 549.

By plotting the values for capillary rise given in the fourth column of the table on the diagram in figure 14 it becomes evident that Hazen's data are in general agreement with those of Hilgard and Atterberg. It must be remembered that the Hazen curve is based on effective size instead of actual size of the grains. As the uniformity coefficient (see p. 7) is low for all samples plotted except No. 6, this does not make much difference except for No. 6, which, as might be expected, causes a decided upward bulge in the curve.

In materials having interstices of various sizes the upper limit of the capillary fringe may be somewhat indefinite. The interstices in most formations that have been observed in their natural condition are sufficiently uniform to produce a rather abrupt transition from the moist zone to the overlying nearly dry material. Much difference of opinion exists, however, as to the extent of capillary rise above the observable capillary fringe.

The available field data as to the height to which water will rise through rock or soil by capillarity are rather abundant but are unsatisfactory and conflicting. The following summary is abbreviated from a review of some literature on the subject by Alway and McDole:[49]

> The authors who maintain the theory "that water can rise to the surface from the deep layers by capillary action" are too numerous to name, but few of them offer any experimental evidence in support of the theory. From field observations during unusually prolonged summer droughts Hall[50] concluded that in certain soils the capillary rise of water might be as much as 200 feet. Mitscherlich,[51] who has calculated the maximum possible elevation of water to be as high as 2 or 3 kilometers in heavy clays and loams, considers this of no practical importance, on account of its extreme slowness of movement. From experiments with "the most varied soils" exposed for 3-month period, he observed no rise exceeding 0.8 meter and concluded that 1.5 meters from ground water may be regarded as the practical limit, so far as plants are concerned.[52] In the case of one soil Tulaikow[53] observed a rise of 135 centimeters in 513 days, and the maximum had not yet been reached; while with three finer-textured soils the rise at the end of a year and a half had become stationary at 60 to 70 centimeters. Leather,[54] from a study of the moisture in a fallow field at Pusa, India, during the dry season of 1906, concluded that "during a dry period water moves upward toward the surface from a limited depth only; this limited depth increases with the period. Below this depth the water is stationary or possibly still draining downward." In the Pusa soil he found the maximum distance that water moved upward during the period to be somewhat more than 3 feet and that eventually it was about 7 feet. Extreme views of the importance of the upward

[49] Alway, F. J., and McDole, G. R., Relation of the water-retaining capacity of a soil to its hygroscopic coefficient: Jour. Agr. Research, vol. 9, pp. 28-31, Apr. 9, 1917.

[50] Hall, A. D., The soil, p. 94, London, 1903.

[51] Mitscherlich, E. A., Bodenkunde für Land und Forstwirte, p. 192, Berlin, 1905.

[52] Mitscherlich, E. A., idem, 2d ed., p. 136, Berlin, 1913.

[53] Tulaikow, N., Einige Laboratoriums-Versuche über die Kapillarität der Böden (abstract): Zhur. Opuitn. Agron. (Russ. Jour. Exp. Landw.), t. 8, kniga 6, p. 665, 1907.

[54] Leather, J. W., The loss of water from soil during dry weather: Dept. Agr. India Mem., vol. 1, No. 6, pp. 105-106, 1908.

capillary movement have been expressed by Cameron[55] and McGee.[56] The former,[57] mentioning that in humid areas the larger part of the water from rains returns to the surface, states that it sometimes does so "through distances of many feet." McGee has estimated that under favorable conditions of subsoil texture it will move during a term of years and progressively equalize the distribution of subsoil water through a depth of 30 or 35 feet.[58] Rotmistrov,[59] using glass tubes and wooden boxes, carried out experiments with soil from the experimental field. Placing these in water, he observed a rise of less than 3 feet in three months. As the movement is so slow in the soil with water less than 3 feet below the surface, he concludes it will not move at all in the field where it is at a depth of over 100 feet. Burr,[60] from a 7-year study (1907 to 1913) of the total moisture in the first 3 to 15 feet of the comparatively uniform loessial soil on the table-land at North Platte, Nebr., where the water table is at a depth of over 200 feet, concludes that there is little upward movement of subsoil water and that "water supply by capillarity is not an important factor in crop production on Nebraska upland soils."[61]

On the basis of numerous observations in Owens Valley, Calif., Lee[62] states that in a coarse sandy soil water will be lifted above the water table through the capillary spaces not more than 4 feet and in fine sandy or clayey soil not more than 8 feet. Slichter[63] found, in tests with a sandy loam changing to coarse sand at a depth of about 3 feet, that where the water table was as much as 3 feet below the surface the capillary rise became sluggish, indicating that the capillary fringe was probably not much more than 3 feet thick. In a number of observations in Big Smoky Valley, Nev., the writer found the visible capillary fringe to range between 3 feet and 8.1 feet in thickness where it did not extend to the surface and was as much as 7 feet thick where it reached the surface.[64] In the Tularosa Basin, N. Mex., where the soil is largely a gypseous silt, the height to which water is lifted above the water table by capillarity is in many places about 8 feet.[65] According to investigations by Burr, Hering, and Freeman[66] on Long Island, water will not rise to the surface by capillarity if the water table is at a depth of 8 feet or more in fine soil or as much as

---

55 Cameron, F. K., The soil solution, Easton, Pa., 1911.

56 McGee, W J, Wells and subsoil water: U. S. Dept. Agr. Bur. Soils Bull. 92, 1913; Field records relating to subsoil water: U. S. Dept. Agr. Bur. Soils Bull. 93, 1913.

57 Cameron, F. K., op. cit., p. 23.

58 McGee, W J, op. cit. (Bull. 92), p. 11.

59 Rotmistrov, F. G., The nature of drought according to the evidence of the Odessa experiment field, Odessa, 1913.

60 Burr, W. W., The storage and use of soil moisture: Nebraska Agr. Exper. Sta. Research Bull. 5, 1914.

61 Idem, p. 10.

62 Lee, C. H., The determination of safe yield of underground reservoirs of the closed-basin type: Am. Soc. Civil Eng. Trans., vol. 78, p. 182, 1915. See also U. S. Geol. Survey Water-Supply Paper 294, 1912.

63 Slichter, C. S., The underflow in Arkansas Valley in western Kansas: U. S. Geol. Survey Water-Supply Paper 153, pp. 43-44, 1906.

64 Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring valleys, Nev.: U. S. Geol. Survey Water-Supply Paper 423, p. 100, 1917.

65 Meinzer, O. E., and Hare, R. F., Geology and water resources of Tularosa Basin, N. Mex.: U. S. Geol. Survey Water-Supply Paper 343, p. 109, 1915.

66 Burr, W. H., Hering, R. H., and Freeman, J. R., Report of the Commission on Additional Water Supply for the City of New York, p. 756, 1904.

3 or 4 feet in coarse sand or gravel. Additional data on this subject are given by Meyer.[67]

That water rises much higher by capillarity in a given material when it is moist than when it is dry was shown by Briggs and Lapham and also by Stewart.[68] The results of tests with four different soils are shown in the following tables. The mechanical analyses of these soils can not be definitely evaluated with respect to capillarity, but apparently the capillary rise in the moist samples is in approximate agreement with the curves shown in figure 14.

Mechanical analyses of four soils and data as to capillary rise of water in dry and moist samples.

Mechanical analyses.

Diameter of grains, in millimeters.	1	2	3	4
2 to 1	0			
1 to 0.5	.4			
0.5 to 0.25	6.0	97.6	96.3	88
0.25 to 0.1	79.1			
0.1 to 0.05	2.5			
0.05 to 0.01	.5	.8	1.2	7.3
Less than 0.01	8.8	.1	.3	.7

Capillary rise.

	1	2	3	4
Dry ... millimeters..	370	318	581	868
Moist ... do....	1,650	1,125	1,418	1,741
Dry ... inches..	14.6	12.5	22.9	34.2
Moist ... do....	65.0	44.3	55.8	68.5

1. Briggs, L. J., and Lapham, M. H., op. cit.
2-4. Stewart, J. B., op. cit.

Two series of experiments were made by G. C. Whipple[69] to determine the extent and rate of capillary rise in materials on Long Island that ranged in effective size of grain from 0.03 to 0.95 millimeter and in uniformity coefficient from 1.17 to 1.53. The first series of experiments was made with materials after they had been dried in an oven and the second with similar materials after they had been saturated and then allowed to drain. The generalized results are shown approximately in the following table, based on a diagram by Whipple. As a rule the rise in the dry materials was considerably less and the rise in the wet materials considerably greater than that for corresponding sizes of grain in the experiments of Hilgard, Atterberg, and Hazen. Whipple concludes that the rise in a given material in a moist condition will be greater than the rise in the material when it is dry and

[67] Meyer, A. F., The elements of hydrology, pp. 231-237, New York, John Wiley & Sons, 1917.

[68] Briggs, L. J., and Lapham, M. H., The capillary movement of water in dry and moist soils: U. S. Dept. Agr. Bur. Soils Bull. 19, pp. 19-30, 1902. Stewart, J. B., Capillary rise of water in soils, Michigan Agr. College, 1901.

[69] Burr, W. H., Hering, Rudolph, and Freeman, J. R., Report of the Commission on Additional Water Supply for the City of New York, pp. 603-613, 1904. Spear, W. E., An additional supply of water for the city of New York from Suffolk County, Long Island, pp. 535-536, 1912.

less than the rise in the material when it is wet. In the dry materials there was a rapid initial rise, which was most marked in the finer grades. The rate of rise then gradually decreased until after a few days it ceased altogether in the coarser materials. In the finer materials it continued at a slow but nearly constant rate for two months, when the experiments were stopped. During the entire period the materials were protected from evaporation.

Capillary rise of water in dry and wet materials tested by Whipple.

[Uniformity coefficients between 1.17 and 1.53.]

Effective size of grain (millimeter).	Rise in dry materials by end of two months (inches).	Rise in wet materials (inches).
1.0	0 -1½	6-11
.5	3 -4	11-17
.4	4 -5	14-20
.3	5½-7	17-25
.25	6½-8	20-28
.03	16 -19	65-78

It was found by Briggs and Lapham[70] that concentrated solutions of all salts have distinctly less capillary activity than pure water but that dilute solutions of neutral salts, such as commonly form soil water and ground water, do not differ appreciably in capillarity from pure water. The solutions have greater surface tension, which tends to allow them to be lifted higher, but they also have greater specific gravity, which tends to hold them down. (See pp. 21–25.) Moreover, other forces may be operative. They found, however, that a solution of sodium carbonate rises considerably higher by capillarity than pure water, possibly because it has a soaplike action in cleaning the walls of the interstices.

In the finer sands used in the experiments by Whipple the capillary rise of sea water, ground water taken from the Brooklyn public supply, and distilled water was approximately in the ratio of 1 : 1.15 : 1.25, but in the coarser sands the differences were irregular.

If the capillary fringe is near enough to the surface to be affected by changes in temperature it may fluctuate slightly in thickness owing to decrease in surface tension with increase in temperature. When the temperature rises some of the capillary water may be allowed to drain down to the water table and be added to the zone of saturation, and when the temperature falls some water may be drawn up from the water table into the capillary interstices.[71] In a discussion

[70] Briggs, L. J., and Lapham, M. H., Influence of dissolved salts on the capillary rise of soil water: U. S. Dept. Agr. Bur. Soils Bull. 19, pp. 5-18, 1902. See also Briggs, L. J., The mechanics of soil moisture: U. S. Dept. Agr. Bur. Soils Bull. 10, p. 20, 1897.

[71] Bouyoucos, G. J., Effect of temperature on movement of water, vapor, and capillary moisture in soils: Jour. Agr. Research, vol. 5, pp. 141-172, 1915.

of this subject with a review of observations made by King on fluctuations of water levels in wells apparently related to fluctuations in temperature, Veatch[72] concludes that changes in surface tension of the water in the capillary fringe due to changes in temperature are theoretically competent to produce appreciable changes in water level. An experiment by King on the same subject is described and commented on by Briggs[73] as follows:

> These conclusions are indirectly verified by some interesting experiments of Prof. King[74] in experimenting with the fluctuations of ground water in a large cylindrical galvanized-iron tank. He found that the water in a circular well in the middle of the cylinder rose daily and fell again during the night. The application of cold water to the outside of the cylinder by means of a hose also caused the water in the well to fall. These results are fully consistent with the phenomena of surface tension. When the temperature of the soil was raised the surface tension of the water was lowered and more water was drawn into the lower part of the cylinder, which raised the level of the water in the well. When cold water was applied to the outer surface of the cylinder the water in the soil was drawn up again through increased surface tension and the level of the water in the well was lowered.

If the capillary fringe is near enough to the surface to lose water by evaporation or by the absorption of the roots of plants there is a continuous movement of water from the water table upward through the capillary interstices. If, however, the water table and overlying capillary fringe are at a considerable depth there is no interchange of water between the zone of saturation and the capillary fringe due to changes in temperature and no persistent upward movement of water to replace that removed by evaporation or plant absorption. At considerable depths the water in the fringe is virtually stationary except as the water table fluctuates, carrying the fringe with it.

DEFINITION OF GROUND WATER.

There has been much confusion in the terms used to denote the water below the surface and the water in the zone of saturation. Thus the terms ground water, underground water, subterranean water, subsurface water, phreatic water, and vadose water have been used with bewildering variety of meanings. The following nomenclature has been adopted for this paper: All the water that exists below the surface of the solid earth is called "subsurface water," to distinguish it from surface water and atmospheric water. That part of the subsurface water which is in the zone of saturation is called "ground water" or "phreatic water."[75] The subsurface water above the zone of saturation—that is, the water in the zone of aeration—is called "suspended subsurface water" or "vadose water."

---

[72] Veatch, A. C., Fluctuations of the water level in wells, with special reference to Long Island, N. Y.: U. S. Geol. Survey Water-Supply Paper 155, pp. 54-59, 1906.

[73] Briggs, L. J., The mechanics of soil moisture: U. S. Dept. Agr. Bur. Soils Bull. 10, p. 21, 1897.

[74] U. S. Dept. Agr. Weather Bur. Bull. 5, pp. 59-61, 1892.

[75] Meinzer, O. E., Quantitative methods of estimating ground-water supplies: Geol. Soc. America Bull., vol. 31, p. 330, 1920.

Ground water is the water in the zone of saturation in the sense that it is the basal or bottom water. The term is understood by many persons to refer only to water in the upper part of the zone of saturation, but it has been used by such eminent geologists as Van Hise[76] and Chamberlin and Salisbury[77] to include the deeper water in the zone of saturation, and it has long been used in this sense by the United States Geological Survey.

The term "phreatic" is derived from the Greek word meaning a well. As wells are supplied by the water in the zone of saturation, the term should, according to its etymology, be applied to all of this water. It was introduced by Daubrée[78] to designate the water in the zone of saturation except the deeper water below impermeable beds. This limitation, however, is not etymologically defensible, is too intangible to be successfully applied in practice, and has not been recognized by the few American geologists who have used the term.[79] The writer believes that the term "phreatic water" will be most useful if it is regarded as a synonym of ground water—including all water in the zone of saturation.

The water in the zone of aeration is literally suspended subsurface water. It is held up against gravity by molecular forces just like a weight that is suspended from a string. The term "vadose water" was originally used by Posepny[80] to designate the water in the zone of aeration—a very appropriate term for a definite and important concept. Unfortunately it has been used by later writers to include parts or all of the water in the zone of saturation, but Daly[81] proposes to return to its original meaning.

The terms "underground water" and its Latinistic equivalent, "subterranean water," have both been widely used. They are etymologically equivalent to subsurface water but are more often used to designate the water in the zone of saturation or only the water in the deeper parts of this zone. It is confusing to use both "ground water" and "underground water," because they are etymologically incongruous.

There are, therefore, two kinds of water in the interstices of the rocks—(1) ground water, or phreatic water, and (2) suspended subsurface water, or vadose water. The water that supplies springs and wells is ground water. If a well is sunk its walls may be moist at various levels above the water table, but not until the well enters the zone of saturation does water flow into it and become available for use as a water supply.

---

[76] Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Survey Mon. 47, p. 123, 1904.

[77] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 1, pp. 202–231, 1904.

[78] Daubrée, A., Les eaux souterraines à l'époque actuelle, vol. 1, p. 19, Paris, 1887.

[79] Hay, R., Artesian and underflow investigations between the 97th meridian and the foothills of the Rocky Mountains: 52d Cong. 1st sess., S. Ex. Doc. 41, pt. 3, p. 8, 1893. McGee, W J, Potable waters of the eastern United States: U. S. Geol. Survey Fourteenth Ann. Rept., pt. 2, pp. 15–16, 1893. Daly, R. A., Genetic classification of underground volatile agents: Econ. Geology, vol. 12, pp. 495, 499, 1917.

[80] Posepny, F., The genesis of ore deposits: Am. Inst. Min. Eng. Trans., vol. 23, p. 213, 1894.

[81] Op. cit., pp. 494–499.

LOWER LIMIT OF POROUS ROCKS.

It is believed that very deep down in the earth the weight of the overlying formations is so enormous that it exceeds the strength of the rocks. Consequently if there were any open spaces in the rocks at such depths they would cave in and close up. According to this theory the rocks below a certain deep level are therefore devoid or nearly devoid of interstices. The depth at which the interstices close depends on the character of the rock—it is evidently greater for strong rocks than for weak rocks. In some places layers of weak rock whose interstices have been obliterated by pressure are probably underlain by stronger rocks that remain porous. At still greater depths, however, according to this theory, the elastic limit of even the strongest rocks is reached and therefore in rocks of all kinds interstices are absent or insignificant.

On this basis the crust of the earth has been divided by Van Hise[82] into three zones—(1) a zone of rock fracture, or upper zone in which the rocks are not under stresses that are sufficient to close their interstices, (2) a zone of rock flowage, or deep zone in which all rocks are under stresses that exceed their elastic limits and therefore undergo deformation that resembles flowage and closes up existing interstices, and (3) an intermediate zone in which the stronger rocks behave like the rocks in the zone of rock fracture and the weaker rocks behave like those in the zone of rock flowage.

The depth at which the zone of rock flowage is reached has not been conclusively determined but seems to be many miles. The early investigations of this subject are summarized by Adams[83] as follows:

That the outer portion of the earth's crust was susceptible of subdivision into a zone of fracture and a zone of flow was set forth by Professor Heim in his great work "Untersuchungen über den Mechanismus der Gebirgsbildung," and was based upon the data which he had obtained from his life-long studies in the Alps.[84] In this epoch-making work Heim states that as a result of his observations in the Alps he concludes that the upper surface of the zone of flow for very resistant rocks, such as granites, is 2,200 to 2,600 meters, or about a mile and a half, below the surface of the earth, and considerably nearer the surface for limestone and other softer rocks. After 30 years of additional study Heim in a recent paper, records his opinion that these depths are too small—that the zone of flow lies deeper within the earth's crust—but as to how much deeper he does not venture an opinion.[85]

President Van Hise, in the interpretation of the results of his classic work on the ancient crystalline rocks of the United States in the district of the Great Lakes, reached a similar conclusion with reference to the twofold subdivision of the earth's crust but placed the upper surface of the zone of flow at a considerably greater depth than Heim, namely, 12,000 meters or 7.4 miles.

---

[82] Van Hise, C. R., Principles of North American pre-Cambrian geology: U. S. Geol. Survey Sixteenth Ann. Rept., pt. 1, p. 593, 1896.

[83] Adams, F. D., An experimental contribution to the question of the depth of the zone of flow in the earth's crust: Jour. Geology, vol. 20, pp. 97-118, 1912.

[84] Heim, Albert, Untersuchungen über den Mechanismus der Gebirgsbildung, Band 2, p. 92, Basel, 1878.

[85] Heim, Albert, Geologische Nachlese, No. 19 (Vierteljahrsschrift der Naturf. Gesell. in Zurich, 1908, p. 45).

Van Hise based his estimate on a mathematical calculation having as its starting point the crushing weight of a cube of granite at the surface of the earth as determined by a testing machine in the ordinary manner adopted in testing the strength of building materials—granite being one of the strongest and at the same time one of the commonest rocks in the earth's crust. This calculation was made for Van Hise by Professor Hoskins,[86] who, taking the figures for the crushing strength of granite thus obtained, endeavored to calculate the depth below the earth's surface at which the pressure would be so great that all empty cavities would close as a result of plastic flow, even in the case of the hardest rocks, like granite. This depth he fixed at 4 miles, or 6,520 meters. If, however, the cavities were filled with water, Hoskins calculated that they would remain open to a depth of 6.4 miles, or 10,350 meters. Van Hise then assumed an additional factor of safety and took 12,000 meters as a depth at which not only all cavities would close but the hardest and most resistant rocks would flow—this being therefore the upper surface of the zone of flow in the earth's crust.

In order to make such a calculation, even in the very simple case treated by Hoskins, certain assumptions must be made, and the result obtained varies widely with these assumptions. Consequently, the figures obtained by Hoskins have not behind them the weight of a mathematical certainty. They are founded on certain assumptions and have a probability no greater than the assumptions on which they are based.

On the basis of a series of experiments made by himself, Adams[87] reaches the following conclusions:

At ordinary temperatures but under the conditions of hydrostatic pressure or cubic compression which exist within the earth's crust, granite will sustain a load of nearly 100 tons to the square inch—that is to say, a load rather more than seven times as great as that which will crush it at the surface of the earth under the conditions of the usual laboratory test.

Under the conditions of pressure and temperature which are believed to obtain within the earth's crust, empty cavities may exist in granite to a depth of at least 11 miles. These may extend to still greater depths and if filled with water, gas, or vapor will certainly do so, owing to the pressure exerted by such fluids or gases upon the inner surfaces of such cavities or fissures.

Later the same problem was investigated by Bridgman,[88] who made the tests by applying hydrostatic pressure. His conclusions are stated in part as follows:[89]

Cavities in the materials dealt with in this paper, which may be broadly characterized by the property of brittleness, exhibit a method of failure under high compressive stresses not shown by ductile materials like the metals. This method consists in the shooting off of minute fragments with considerable violence from the walls of the cavity. The frequency and probably the velocity of projection varies with the pressure, the rapidity of disintegration becoming greater at higher pressures. This mode of disintegration is shown both by rocks and by single crystals; in rocks the splinters show no relation to the boundaries between chemically homogeneous parts of the mixture, and in the crystals there is no obvious connection with the crystalline symmetry. The rate of change of speed of disintegration with pressure

---

[86] Hoskins, L. M., Flow and fracture of rocks as related to structure: U. S. Geol. Survey Sixteenth Ann. Rept., pt. 1, pp. 845–875, 1896.

[87] Op. cit., p. 117. See also King, L. V., On the limiting strength of rocks under conditions of stress existing in the earth's interior: Jour. Geology, vol. 20, pp. 119–138, 1912.

[88] Bridgman, P. W., The failure of cavities in crystals and rocks under pressure: Am. Jour. Sci., 4th ser., vol. 45, pp. 243–280, 1918.

[89] Idem, pp. 266–268.

may vary greatly from substance to substance, being comparatively small for quartz and high for tourmaline and andesite.

The phenomenon of rupture by flaking off is independent of other phenomena accompanying high stress. Some substances develop cracks at the same time that they erode; the number of cracks may be great, as in calcite, or small, as in quartz. Or the erosion may be accompanied by no cracks whatever, as in feldspar, porphyry, and andesite. The substance may show no viscous flow during erosion, or it may flow like granite and barite. The formation of cracks was never in these tests the cause of final rupture, except with glass. Cracks are probably in many cases due to the attempt of the solid to slip bodily into the cavity, but such slip can never go far before it is stopped by the mutual supporting action of the walls. Such slip may be prominent in a substance with easy cleavage, or slight, as in quartz. It is probable that the cracks in quartz and calcite were essentially the same in character, one being merely more prominently developed than the other.

Flaws in the original specimen are apparently so tightly closed by pressure that they play no part in fracture.

This paper mentions the results of a new mathematical analysis of the effect in crystals of hydrostatic pressure applied as in these experiments. It appears that the new phenomena introduced by crystalline structure are not prominent enough to lead one to expect rupture because of them, and that in most cases an approximate solution may be obtained by treating the crystal as isotropic with mean values of the elastic constants.

The stresses which these brittle materials stand are many times higher than would be predicted by ordinary compression tests. If one neglects the flaking-off effect, which is entirely uncontemplated in mathematical theory, stresses at least 20 times higher than those of ordinary compression tests may be reached without rupture. At the same time the possible stresses are very appreciably lower than those found by Adams. His results were affected by the unknown action of shrunk-on-steel jackets.

Attempts to weld together finely powdered quartz, feldspar, and talc failed up to 30,000 kilograms per square centimeter [about 450,000 pounds per square inch]. There is, however, no evidence that such welding would not take place if the adherent film of air could be entirely removed; this is a matter of extreme experimental difficulty. The amount of interstitial space in compressed powders has been measured, but caution must be used in inferring from these figures the density of a compressed sand while actually under pressure. The results of these collapsing tests makes it extremely probable, however, that minute crevices, at least large enough for the percolation of liquids, exist in the stronger rocks at depths corresponding to 6,000 to 7,000 kilograms per square centimeter [about 90,000 to 105,000 pounds per square inch], and possibly more.

LOWER LIMIT OF GROUND WATER.

The zone of rock flowage is significant with respect to the occurrence of ground water. If this zone marks the lower limit of interstices it also marks the lower limit of the existence of water in its ordinary mode of occurrence. The experience from drilling deep wells shows, however, that in most places recoverable water becomes very scarce long before the theoretical depth at which interstices are impossible is reached.

There is no regular relation between the porosity or aqueous capacity of rocks and their depth below the surface. A very dense granite may be found at the surface, whereas a porous sandstone may lie a few thousand feet below the surface. On an average, however, the porosity decreases as the depth increases, the large openings especially disappearing as greater depths are reached. Most of the water in crystalline rocks is within 300 feet of the surface, comparatively little being found by drilling to greater depths in these rocks.[90] Porous rocks that yield water freely have been encountered at depths of more than 6,000 feet, but most of the wells drilled deeper than 2,000 feet have found but little water below this depth. This decrease of interstices and especially of large openings with increase in depth is due partly to increase in pressure on the rocks, which closes the openings in soft formations even relatively near the surface, and partly to the processes of weathering, which enlarges the interstices near the surface, and cementation, which commonly closes them at greater depths.

The following table, giving a list of some of the deepest wells drilled in the United States for water, shows how unfavorable have been the results in drilling below the depth of 3,000 feet. Most of the wells that yielded little or no water were, however, in crystalline rocks, and some of the failures in other formations were due to the poor quality of the water rather than the small quantity. Many sandstones are apparently water bearing where they extend to depths of more than 3,000 feet.

Wells 3,100 feet or more in depth drilled for water in United States.

[Compiled by Harold S. Palmer.]

Place.	Depth of well (feet).	Kind of rock.	Results obtained.	References.[a]
Putnam Heights, Conn.	6,004	Crystalline rock	2 gallons per minute	Water-Supply Paper 149, p. 24.
Jacksonville, Fla	5,000	"Rock and clay"	Apparently unsuccessful.	Water-Supply Paper 102, p. 245.
Northampton, Mass.	4,022	Red sandstone or crystalline rocks.	Unsuccessful; little or no water.	Water-Supply Paper 149, p. 64; Water-Supply Paper 257, p. 32; Water-Supply Paper 160, p. 67.
New Haven, Conn.	4,000	"Red sandstone, etc."	do	Water-Supply Paper 257, p. 32; Water-Supply Paper 160, p. 67.
St. Louis, Mo	3,843	Sandstone, limestone, etc., to 3,558 feet; then mostly granite.	Salty water	Water-Supply Paper 195, p. 163.
New Haven, Conn.	3,800		Unsuccessful	Water-Supply Paper 149, p. 24.
Northampton, Mass.	3,700	Arkosic sandstone or conglomerate.	No water	Water-Supply Paper 110, p. 75.
Rockville, Conn	3,440	Red sandstone or crystalline rock.	do	Water-Supply Paper 149, p. 24.
Marlin, Tex	3,350	Sedimentary rocks probably to bottom.	Head+322 feet; yield, 140 gallons per minute.	Water-Supply Paper 149, p. 146.
Hubbard City, Tex.	3,166	Sandstone, etc	Salty water	Twenty-first Ann. Rept., pt. 7, p. 548.
Fishkill on Hudson, N. Y.	3,100	"Rock." Doubtless crystalline rock.	Water supply from less than 500-foot depth, 10 gallons per minute.	Water-Supply Paper 102, p. 181.

[a] All references indicate U. S. Geological Survey publications.

[90] Ellis, E. E., Occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 160, pp. 19-28, 1906.

The usual experience in drilling deep oil wells has also been that not much water enters the wells below depths of 3,000 or even 2,000 feet. Lindgren[91] cites an example of a well at Wheeling, W. Va., 4,262 feet deep, which passed through "absolutely dry rock" in the lower 1,500 feet. The deepest wells in the world are two recently drilled in the United States—the Goff well, near Clarksburg, W. Va., and the Lake well, near Fairmont, W. Va. The Goff well is 7,386 feet deep, and the Lake well is 7,579 feet deep. The mouth of the Goff well is 1,164 feet above sea level, and the mouth of the Lake well about 1,300 feet. Both wells therefore extend more than 6,000 feet below sea level. Both are entirely in sedimentary strata. The Goff well penetrated recognized water, oil, and gas bearing sands at various levels in the first 2,000 feet and passed through the Bayard sand between the depths of 2,300 and 2,310 feet, below which the formations are described as alternating strata of "lime" and "slate." Below the depth of 2,307 feet the well is not cased except between 5,405 and 7,071 feet, where it was cased to protect the hole from caving. Below 2,307 feet no water entered the well, and it was necessary to introduce the water required for drilling. The casing between 5,405 and 7,071 feet fits so loosely that it would not have shut out any water.[92] The Lake well was cased only to a depth of 2,118 feet. The strata below 2,118 feet are reported as alternately "lime," "slate," and some "sand"; they did not yield any water.[93]

The Geary well, near McDonald, Pa., about 20 miles southwest of Pittsburgh, reached a depth of 7,248 feet, or about 6,200 feet below sea level. It penetrates the Gordon stray sand, the last of the usual gas sands in this region, at a depth of 1,971 feet. From this depth to the bottom the strata consist chiefly of "lime" and "slate" with some rock salt in the last few hundred feet. Below 6,045 feet there is, however, much sand, some beds of which yielded large amounts of salty water. The water found at 6,260 feet rose in the hole to a height of 5,560 feet, or within 700 feet of the top of the well. Drilling was finally stopped by the collapsing of the casing due to hydrostatic pressure of the water on the outside.[94]

In Australia, where certain water-bearing formations pass to great depths, there are numerous successful flowing wells that derive their supplies from depths of more than 3,000 feet and a considerable number that are supplied from depths of more than 4,000 feet, as is shown in the following table:

---

[91] Lindgren, Waldemar, Mineral deposits, p. 36, New York, 1913.

[92] White, I. C., Discussion of the records of some very deep wells in the Appalachian oil fields of Pennsylvania, Ohio, and West Virginia: West Virginia Geol. Survey County Repts., Barbour and Upshur counties and western portion of Randolph County, pp. lv-lx, cii, 1918. Also written communication from Dr. White.

[93] White, I. C., West Virginia's second deepest well of the world: Ohio Gas and Oil Men's Jour., vol. 1, pp. 17-22, September, 1919. Also written communication from Dr. White.

[94] White, I. C., op. cit., pp. xxvi-xxxii.

Wells more than 4,000 feet deep drilled for water in Australia.[a]

Name of well.	Province.	Depth of well (feet).	Depth from which water is derived (feet).	Artesian head (feet above surface).	Artesian flow (gallons).	
					Per minute.	Per day.
Patchawarra [b]	New South Wales	5,337	4,000	Flow.	Small supply.	
Whitewood	Queensland	5,045			49	70,000
Bothwell	do	4,860	4,250	49-60	18	19,320
Goyder's Lagoon	South Australia	4,850	4,700	398	417	600,000
Cathedral	Queensland	4,523	4,500		694	1,000,000
Bonnie Downs	do	4,515	3,930	16	32	46,080
Wokingham No. 2	do	4,438	4,360		243	350,000
Mount Gason [c]	South Australia	4,420	4,304	336	333	480,000
Borongo	New South Wales	4,338	3,510-4,207	271	738	1,062,133
Mutti Mutti No. 4	Queensland	4,333	3,900	15	30	43,360
Mungeri	do	4,310	3,925	10	4	6,300
Eromanga No. 2	do	4,270	4,256	508	178	256,820
Glenariffe	do	4,220	3,760	4½-8	9	12,430
Gable End	do	4,205			14	20,000
Deep Bore	do	4,150	260		174	250,000
Melton	do	4,105	4,070		236	340,000
Dolgelly	New South Wales	4,086	3,300-4,040	249	432	622,185
Lorne	Queensland	4,057	3,999		174	250,000
Fourteen Miles [d]	do	4,040			139	200,000
Malboona [e]	do	4,032	3,700			
Careungo	New South Wales	4,013	3,300-4,000	202	475	684,352
Winton	Queensland	4,010	3,700	269-283	486	700,000
Jellitt Bros	do	4,011	3,420		63	90,000
Boomi	New South Wales	4,008	3,200-4,008	346	992	1,428,640
Overnewton	Queensland	4,006	3,320	78	103	148,640
Thornleigh	do	4,003	3,975		236	340,000
Euraba	New South Wales	4,002	3,718-4,002	246	762	1,097,420
	Queensland	4,000	3,900		208	300,000

[a] Compiled from well records given in report of the interstate conference on artesian water (Sydney, 1912), 1913; report of the second interstate conference on artesian water (Brisbane, 1914), 1914; twenty-second annual report of the hydraulic engineer of Queensland (Brisbane, Nov. 22, 1911), 1912.
[b] Water that did not rise to the surface was struck at 83, 450, 2,910, and 3,991 feet below the surface.
[c] Water that did not rise to the surface was struck 3,434 feet below the surface.
[d] Water rose to a level 120 feet below surface. Pumped.
[e] This well originally flowed at the rate of 193,000 gallons a day. Ceased flowing. In May, 1907, water level was 35 feet below surface.

Evidence in regard to this subject obtained from deep mines was compiled by Fuller [95] in the following table. He sums up these data as follows:

In three of the fifteen districts water occurs in abundance without much diminution to the bottom of the workings. In four it occurs in abundance, at least locally, to a depth of 1,500 feet. In the remaining eight, or more than half of the deep mines considered, there is a general absence of water below the 1,000-foot level.

[95] Fuller, M. L., Total amount of free water in earth's crust: U. S. Geol. Survey Water-Supply Paper 160, pp. 64-67, 1906.

Summary of ground-water conditions in deep mines in the United States.

[Compiled by M. L. Fuller in 1906.]

Mining district.	Maximum depth of mines (*feet*).	Character of rocks.	Topographic conditions.	Ground-water conditions.	Authority (oral statements to writer, except where otherwise indicated).
Ely, Vt.	[a] 1,700	Crystalline schists	On slope, 200 feet above drainage.	No water below 600 feet	W. H. Weed.
Calumet, Mich.	5,000	Interbedded traps and felsitic conglomerates.	Not elevated	Water mainly in upper 500 to 600 feet. Little water in lower levels; is salty. Separated from fresh by sharp line.	A. C. Lane.[b]
Boundary Creek, Canada.	800	Volcanic tuffs and some limestone; intrusives near.	Local drainage level with springs 200 to 400 feet below mines.	All dry	W. H. Weed.
Marysville, Mont.	1,600	Argillite and diorite	Sidehill, 600 feet above drainage.	Most of water is above 900-foot level, although vein is open.	Do.
Elkhorn, Mont.	1,800	Limestone	In valley, at drainage level	Open solution channels to bottom, but present water mostly above 1,400 feet.	Do.
Butte, Mont.	2,400	Granitic rocks	Sidehill, 400 feet above drainage.	Water is descending, reaching to bottom in places, but with large bodies of dry rock. One at 1,600 feet, 1,200 feet in width, is absolutely dry.	Do.
Lincoln County, N. Mex. (Old Abe mine.)	1,370	Calcareous shales and porphyry	Sidehill, 500 feet above drainage.	Damp, but only a few bucketfuls raised per week.	L. C. Graton.
Leadville, Colo.	1,500	Limestones, sandstones, and shales. Faulted and folded into local basins.	Deepest mines are on mountains, 1,000 feet or thereabouts above drainage. Others in valleys.	Water occurs under artesian pressure in each fault basin. Mainly along faults, especially in limestone. Not much diminution with depth.	S. F. Emmons.
Cripple Creek, Colo.	1,500	Closed "basin" of porous breccia in granite.	Plateau a few hundred feet above drainage.	Joints everywhere saturated with water. No diminution with depth.	W. Lindgren.
Coeur d'Alene, Idaho.	1,950	Quartzite	Deepest mine starts at drainage level.	Much surface water, but no strong flows in lower levels.	F. L. Ransome.
Nevada City and Grass Valley, Calif.	2,200	Granodiorite and diabase	Undulating foothills, slightly above drainage.	Water in fissures in first 1,000 feet. Little water in lower level. Some stopes entirely dry.	W. Lindgren.
Mother Lode, Calif.	2,800	Black slate and diabase, some granite.	do	Considerable water in fissures in upper 1,000 feet. Little water in the lower levels, but some to bottom.	Do.
Do.				Water mainly in upper 800 feet. If this is collected, balance of mine is dry. Water is hoisted with ore, pumping not being necessary.	Ross E. Browne.[c]
Bisbee	1,200	Limestone	In valley, within 200 feet of drainage level.	Much water to bottom levels. Possibly connected with faulting.	F. L. Ransome.
Globe	1,200	Fault in diabase limestone, and quartzite.	Hillside, 50 to 200 feet above drainage.	Not much water until mines strike faults connecting laterally with adjacent gravel-filled basin.	Do.

[a] 3,000 feet on incline of about 25°

[b] Am. Geologist, vol. 34, p. 303, 1904.

[c] California mines and minerals, p. 66, California Miners Association, 1899.

The following additional information on water in deep mines is given by Lindgren:[96]

At Cripple Creek, Colo., we have a granitic plateau at an elevation of 9,000 feet above the sea; this plateau contains a volcanic plug about 2 miles in diameter which is largely filled with porous breccias and tuffs. The water fills the volcanic rocks as in a sponge inserted in a cup, and the mining operations to a depth of 1,500 feet have tapped heavy flows. But even in this water-logged mass there are solid intrusive bodies—for instance, at the Vindicator mine, at a depth of 1,000 feet—which are so dry that water must be sent down for drilling. The granite which surrounds this water-soaked plug contains very little water and at most places is practically dry in spite of the great hydrostatic pressure.

In the copper mines of Butte, Mont., where the granitic rocks are greatly faulted by movements of late date, much water was encountered, extending in places down to 2,400 feet, or the bottom of the mines. No ascending springs are found at the surface, nor any hot springs, although a high range adjoins the mines on the east, and conditions seem to be favorable for deep circulation. The water is probably almost stagnant, and Weed mentions the existence of large bodies of dry rock. One such body on the 1,600-foot level, 1,200 feet in width, is absolutely dry.

At Rossland, British Columbia, according to Bernard McDonald,[97] the mine waters increase greatly during the spring months. The water level is at 40 feet, and the quantity increases to a depth of 200 to 350 feet. Below 350 feet a decrease begins, slowly at first but soon more rapid, until at 900 feet there is only a slight seepage, and below 1,000 feet the mine is dry.

One of the most convincing examples is that furnished by the deep copper mines of Michigan and fully set forth by Lane.[98] He shows that the surface waters are of the normal potable type and that they descend in diminishing quantities only to a depth of about 1,000 or 1,500 feet below the surface. Below this depth moisture is scant, but where it appears it consists of drippings of strong calcium chloride brine which can not in any way be explained as being derived from the surface water. Many levels are absolutely dry, and water must be sent down for drilling. This case is particularly convincing, for we have here many features in favor of a strong circulation—moist climate, inclined position of beds, and great permeability.

The existence of anhydrite deposits has been cited as showing the absence of water at considerable depths in some localities. This evidence is presented by Fuller[99] as follows:

Anhydrite, or anhydrous calcium sulphate, is deposited from solutions saturated with sodium chloride and calcium sulphate at 26° F., a temperature often reached in summer seasons even in high latitudes, and, although doubtless formed under a variety of other conditions, it has probably been most commonly deposited from supersaturated sea water through evaporation.

When fresh waters are brought into contact with the anhydrite, however, water is taken on and the rocks are converted into gypsum, or hydrous sulphate of calcium. The occurrence of anhydrite in the rocks, therefore, is of special interest in connection with the problem of underground waters, pointing to the absence of circulation at the points at which the anhydrite occurs.

---

[96] Op. cit., pp. 37-39.

[97] Rickard, T. A., Min. and Sci. Press, June 27, 1908.

[98] Lane, A. C., Mine waters: Lake Superior Min. Inst. Trans., vol. 12, pp. 154-163, 1908.

[99] Fuller, M. L., Total amount of free water in the earth's crust: U. S. Geol. Survey Water-Supply Paper 160, pp. 68-69, 1906.

When the beds are exposed at the surface the calcium sulphate is usually in the hydrous form, owing to the circulation of fresh ground waters. In the large quarries near Windsor, New Brunswick, however, only the upper few feet have been converted into gypsum, the great mass of the deposit still being in the anhydrous state.

Deposits have been frequently penetrated by deep borings in both this country and in Europe, but in most cases, unfortunately, no distinction is made between the anhydrous and hydrous types. At Stassfurt, however, the salt beds, which have an aggregate thickness of 1,197 feet, include thousands of anhydrite layers averaging about one-fourth of an inch in thickness and occurring at intervals of from 1 to 8 inches. At Hartlepool, in Yorkshire, borings show the limestone to be interleaved with anhydrite and to be overlain by more than 250 feet of that deposit.[1] Again, in the Mont Cenis tunnel, in the Alps, over 1,500 feet of alternating anhydrite, talcose schist, and limestone are reported.[2]

From these and numerous other instances that might be cited it is clear that not only are circulating waters practically absent in many regions, even near the surface, but interstitial water is also absent. If any fresh water whatever were present in the pores of the anhydrite, hydration to gypsum would take place.

The presence of anhydrite appears, however, to prove only the absence of fresh water and not the absence of salty water.

Hot springs are found in many localities that have not been recently affected by volcanism, some of them with large flows and some issuing at temperatures near the boiling point.[3] It would be difficult to avoid the conclusion that the water of these springs comes from depths of several thousand feet.

It is widely believed, not only by well drillers but also by geologists, that at deep levels there are porous beds whose interstices are empty—that is, presumably not filled with water or oil nor with gas under great pressure. This view is strongly stated by Fuller,[4] as follows:

This absence of water is, moreover, not due to lack of porous rock, as shown by the two wells last mentioned and by the W. J. Bryan well No. 11, Aleppo Township, Greene County, Pa. This well is 3,397 feet deep and is cased to 3,110 feet, which represents the last water. Below the casing, however, were found the Thirty-foot, Fifty-foot, and Gordon sands, 20, 60, and 18 feet in thickness, respectively, making 100 feet of porous but perfectly dry sandstones. The depth at which water was found in this well is greater than the normal, no fresh water being found in many wells beyond a depth of 500 feet. * * *

The finding of porous deposits capable of holding immense quantities of water, but in which none whatever is actually found, is a common experience of almost every driller working in deposits of stratified drift in this country. Often they are found several hundred feet below the surface, far below the true water table or that lying above the first impervious stratum and, in many instances, much below the level of the lowest surface drainage.

---

[1] Geikie, Archibald, Text-book of geology, vol. 2, p. 1071, 1903.

[2] Hunt, T. S., Chemical and geological essays, p. 335, 1875.

[3] Meinzer, O. E., Ground water in Juab, Millard, and Iron counties, Utah: U. S. Geol. Survey Water-Supply Paper 277, 1911; Geology and water resources of Big Smoky, Clayton, and Alkali Springs valleys, Nev.: U. S. Geol. Survey Water-Supply Paper 423, 1917. Clark, W. O., and Riddell, C. W., Exploratory drilling for water and use of ground water for irrigation in Steptoe Valley, Nev.: U. S. Geol. Survey Water-Supply Paper 467, 1920.

[4] Fuller, M. L., Total amount of water in the earth's crust: U. S. Geol. Survey Water-Supply Paper 160, pp. 67–68, 1906.

Fuller even estimates for the earth's crust as a whole that in stratified rocks only 37 per cent and in igneous rocks only 50 per cent of the theoretical aqueous capacity is actually taken up by water.

Various explanations involving hydration, evaporation, or drainage have been offered to account for the supposed absence of water from porous strata at great depths. An ingenious but apparently untenable hypothesis recently advanced by Reeves[5] to account for the non water-bearing sandstones of the Catskill formation in Pennsylvania and West Virginia is that they were dried out by the semi-arid conditions that existed during Catskill time, which also brought about the formation of continental red beds.

The extensive occurrence of nonsaturated strata below the zone of saturation is difficult to understand. It is hard to see how the water present at their deposition could have been removed, or how, if once dry, they would be kept from becoming saturated unless they were entirely incased by impervious materials. Much evidence of the existence of such dry strata has been presented, but it is generally of a hearsay character, lacking specific proof. Definite scientific investigation of this subject is greatly to be desired, but until such investigation is made it would seem that the burden of proof remains with the affirmative. The question is whether the strata that do not yield water or other fluid actually contain empty interstices—whether they have such a texture that they would yield water if they were saturated.

Recently the assumption of abundant extensive nonsaturated beds below the zone of saturation has been challenged by Munn[6] and Shaw.[7] Shaw states:

> The doubt concerning the validity of the general inference—the suspicion that most of the dry sands are really saturated with water that for some reason can not get out—arose after some years of discussion with Munn, during which time attempts were made to grasp the significance of the phenomenon and to find the explanation. Rock samples were obtained from deep mines, a special examination of some thousands of well logs was made, and drillers and others were questioned.

Shaw also presents the following pertinent argument:

> At the surface of the earth we have to deal with pressure not far from 15 pounds to the square inch. If the pressure here should depart 2 pounds from this figure there would be a most violent storm. We are so accustomed to living under and dealing with this essential condition of our daily life that we too easily assume that similar conditions commonly affect the contents of rock pores within the earth. The most impressive part of experience with diving apparatus is the tremendous pressure in water only 50 to 100 feet deep. Even at 20 to 30 feet one's ear drums sometimes

---

[5] Reeves, Frank, The absence of water in certain sandstones of the Appalachian oil fields: Econ. Geology, vol. 12, pp. 354–378, 1917.

[6] Munn, M. J., The Menifee gas field and the Ragland oil field U. S. Geol. Survey Bull. 531, p. 24, 1913.

[7] Shaw, E. W., Discussion of Roswell Johnson's paper on Rôle and fate of connate water in oil and gas sands: Am. Inst. Min. Eng. Trans. vol. 93, pp. 221–227, February, 1915; Discussion of Reeves's paper (op. cit.): Econ. Geology, vol. 12, pp. 610–628, 1917.

ache severely, though the pressure is only about 2 atmospheres, and the cause of caisson disease is said to be gas pressure in the blood, due to the change in external pressure of 1 or 2 atmospheres. Two atmospheres is about 2 tons to the square foot, but this is a small quantity compared with the pressure thousands of feet down in the earth. At the bottoms of the Clarksburg and MacDonald wells the pressure on the rock is roughly 500 tons to the square foot, or far above the critical pressure for water. If the strata have connecting pores and cracks extending to the surface the pressure on the rock pores should approach the weight of a column of water extending to the top of ground water, and in deep wells where we have definite information it is generally not far from the hydrostatic head. The average is far nearer this amount than either the weight of the superincumbent rock or the weight of nothing but the atmosphere, and the departures are presumably due to one or more modifying factors almost certainly operative. It seems to me that it can not be too strongly emphasized that the occurrence of a pressure of 1 atmosphere in a sand one or several thousand feet below the surface would be so unlikely as to be practically beyond possibility, and the inference that such a pressure exists in hundreds and even thousands of places becomes an absurdity. If the sand has large and open pores connecting with portions that are gas or oil bearing, the pressure should become equalized and some fluid should enter the well. On the other hand, if the pools are in parts of the sand shut off from other parts by some sort of barrier, the so-called dry sands may be either portions of the sand that are not impervious but are so sealed off from the surrounding fluid-bearing sands that they can not readily yield the contents of their pores into the wells or they may be tighter than realized, the pores being closed by cement or some plastic, clogging material.

Perhaps the most cogent argument against true dryness of the so-called dry sands is the fact that they do not contain air under great pressure, for it seems quite inconceivable that the connate air of an air-dried sand should remain at or near 1 atmosphere so that when penetrated, after having been buried millions of years, under thousands of feet of water-soaked rock, no air should rush into or out of it.

With respect to the character of the strata in the three deep wells already described (p. 44) Dr. White[8] makes the following statement:

The strata penetrated [in the Goff well below 2,307 feet] were evidently too close and nonporous to hold water, so that none whatever was found below the casing. The 6-inch liner [between 5,405 and 7,071 feet] would not have shut any water off, since it was inserted only to stop a bad cave. The Lake well was cased only to a depth of 2,118 feet, and although it was drilled to a depth of 7,579 feet no evidence [of water] was obtained in all that interval of more than a mile of strata, the reason, I think, being that no porous rocks were encountered, since nothing but slate, close-grained sands, and limestone were encountered. In the Geary well, however, a coarse sand (Oriskany) occurred at 6,045 feet, and this sand yielded large quantities of very salt water at two or three horizons. Had the same sand been encountered in the Goff and Lake wells, I have no doubt, it, like the Geary, would have held large quantities of water.

WATER-YIELDING CAPACITY OF ROCKS.

DEFINITION OF TERMS.

Not all the water in the zone of saturation is available for recovery through wells—a fact of great practical importance in making ground-water developments. A part will drain into wells, and a part will be retained by the rock formations. The part that will drain into wells is

[8] Written communication.

called "gravity ground water." This distinction can be illustrated as follows: If the water is withdrawn from the zone of saturation more rapidly than it is replenished, as happens in dry seasons or during heavy pumping, the water table will move downward, and with it will go the capillary fringe, which is always definitely related to the water table. The gravity ground water in a given body of rock or soil in the zone of saturation is the water that will be withdrawn from the body by the direct action of gravity if the water table and capillary fringe move downward until both are entirely below it (fig. 13, p. 31).

The water-yielding capacity and water-retaining capacity of a rock or soil when expressed in percentages of the total volume of rock or soil may be called, respectively, its "specific yield" and its "specific retention." Thus, if 100 cubic feet of saturated rock when drained in the manner described will supply 8 cubic feet of water the specific yield of the rock is said to be 8 per cent. If after it is drained it still retains a total of 13 cubic feet of water in its interstices its specific retention is said to be 13 per cent. The specific yield of a rock or soil is the percentage of its total volume that is occupied by gravity ground water, and the specific retention is the percentage of its total volume that is occupied by water which is not gravity ground water and which it will not yield to wells. Thus, the specific yield and the specific retention of a rock or soil are together equal to its porosity. If a rock has a specific yield of 8 per cent and a specific retention of 13 per cent its porosity is obviously 21 per cent. The specific yield of an impermeable rock is zero, its specific retention being equal to its porosity.

The specific yield has frequently been called the "effective porosity" or "practical porosity," because it represents the pore space that will surrender water to wells and is therefore effective in furnishing water supplies. These terms, however, seem singularly inappropriate to students of agriculture, because to the extent that a soil will allow water to drain through it, it fails to hold water for the use of vegetation. Water that is yielded by gravity is, for the most part, not available to plants, whereas the water that is retained against gravity is largely effective in producing plant growth. Moreover, the term "effective porosity" is used by petroleum geologists in a more general sense than the term "specific yield" as here defined. As used by them it may be defined as the percentage of the total volume of a rock that is occupied by oil which will be yielded under specified conditions. For example, suppose a well is drilled to an oil-bearing bed 1,000 feet below the surface, and the oil is under sufficient hydrostatic pressure to rise to the surface in the well. If this well is pumped so hard that it is kept nearly empty of oil, the oil will be forced through the rock into the well under great pressure, the

497781 O-59-5

pore space vacated by the oil probably being taken by ground water that transmits the pressure. The effective porosity in this case is understood to be the ratio of volume of oil yielded to volume of rock that is drained of oil, this ratio being expressed in percentage. Obviously much more oil may be yielded under these conditions than if the rock were simply allowed to drain by gravity. This kind of effective porosity is very important with respect to petroleum but has no application in hydrology. Though it is desirable to displace petroleum with water in the manner indicated nothing is accomplished by displacing water with water.

The distinction between gravity water and that which is retained by the rock or soil is not entirely definite, because the amount of water that will drain out depends on the length of time it is allowed to drain, on the temperature[9] and mineral composition[10] of the water, which affect its surface tension, viscosity, and specific gravity, and on various physical relations of the body of rock or soil under consideration. For example, a smaller proportion of water will drain out of a small sample than out of a large body of the same material. As the methods of determining specific yield have not been standardized, and as it may continue to be desirable to use different methods for different purposes and under different conditions, data as to specific yield should always be accompanied by a statement of the methods used in determining it.

IMPORTANCE OF WATER-YIELDING CAPACITY.

The quantity of water that a saturated rock will furnish, and hence its value as a source of water supply, depends on its specific yield—not on its porosity. Clayey or silty formations may contain vast amounts of water and yet be unproductive and worthless for water supply, whereas a compact but fractured rock may contain much less water and yet yield abundantly.

To estimate the water supply obtainable from a given deposit for each foot that the water table is lowered, or to estimate the available supply represented by each foot of rise in the water table during a period of recharge, it is necessary to determine the specific yield. Estimates of recharge or of available supplies based on porosity, without regard to the water-retaining capacity of the material, may be utterly wrong.

AQUIFERS.

A rock formation or stratum that will yield water in sufficient quantity to be of consequence as a source of supply is called an "aquifer," or simply a "water-bearing formation," "water-bearing

[9] King, F. H., Observations and experiments on the fluctuations in the level and rate of movement of ground water on the Wisconsin Agricultural Experiment Station farm and at Whitewater, Wis.: U. S. Weather Bur. Bull. 5, 1892; also Wisconsin Agr. Exper. Sta. Ann. Repts., 1889-1893. Veatch, A. C., Fluctuations of the water level in wells, with special reference to Long Island, N. Y.: U. S. Geol. Survey Water-Supply Paper 155, pp. 54-59, 1906.

[10] Kerraker, P. E., Effect on soil moisture of changes in the surface tension of the soil solution brought about by the addition of soluble salts: Jour. Agr. Research, vol. 4, pp. 187-192, 1915.

stratum," or "water bearer." It should be noted that the term "water-bearing formation," as here defined and as generally used, means a water-yielding formation—one that supplies water to wells and springs, one that contains gravity ground water. The term has no reference to the quanitity of water that the formation may contain but will not yield to wells and springs. It is water-bearing not in the sense of holding water but in the sense of carrying or conveying water. Few if any formations are entirely devoid of gravity ground water, but those that do not contain enough to be practical sources of water supply are not considered to be aquifers; they are not called water-bearing formations. Hence it may happen that in a region underlain by strong aquifers a formation yielding only meager amounts of water will not be classed as water bearing; whereas in a region nearly destitute of available water a similar formation may be a recognized aquifer tapped by many wells. The different kinds of aquifers are discussed in the next chapter (pp. 102–148), and the principal aquifers in the United States are described in Chapter IV (pp. 193–314).

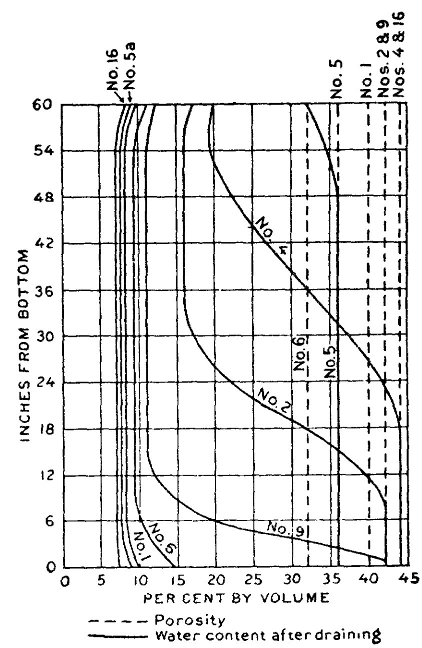


FIGURE 15.—Diagram showing porosity and specific retention of materials shown in figure 4 (p. 6). [Experiments by Allen Hazen.]

DATA ON SPECIFIC YIELD AND SPECIFIC RETENTION.

In 1892 Hazen[11] published some very significant results of tests of the water-retaining and water-yielding capacities of eight different sands used for filtering sewage. The character of these sands is shown by the table on page 7, which gives their mechanical composition, effective size of grain, uniformity coefficient, and porosity. Their mechanical composition is shown graphically in figure 4 (p. 6), in which the points where the curves cut the 10 per cent line give the effective sizes, and the slopes of the curves indicate the degree of uniformity of grain, the steepest curves representing the best-assorted materials, which have lowest uniformity coefficients.

The porosity and specific retention of these sands, as determined by Hazen, are shown in figure 15. The oblique parts of the curves

[11] Hazen, Allen, Experiments upon the purification of sewage and water at the Lawrence experiment station: Massachusetts States Board of Health Twenty-third Ann. Rept., for 1891, pp. 428–434, 1892.

represent capillary rise (see p. 33); the vertical parts indicate the specific retention. The difference between the porosity and the specific retention of each sample is its specific yield. The results as taken from this diagram given by Hazen can be tabulated as shown below, and the relation of the specific retention and specific yield to the effective size can be graphically represented as in figure 22 (p. 64).

Specific retention and specific yield of sands used in tests by Hazen.

No. of sample.	Effective size of grain [a] (millimeters).	Uniformity coefficient.	Porosity [b] (per cent by volume).	Specific retention [b] (per cent by volume).	Specific yield [b] (per cent by volume).
5	0.02	9.0	36	....	....
4	.03	2.3	44	19?	25?
2	.06	2.3	42	16	26
9	.17	2.0	42	11	31
6	.35	7.8	32.5	9.5	23
1	.48	2.4	40	8	32
5a	1.40	2.4	....	7.5	....
16	5.00	1.8	44	7.0	37

[a] Diameter of a grain of such size that 10 per cent of the sample (by weight) consists of smaller grains and 90 per cent of larger grains.
[b] Data taken from the curves in figure 15. The specific yield is obtained by subtracting the specific retention from the porosity.

In 1899 King[12] gave the results of laboratory experiments on the quantities of water yielded and retained by assorted sands of five different sizes of grain, when these sands were saturated and then allowed to drain. The effective size of grain and the porosity of each sample are given in the following table, and the true size of grain of each sample is shown in Plate II. Five galvanized-iron cylinders, 8 feet long and 5 inches in diameter, were filled, each with one of the five kinds of sand, and were set up for the experiment in the manner shown in figure 16.

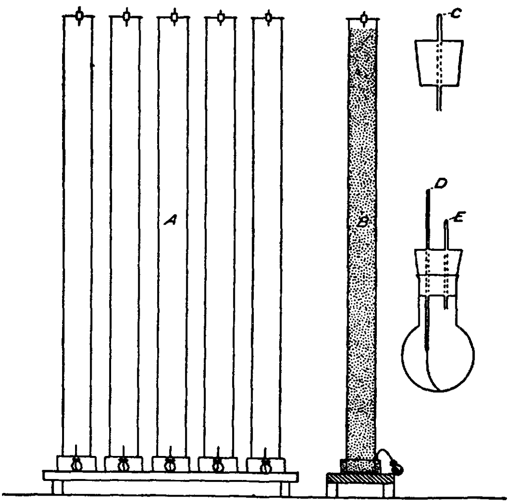


FIGURE 16.—Diagram showing apparatus used by King to test the water-yielding and water-retaining capacities of sand. *A*, Galvanized-iron cylinders 8 feet high and 5 inches in diameter; *B*, section of cylinder; *C*, cork with glass tube drawn to a fine point to prevent evaporation; *D*, collecting flask; *E*, vent.

After the apparatus had been filled with sand, water was slowly introduced from the bottom, so as to expel the air, until the sand in each cylinder was saturated to the top. The cylinders were then

[12] King, F. H., Principles and conditions of the movements of ground water: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, pp. 86–91, 1899.

allowed to drain into the attached flasks, and the discharged water was measured or weighed from time to time—first at frequent intervals and later only every few days, weeks, or months. The experiment was continued about two and one-half years, when the amount of water remaining in each 3-inch layer of sand was determined. The apparatus was designed to prevent loss by evaporation. A water table was apparently maintained at the bottom of the 8-foot column of sand.[13] The results of the experiments are shown in the following table, which is condensed from those given by King and in which King's data have been recalculated from grams of water or per cent of water by weight to per cent by volume, the method of expression best adapted for the purposes of hydrology. The quantities of water yielded during different periods of draining and the quantities retained

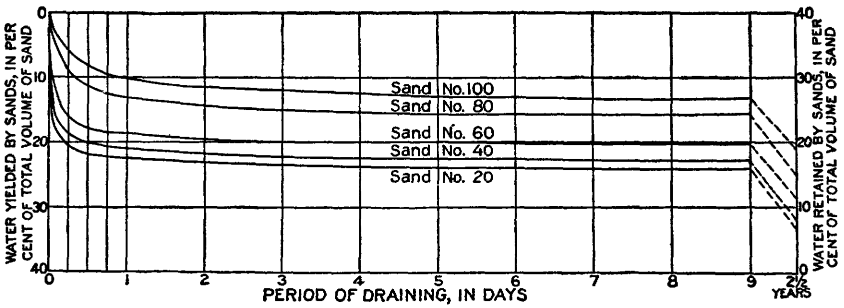


FIGURE 17.—Diagram showing rates at which water was yielded by assorted sands and the quantities of water retained at the end of 2½ years in King's experiment. The drop in the curve from 9 days to 2½ years represents in part the drainage during that period but chiefly the discrepancy between porosity and total water accounted for.

at the end of the two and one-half year period are shown in figure 17; the quantities of water retained by the sands at different levels at the end of the two and one-half year period are shown in figure 18. The table and figure 17 show discrepancies of 5.11 to 7.32 per cent between the porosity and the total water accounted for. Because of these discrepancies it is not possible to make any close interpretation of the results of the experiment. Figure 18 shows that the water retained near the bottom of each sand column was nearly equal to the porosity. Hence, in the upper part the percentage of pore space not accounted for is even greater than the discrepancies shown in the table. Evidently the water in the lower parts of the sand columns is fringe water—lifted above the water table by capillarity—and that in the upper parts represents more nearly the specific retention. In this respect the King curves (fig. 18) are like the Hazen curves (fig. 15). However, the curves in figure 18 do not indicate very clearly the height of the capillary fringe in the different samples.

[13] King, F. H., Irrigation and drainage, p. 112, New York, Macmillan Co., 1899.

Water yielded and retained during different periods by columns of saturated sand 8 feet high.

[King's experiment.]

Designation of sand	No. 20.	No. 40.	No. 60.	No. 80.	No. 100.
Effective size of grain ... millimeters..	0.475	0.185	0.155	0.118	0.083
Volume of sand used in experiment ... cubic centimeters..	30,890	30,890	30,890	30,890	30,890
Weight of dry sand ... grams..	50,050	49,060	48,490	48,650	49,340
Specific gravity of dry sand ...	1.62	1.59	1.57	1.58	1.60
Porosity (per cent of total volume of sand occupied by interstices) ...	38.86	40.07	40.76	40.57	39.73
Yield of water by draining:					
In grams—					
In first 30 minutes ...	3,298	2,427	1,730	486	390
In second 30 minutes ...	1,506	1,687	1,452	417	278
From end of first hour to end of first 9 days.	2,695	2,929	3,052	3,970	3,486
From end of first 9 days to end of 2½ years ..	805	839	580	840	621
Total yielded in 2½ years ...	8,304	7,882	6,814	5,713	4,775
Water remaining in sand after draining 2½ years ...	2,121	2,475	3,515	4,576	5,831
Total water accounted for ...	10,425	10,357	10,329	10,289	10,606
Per cent by volume (grams divided by 30,890 and multiplied by 100)—					
In first 30 minutes ...	10.68	7.85	5.60	1.57	1.26
In second 30 minutes ...	4.88	5.46	4.70	1.35	.90
From end of first hour to end of first 9 days..	8.72	9.48	9.88	12.85	11.29
From end of first 9 days to end of 2½ years...	2.60	2.71	1.87	2.72	2.01
Total yielded in 2½ years ...	26.88	25.50	22.05	18.49	15.46
Water remaining in sand after draining 2½ years ...	6.87	8.01	11.37	14.81	18.87
Total water accounted for ...	33.75	33.51	33.43	33.31	34.33
Difference between porosity and total water accounted for ...	5.11	6.56	7.33	7.26	5.40
Water retained at different levels after draining 2½ years (per cent of total volume of sand):					
7 to 8 feet from bottom ...	.38	.25	.41	2.12	5.81
6 to 7 feet from bottom ...	.75	.55	1.80	3.88	6.97
5 to 6 feet from bottom ...	2.50	2.42	3.09	5.51	9.19
4 to 5 feet from bottom ...	2.74	3.04	3.62	7.52	13.00
3 to 4 feet from bottom ...	3.39	3.44	4.61	11.63	18.97
2 to 3 feet from bottom ...	4.11	4.73	9.53	19.88	26.40
1 to 2 feet from bottom ...	9.66	14.12	34.79	30.46	32.94
0 to 1 foot from bottom ...	31.57	36.90	35.97	37.60	40.16

It will be noted that there are some rather wide differences between the results of King and those of Hazen, King's tests apparently giving lower values for specific retention than Hazen's, especially for the coarser samples. These differences are probably in part due to the better assorting and more nearly uniform size of grain in King's tests, which would tend toward lower values for specific retention, but it does not seem possible to account for the entire difference in this way.

Since the classic experiments made by Hazen and King relatively little work has been done by hydrologists, at least in this country, to determine water-yielding capacities. Various elaborate series of tests have been made by students of agriculture, both in the laboratory and in the field, to determine the water-retaining capacity of soils, but these have only limited applicability to problems of hydrology, because they relate to soils rather than to water-bearing materials. Although Hazen's and King's results are of great value, it is evident that they are inadequate and can not safely be used as a basis for very definite conclusions as to water-yielding and water-retaining capacity. Many more tests of the same sort are obviously needed. More field tests adapted to the purposes of hydrology are also needed.

A series of field tests of the water-retaining and water-yielding capacity of soils of different types was made by Israelsen[14] in Sacramento Valley, Calif. His method was to determine the porosity of different soils and their water content at successive depths immediately before irrigation and again about four days after irrigation. The second determination gives approximately the specific retention with limited time for draining, provided the irrigation was sufficiently heavy, the soil was permeable enough to admit the water, and the loss by evaporation and transpiration during the four-day period was not excessive. As the specific yield is equal to the difference between the porosity and the specific retention, the amount of water that a soil would yield by gravity if it were saturated is approximately the difference between the total space occupied by the interstices and the volume of water still held by the soil at the end of the given period of drainage. In the following table some of Israelsen's results are summarized, and in figures 19–21 a part of the data are shown graphically. All three of the diagrams represent soil columns entirely above the water table, but the lower parts of the clay-soil columns represented in figure 21 were partly within the capillary fringe, and for this reason they approach the porosity curve near the bottom, like the curves in Hazen's and King's experiments (figs. 15 and 18). The bulge to the left in the middle part of the curve in figure 21 showing water content after irrigation is believed by Israelsen to be

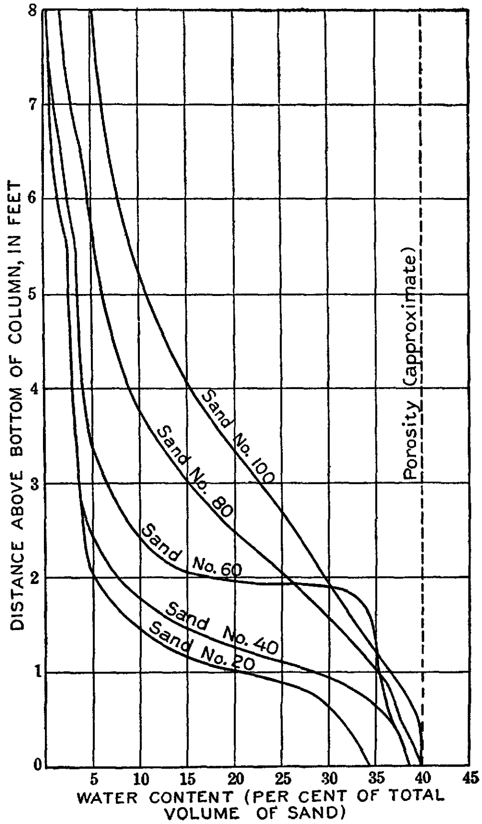


FIGURE 18.—Diagram showing water retained by assorted sands at different levels in King's experiment.

[14] Israelsen, O. W., Studies in capacities of soils for irrigation water: Jour. Agr. Research, vol. 13, pp. 1-28, Apr. 1, 1918.

due partly to the difficulty in getting irrigation water far into these dense clay soils, so that this curve for the soils above the capillary fringe may represent less than the specific retention.

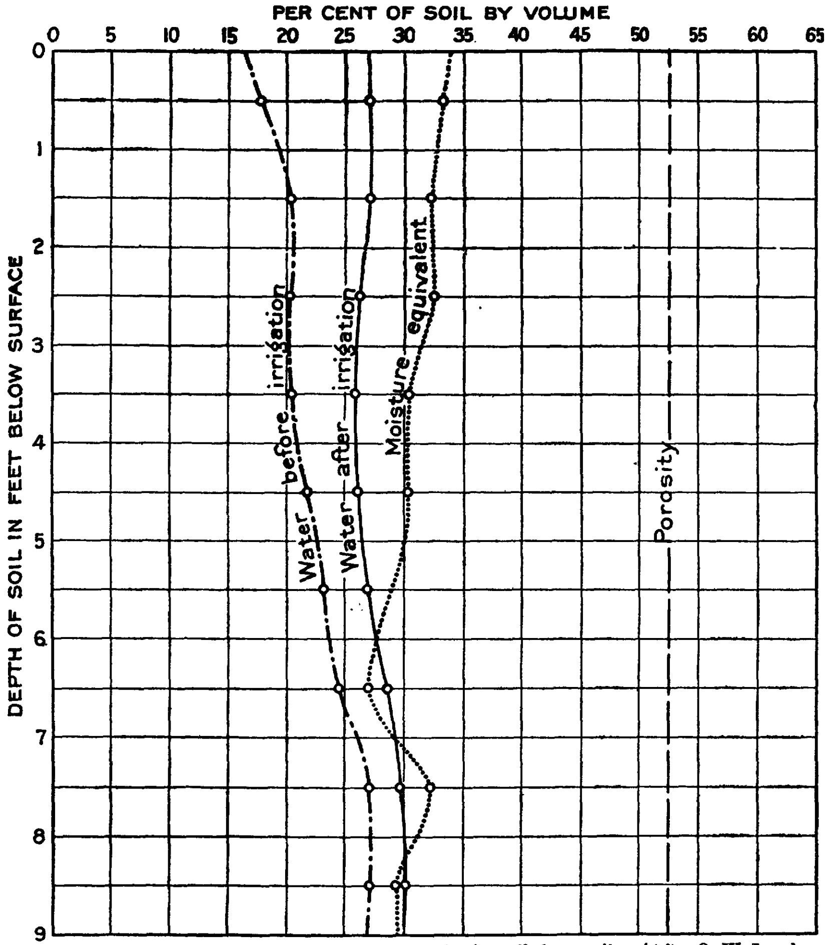


FIGURE 19.—Diagram showing water retained and yielded by silt-loam soils. (After O. W. Israelsen.) Each water-content curve is based on the average results from 87 borings.

Water retained and yielded by soils in Sacramento Valley, Calif.

[Field tests by Israelsen. Porosity, water content, and moisture equivalent are expressed as percentages of the total volume of the soil.]

Kind of soil.	Number of borings.	Depth of soil examined[a] (feet).	Porosity.	Water content.		Difference between porosity and water content four days after irrigation.	Moisture equivalent.[b]
				Before irrigation.	Four days after irrigation.		
Silt loam	87	9	52.2	22.6	27.6	24.6	32.3
Clay loam	148	6	50.1	23.2	28.1	22.0	35.4
Clay	43	6	37.3	22.3	25.1	12.2	43.7

[a] Samples were usually taken at intervals of 1 foot—at depths of 0.5 foot, 1.5 feet, etc. [b] See p. 72.

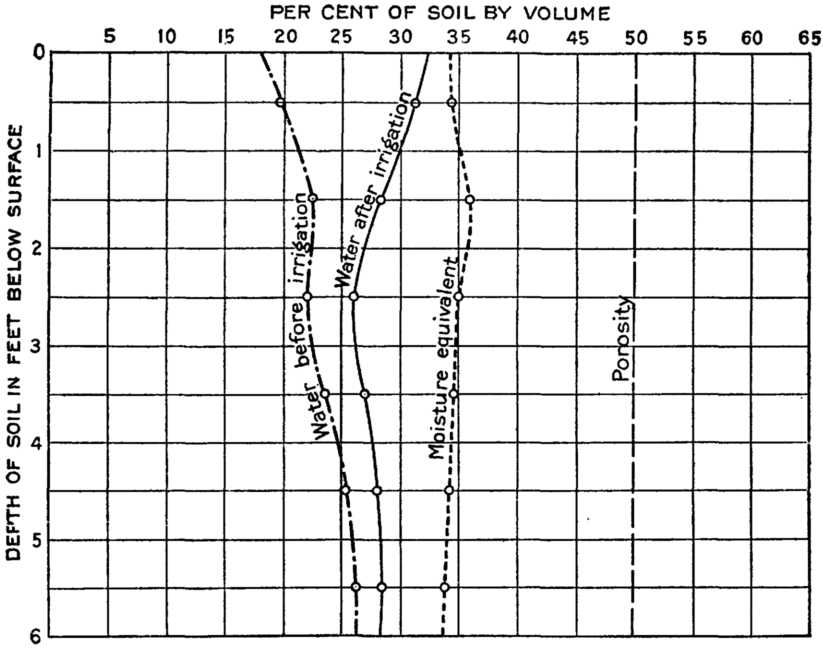


FIGURE 20.—Diagram showing water retained and yielded by clay-loam soils. (After O. W. Israelsen. Each water-content curve is based on the average results of 148 borings.

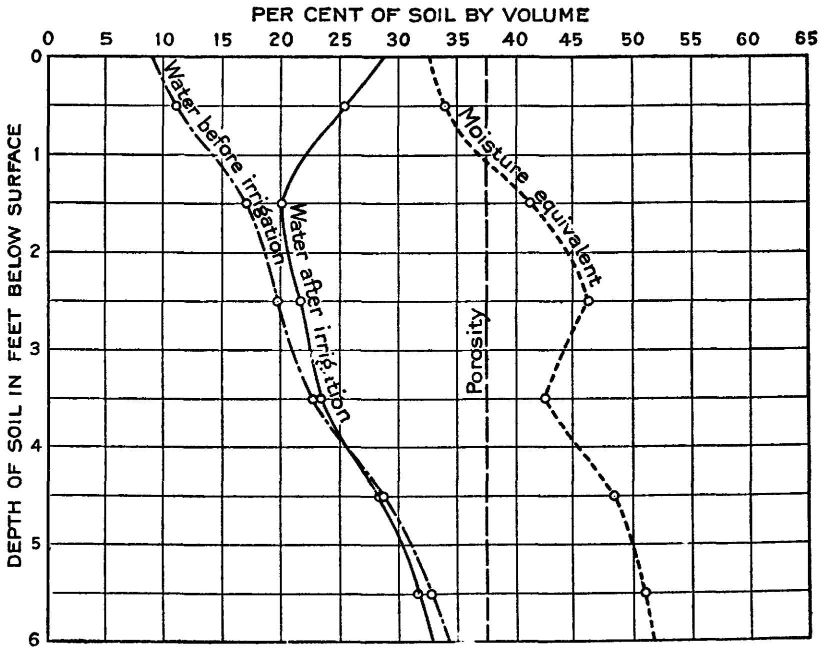


FIGURE 21.—Diagram showing water retained and yielded by clay soils. (After O. W. Israelsen.) Each water-content curve is based on the average results from 43 borings.

Israelsen [15] makes the following statement:

It is desirable, especially where irrigation is practiced, to have accurate knowledge of the maximum water-holding capacity of the soil in place. Burr [16] found the maximum capacity of a fine sandy loam (loess) to be 16 to 18 per cent of the weight of the dry soil. Quantities of water found by various investigators [17] after heavy irrigations or rainfall seem to be in agreement with the results of Burr's experiment. Indirectly, therefore, the maximum water capacities of soils in place have been determined by a number of workers under various conditions.

It was found by Mathews [18] that a gumbo or heavy clay soil which he investigated will carry about 30 per cent of water, by weight, and that oven-dried samples from the first foot when immersed in water expanded to 2.2 times their original volume; and similar samples from the second and third foot expanded to 2.5 times their original volume.

Experiments made by Charles H. Lee [19] on 36 samples from the fill of the major stream valleys of San Diego County, Calif., of material ranging from coarse sand to silt, indicated total voids as follows: Coarse sand, 39 to 41 per cent by volume; medium sand, 41 to 48 per cent; fine sand, 44 to 49 per cent; fine sandy loam, 50 to 54 per cent. The average porosity of all 36 samples was 45.1 per cent. The classification of materials is that used by the Bureau of Soils of the United States Department of Agriculture. (See p. 17.) These percentages represent the porosity of the materials under natural conditions. The methods of determining porosity, specific retention, and specific yield, and the results obtained are described by Lee as follows:

A pit was dug to the level from which it was desired to take the sample, a part of the bottom being excavated to a further depth of about a foot so as to leave a vertical face; a metal cylinder 5⅝ inches in inside diameter and 9 inches long, the lower edge being beveled from the outside so as to make a cutting edge, was pressed down vertically, cutting out a core of undisturbed material; the material was then carefully dug away from the front of the cylinder and a stiff sheet of metal pushed under to cut off the sample at the bottom of the cylinder; the metal plate and cylinder were then removed and the top of the sample was leveled off. This method gave a sample of the known volume as it existed in its natural state. The sample was

[15] Op. cit., p. 2.

[16] Burr, W. W., The storage and use of soil moisture: Nebraska Agr. Exper. Sta. Research Bull. 5, 1914.

[17] Allen, R. W., The work of the Umatilla reclamation project experiment farm in 1914, U. S. Dept. Agr. Bur. Plant Industry, 1915. Loughridge, R. H., and Fortier, Samuel, Distribution of water in the soil in furrow irrigation: U. S. Dept. Agr. Off. Exper. Sta. Bull. 203, p. 63, 1908. Müntz, A., and Lainé, E., La quantité d'eau et la fréquence des arrosages, suivant les propriétés physiques des terres: Compt. Rend., vol. 154, No. 8, pp. 481–487, 1912. Powers, W. L., Irrigation and soil-moisture investigations in western Oregon: Oregon Agr. Exper. Sta. Bull. 122, 1914. Widtsoe, J. A., The storage of winter precipitation in soils: Utah Agr. Exper. Sta. Bull. 104, pp. 279–316, 1908. Widtsoe, J. A., and McLaughlin, W. W. The movement of water in irrigated soils: Utah Agr. Exper. Sta. Bull. 115, pp. 195–263, 1912.

[18] Mathews, O. R , Water penetration in the gumbo soils of the Belle Fourche reclamation project: U. S. Dept. Agr. Bull. 447, p. 3, 1916.

[19] Ellis, A. J., and Lee, C. H., Geology and ground waters of the western part of San Diego County, Calif.: U. S. Geol. Survey Water-Supply Paper 446, pp. 121–123, 1919.

then oven-dried and the specific gravity of a selected portion determined. The porosity was then computed by the following formula:

$$P=100\left(1-\frac{a}{S}\right)$$

in which P=porosity expressed in percentage.
a=specific gravity of the dried sample.
S=average specific gravity of the minerals comprising the sample.

A certain proportion of the moisture that occupies the voids of any saturated porous material does not readily drain out, even when the zone of saturation has fallen below the depth from which the capillary rise of water is rapid. This moisture can not be extracted by pumping nor does it represent water that drains out and is replenished during the natural fall and rise of the water table. To determine the water-retaining capacity of various valley-fill materials, six experiments were made after the annual summer lowering of the water table had taken place. The water-retaining capacity was found to range from 6 to 10 per cent in the coarse, medium, and fine sands, but no finer materials were examined where the depth to the water table was great enough to enable the field capacity to be determined with certainty. Etcheverry,[20] quoting from Widtsoe's extensive experiments, gives the water-retaining capacity of sandy loam as 14½ per cent by weight, which is equal to about 22 per cent by volume, and this percentage can be considered as representing roughly the condition in sandy loam soils of the major river valleys under consideration. The total volume of water that might be drained from the valley fill by the slow lowering of the water table can be estimated as ranging from about 33 to 37 per cent by volume. Such complete drainage, however, requires considerable time, and the relatively quick drainage resulting from the artificial lowering of the water table by pumping undoubtedly represents the extraction of far less of the total water content. In practice the proportionate volume that could be extracted from the valley fill of the major valleys probably does not exceed 20 to 25 per cent. * * *

The method used by the writer for determining the water-retaining capacity was as follows: Pits were sunk to the ground water at points selected so as to give differing distances to the water table and differing types of material. Samples of the material were taken at intervals of a foot from the surface down to the water table, as described above for porosity samples. The initial weight of the samples with the contained moisture was ascertained immediately after removal from the pit, and the dry weight was obtained after oven drying, the difference in weight, representing the retained water expressed as a percentage by volume, gave the percentage of retained water by volume when divided by the initial volume of the sample. This percentage was found to vary at different distances above the water table. The maximum was at the water table, where the material was saturated and the percentage of initial moisture was practically equal to the total porosity of the material; the minimum occurred near the surface of the ground but at a depth sufficiently great to be beyond the range of evaporation. It was found that by representing the data graphically, the water-retaining capacity of samples ranging from coarse to fine sand could be approximately ascertained by inspection. The zone of saturation was too near the surface, however, to enable this to be done with finer materials.

The volume of water represented by the annual rise and fall of the zone of saturation was computed from these same diagrams. For the average annual fluctuation of approximately 3.5 feet, it was found that the effective porosity—that is, the difference between the total porosity and the water-retaining capacity—ranged from an average of 41 per cent for sand of differing grades and with differing depths to the water table to 16 per cent for fine sandy loams. The average for the six typical conditions studied was 34 per cent.

---

[20] Etcheverry, B. A., Irrigation practice and engineering, vol. 1, p. 4, New York, McGraw-Hill Book Co., 1915.

A number of samples of sand at Fort Caswell, N. C., were tested for moisture content by Norah E. Dowell,[21] of the United States Geological Survey, in May, 1922, the day after a rain of 2.12 inches. This sand was found to have a porosity of 46 to 49.4 per cent, an effective size of grain of about 0.14 millimeter, a uniformity coefficient of a little less than 2, and a capillary fringe between 2 and 3 feet high. Nine samples were taken from above the capillary fringe in a locality where the water table stood from 3½ to 5½ feet below the surface and were found to contain from 4.9 to 12.8 per cent of water, the average being 7.8 per cent. It is not certain, however, that all the sand had received as much rain water as it could retain.

Two samples of water-bearing material in the Salt River valley, Ariz., were tested for porosity by Willis T. Lee.[22] One sample, consisting of sand, pebbles, and boulders, was found to have a porosity of 20.5 per cent by volume; the other, consisting of coarse gravel and boulders half an inch to 8 inches in diameter, was found to have a porosity of 35.8 per cent. Lee estimated that the water actually available for pumping is between 15 and 30 per cent. Obviously, for coarse gravel devoid of fine material the specific yield can not be much less than the porosity.

In estimating the specific yield of the alluvial fill in the Morgan Hill area, Calif., Clark[23] reached the following conclusions, based on well logs and on data published by King and others, as to porosity and specific yield: The alluvium is composed of 69 per cent clayey material, 29 per cent gravel, and 2 per cent sand. The sand and gravel have an average porosity of about 35 per cent by volume and will yield about 90 per cent of their water content (giving a specific yield of 31.5 per cent). The clayey materials, somewhat like clay loam in texture, have an average porosity of 32 per cent and will yield about 10 per cent of their water content (giving a specific yield of 3.2 per cent). The total water that the saturated alluvium will give up is therefore calculated to be 12.06 per cent of its volume. These conclusions were, to some extent, corroborated by heavy pumping tests, which indicated a specific yield of 11.6 per cent for the alluvium that was drained by pumping. (See pp. 69–70.)

King[24] summed up the subject by saying that soil which does not lie below the water table usually contains about 75 per cent of the amount of water required for full saturation, and that the water content in materials above the water table ranges from about 4 per

---

[21] Unpublished manuscript.

[22] Lee, W. T., Underground waters of Salt River valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 136, pp. 173–175, 1905.

[23] Clark, W. O., Ground water for irrigation in the Morgan Hill area, Calif.: U. S. Geol. Survey Water-Supply Paper 400, pp. 82–87, 1917.

[24] King, F. H., Principles and conditions of the movements of ground water: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, p. 71, 1899.

cent of the dry weight for coarse mixed sands such as are used for plastering to 32 per cent for clays of fine texture. This range is equivalent to about 6 to 37 per cent by volume. These figures doubtless refer to the specific retention of materials above the capillary fringe, as well as above the water table.

RELATION OF WATER-YIELDING CAPACITY TO ROCK TEXTURE.

The relative amounts of ground water yielded and retained differ in different kinds of rocks and soils. The retaining force is chiefly adhesion, which increases with the aggregate area of the rock surfaces in contact with the water. Therefore, in rocks of uniform porosity the yield is least in those which have the smallest interstices. A clean gravel—that is, one which is not mixed with fine-grained materials—may have no higher porosity than a bed of silt or clay, yet it may be an excellent source of water, whereas the silt or clay may be worthless. The specific yield of the gravel may be nearly equal to its porosity, but that of the clay may be almost or quite zero, all or nearly all of its water being held against gravity. Dense rocks, such as limestone or lava containing good-sized solution channels or joints, may have a low porosity and yet be excellent sources of water because the interstices which they contain are large and hence yield freely nearly all of their water. Unassorted clayey material, such as the more dense boulder clay deposited by glaciers, has a low porosity, and, moreover, most of its interstices are small. It does not contain very much water even when saturated, and it holds against gravity most of that which it does contain. Its specific yield is still lower than its porosity.

The great influence of the texture of a rock upon its specific yield is rather forcibly illustrated by the data that have been given. Thus, in King's experiment the specific yield decreases and the specific retention increases as the size of the sand grains decreases. (See table on p. 56 and figs. 17 and 18.) The samples used by King were all artificially sorted and hence contained no clayey material. Natural soils, such as those investigated by Israelsen, consist of sand grains with an admixture of clayey materials that coat the grains or lie between them. This admixture of fine-grained material increases the water-retaining capacity very greatly, as is strikingly shown by comparing figures 19, 20, and 21, which show the specific retention of silt loam, clay loam, and clay soils, with figure 18, which shows the specific retention of assorted sand. Even sample No. 100, which has an effective size of grain of less than 0.1 millimeter (see Pl. II), apparently retained but little water as compared with the soil samples.

The samples used by Hazen were doubtless intermediate between those of King and those of Israelsen in degree of assortment and in content of very fine material. Their specific retention is also intermediate. In figure 22 the relation between specific retention and effective size of grain is represented by a rather regular curve for samples with low uniformity coefficients (between 1.8 and 2.4), but in sample No. 6, which is less well assorted and has a uniformity coefficient of 7.8, the specific retention is higher with respect to the effective size of grain, showing clearly the great importance of a small percentage of fine material in retaining water against gravity. On

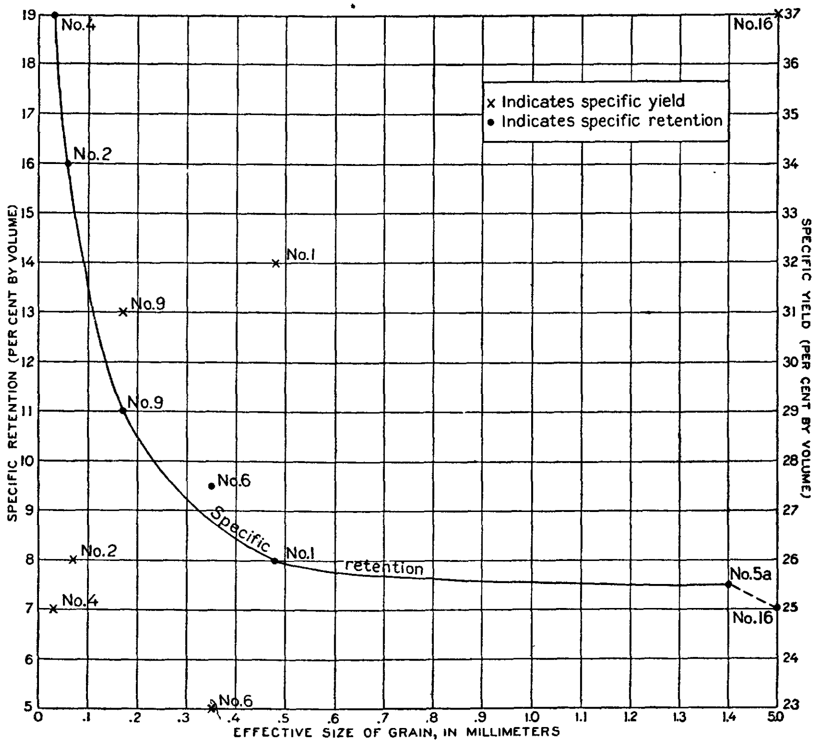


FIGURE 22.—Diagram showing relations of specific yield and specific retention to effective size of grain in Hazen's experiments.

account of the relatively low porosity produced by poor assortment the specific yield of sample No. 6 is relatively very low.

The actual conditions in nature are, of course, very complex. When a system of interstices is drained it retains water not only on its wetted walls but also in crannies of various kinds that act as small detached or independent capillary tubes. A few of many possible conditions of this kind are shown in figure 23. The condition shown in diagram *a* is very common in deposits made up of rounded grains. It can easily be produced by any one with a couple of pebbles and a little water.

RELATION OF YIELD TO PERIOD OF DRAINING.

Most of the gravity water is yielded promptly, but there is apparently almost no limit to the period during which slow draining will continue. The coarsest sand in King's experiment yielded 26.88 per cent of its volume in two and one-half years. It yielded 10.68 per cent in the first half-hour, 15.56 per cent in the first hour, and 24.28 per cent in the first nine days, leaving only 2.60 per cent yielded in the entire period after the 9th day. It was, however, still yielding minute quantities of water at the end of the two and one-half year period, when the experiment was brought to a close. In the last year of the experiment it yielded 19.6 grams, or about one-sixteenth of 1 per cent.

Fine-grained materials not only yield less water than coarse-grained materials but they also yield it more tardily. Thus the finest sand in

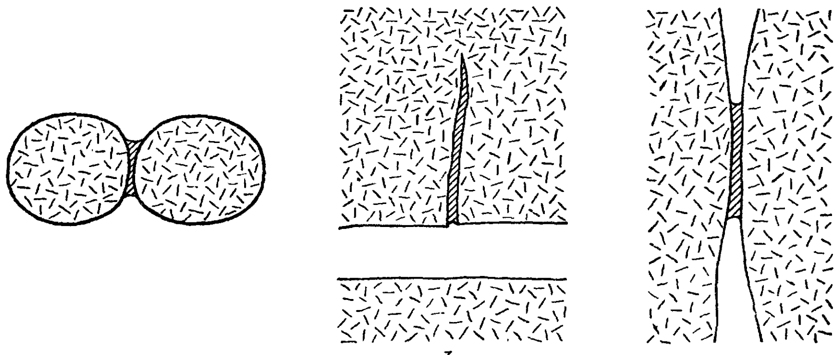


FIGURE 23.—Diagrams showing how water is retained against gravity in crannies of rocks by capillarity. Hachured areas represent rock; shaded areas, water; blank spaces, openings from which water has drained out.

King's experiment (No. 100) yielded only 1.26 per cent in the first 30 minutes, as against 10.68 per cent yielded by the coarsest sand, and 2.16 per cent in the first hour, as against 15.56 per cent yielded by the coarsest. Between the end of the first hour and the 9th day it yielded 11.29 per cent, or nearly three-fourths of the total yield. It ceased yielding much earlier than the coarsest sand, however, no measurable yield being recorded after the first half-year.[25]

For most water-bearing materials the water drained out by rapid lowering of the water table in the immediate vicinity of a heavily pumped well is doubtless considerably less than the total that would be yielded by long-continued draining, but the draining that accompanies the annual fluctuation of the water table is practically complete. For most materials no serious error is involved if the water content after several days of draining is regarded as the specific retention.

[25] King, F. H., op. cit., pp. 88-89.

RELATION OF YIELD TO SIZE AND CONTACT OF SAMPLE.

The specific yield and specific retention of a rock or soil are not the same as the percentage of water respectively yielded and retained by small isolated samples of the same material that are saturated and then allowed to drain. The percentage of water yielded by small samples is less than the specific yield.

This difference results from the fact that a short capillary tube if filled with water may hold all of its supply, whereas a longer tube of the same diameter if filled with water and held in an upright position may allow a part of its supply to drain out because the molecular attraction is not competent to hold a column of water that is higher than the capillary range. The communicating interstices of a rock or a soil may form irregular capillary tubes. In a small sample these tubes are short and they hold their water; in nature, however, many of these tubes are indefinitely long and hence are drained down to a certain level above the water table determined by their diameters. The principle involved can be illustrated by many familiar examples. For instance, if a blanket is washed, put through a wringer, and then deposited in a basket, it may hold all the moisture remaining in it. If, however, it is hung up, so as to have a longer vertical range, it may soon become very wet at the bottom and begin to drip.

This difference is recognized by Israelsen,[26] who says:

> The various laboratory methods which have been used to determine the maximum retentive power of soils for water usually give results which are far in excess of the retentive powers of the same soils under field conditions, because, first, they consider a very short column of soil which is acted upon by special capillary forces, and, second, the samples of soil used have, in most cases, volume weights [specific gravities] which are much lower than those obtaining in the undisturbed condition.

It has already been shown that where a column of material under investigation is in contact with a body of water at the bottom, as in King's experiment (fig. 18), a capillary fringe is maintained for some distance above the water body, and the water content within this distance is greater than the true specific retention. If the water body is removed and the material is free to drip from the bottom, the lower part of the column will presumably still retain a larger percentage of water than higher parts, just as a long capillary tube filled with water and then placed in an upright position will allow its water to drain down to a certain level but will remain filled near the bottom, even though it is free to drip. This wet lower part, detached from any water table, may be called a "suspended capillary fringe." Water that falls in light rains on a dry soil is doubtless sometimes held in such a suspended capillary fringe because there is not enough water to fill the capillary tubes to a sufficient depth to cause downward percolation by gravity, and the underlying dry soil may be in such

[26] Op. cit., p. 1.

physical condition that it will exert little or no capillary attraction. A coarse-grained material, with large interstices, underlying a fine-grained material will also tend to leave a suspended capillary fringe in the lower part of the fine material.

If material that is filled to the limit of its normal water-retaining capacity is underlain by material that is not filled to this limit, the lower material may act as a blotter, drawing water out of the upper material by capillary attraction and thus depleting the water content of at least the lower part of the upper material to an amount less than the true specific retention. This blotter effect may be operative even if the underlying material is of the same texture as the upper material, but it will be especially pronounced if the underlying material is of finer texture. If the moist material is overlain by material that contains less moisture or has finer texture the overlying material will act as a blotter and will tend to draw water upward, but this difficulty is not generally involved in making tests of specific retention and specific yield.

Obviously, whether a test is made in the laboratory or in the field, the true specific retention and the true specific yield of a material can be ascertained only by using a high column of the material and disregarding the lower part.

METHODS OF DETERMINING SPECIFIC YIELD.

The conditions just explained render it impossible to determine the specific yield of a deposit by means of laboratory experiments with small samples unless some indirect method is devised, as, for example, the application of a certain amount of centrifugal force. Direct determinations of specific yield require large samples or tests of the formation in place. Most available methods involve a disturbance of incoherent deposits that introduces a more or less serious error. In making tests with incoherent material care should be taken to get it as nearly as possible into the condition it had in the undisturbed deposit.

The various methods for determining specific yield may be classified as follows: (1) Draining high columns of saturated materials in the laboratory, (2) saturating in the field a considerable body of material situated above the water table and above the capillary fringe and allowing it to drain downward naturally, (3) collecting samples immediately above the capillary fringe after the water table has gone down an appreciable distance, as it commonly does in summer and autumn, (4) ascertaining the volume of sediments drained by heavy pumping, a record being kept of the quantity of water that is pumped, (5) ascertaining the volume of sediments saturated by a measured amount of seepage from one or more streams, (6) making indirect

497781 O-59-6

determinations in the laboratory with small samples by the application of centrifugal force, and (7) making mechanical analyses and estimating therefrom the specific retention and the specific yield.

LABORATORY SATURATION AND DRAINAGE METHOD.

The first method named above, which is the one used by King, has already been discussed (pp. 53–57). The columns must be high enough to avoid the vitiating effects of a true or suspended capillary fringe, and great care must be taken to have the samples completely saturated at the beginning and to prevent loss by evaporation. The specific yield can be obtained by ascertaining the porosity of the material and the water content at each level at the end of the experiment. If both the yielded and the retained water are ascertained, as in King's experiment, there is an opportunity to check the accuracy of the results. The quantity $100\left(\frac{Y+R}{V}\right)$ should be equal to the porosity, if Y is the volume of water yielded by draining, R the volume of water retained at the close of the period of draining, and V the volume of the sample of material tested. The porosity can be independently determined by one of the methods given on pages 11–17.

FIELD SATURATION AND DRAINAGE METHOD.

The second method is the one used by Israelsen and other students of soil water. It is doubtless one of the most convenient and reliable where the material at the surface is like the aquifer under investigation. If it is not, representative material from the aquifer can be put into a good-sized upright cylinder in contact with a wet soil of proper texture, as in experiments by Alway and McDole,[27] and allowed to drain into the soil. Care must be taken to keep the evaporation to a minimum and to have proper conditions at the bottom. The results would, of course, be inaccurate if the water table were too near the surface or if the underlying soil contained so little water that it would act as a blotter. They might also be vitiated by having the material in the cylinder in contact with coarser material that would break the capillary continuity and leave a suspended capillary fringe in the cylinder, or by having the material in the cylinder in contact with much finer material that would have the blotter effect on the water in the cylinder. In this method the specific yield is most conveniently obtained by determining the porosity and specific retention and assuming that the specific yield is the difference between these two.

[27] Alway, F. J., and McDole, G. R., Relation of the water-retaining capacity of a soil to the hygroscopic coefficient: Jour. Agr. Research, vol. 9, pp. 27–71, 1917.

The equation for specific yield is as follows:

$$y = P - 100\left(\frac{R}{V}\right) = P - r.$$

where y = specific yield.
P = porosity.
R = water content of the sample.
V = volume of the sample.
r = specific retention.

DIRECT-SAMPLING METHOD.

The third method is essentially the one used by Charles H. Lee in San Diego County, Calif., and described on pages 60–61. The essential feature in this method is to take a sample where the water table has gone down, as it invariably does during the dry summer season in California. For the most conclusive results the sample should be taken from a point which in the preceding wet season was below the water table and which at the time of taking the sample is far enough above the water table not to be seriously affected by the capillary fringe. Where the fluctuation of the water table is less than the thickness of the capillary fringe the most significant samples are those taken just above the fringe. As this position can not, in practice, be very definitely determined it is advisable to take samples at several levels, as Lee did. Each sample should first be tested for its water content and then for its porosity. The difference between its total pore space and its water content gives the quantity of water which it has yielded since it was in the zone of saturation and also the quantity of water which, if it had been left undisturbed, it would have received into storage the next time the water table rose above it. The equations are the same as for the second method.

In making tests of this kind it is essential to ascertain that the part of the deposit from which the sample was taken has not received any recent contribution of water from rain or irrigation and has not been exposed to evaporation or to absorption by plants, both of which consume water that is retained against gravity by molecular attraction. If there has been recent wetting by rain or irrigation the result for specific yield may be too low, and if there has been loss by evaporation or plant absorption it will be too high. If the material investigated is near the surface it undergoes an annual fluctuation in temperature and a corresponding fluctuation in specific retention and specific yield, the specific retention doubtless being least in summer.

PUMPING METHOD.

The fourth method was used by W. O. Clark in the Morgan Hill area, Calif. It consists in observing the lowering of the water table and hence the volume of sediments drained by pumping a measured volume of water. The specific yield is, of course, the ratio of the volume of water pumped to the volume of sediments drained. The equation for specific yield is as follows:

$$y=100\left(\frac{Y}{V}\right)$$

where y = specific yield,

Y = total volume of water pumped,

V = total volume of sediments drained.

The experiment is described by Clark[28] as follows:

In 1904–5 the Bay Cities Water Co. conducted a pumping test at the lower gorge of Coyote River, about 8 miles northwest of Morgan Hill, Calif. An attempt is here made to determine the approximate storage capacity of the alluvium by making use of two curves which were prepared by Mr. H. L. Haehl, hydraulic engineer for the company, on the basis of data obtained from this test. One curve, not reproduced in this paper, shows the quantity of water pumped; the other, reproduced in simplified form in figure 24, shows the lowering of the water table due to pumping. The pumpage ranged between 8,000,000 and 20,000,000 gallons a day, and from November 15, 1904, to January 16, 1905, amounted to 535,372,000 gallons, or 1,643 acre-feet. The following table gives the estimated area, depth, and volume of alluvium drained by the pumping operations. There was no observed lowering of the water table due to pumping at distances more than 5 miles from the pump.

Area, depth, and volume of alluvium drained by pumping test of Bay Cities Water Co., Nov. 15, 1904, to Jan. 15, 1905.

	Area underlain by alluvium.[a]	Average lowering of water table due to pumping.[b]	Volume of material drained.
	Acres.	*Feet.*	*Acre-feet.*
Less than half a mile south of pump	128	17.5	2,240
Between ½ and 1 mile south of pump	428	7.7	3,296
Between 1 and 1½ miles south of pump	460	4.7	2,208
Between 1½ and 5 miles south of pump	3,584	1.8	6,451
			14,195

[a] Based on planimeter measurements. [b] Based on figure 24.

If the volume of materials drained was 14,195 acre-feet and the quantity of water pumped was 1,643 acre-feet, the available pore space [specific yield] was 11.6 per cent. This figure is in close agreement with the 12.06 per cent found by the first method. The calculations by the first method were completed before any of the data used in the second method had been obtained, and the two results are therefore entirely independent of each other. The close agreement is of course accidental, but the fact that the two methods lead to the same general result is probably significant. It should be recognized that the base data are far from being adequate for the purpose for which they are used. The amounts of water that percolated into the area, that escaped northward through the gravels in the lower gap, and that were drawn to the pump from the area below the gap are undetermined and introduce large uncertainties.

[28] Clark, W. O., Ground water for irrigation in the Morgan Hill area, Calif.: U. S. Geol. Survey Water-Supp[illegible]r 400, pp. 84–86, 1917.

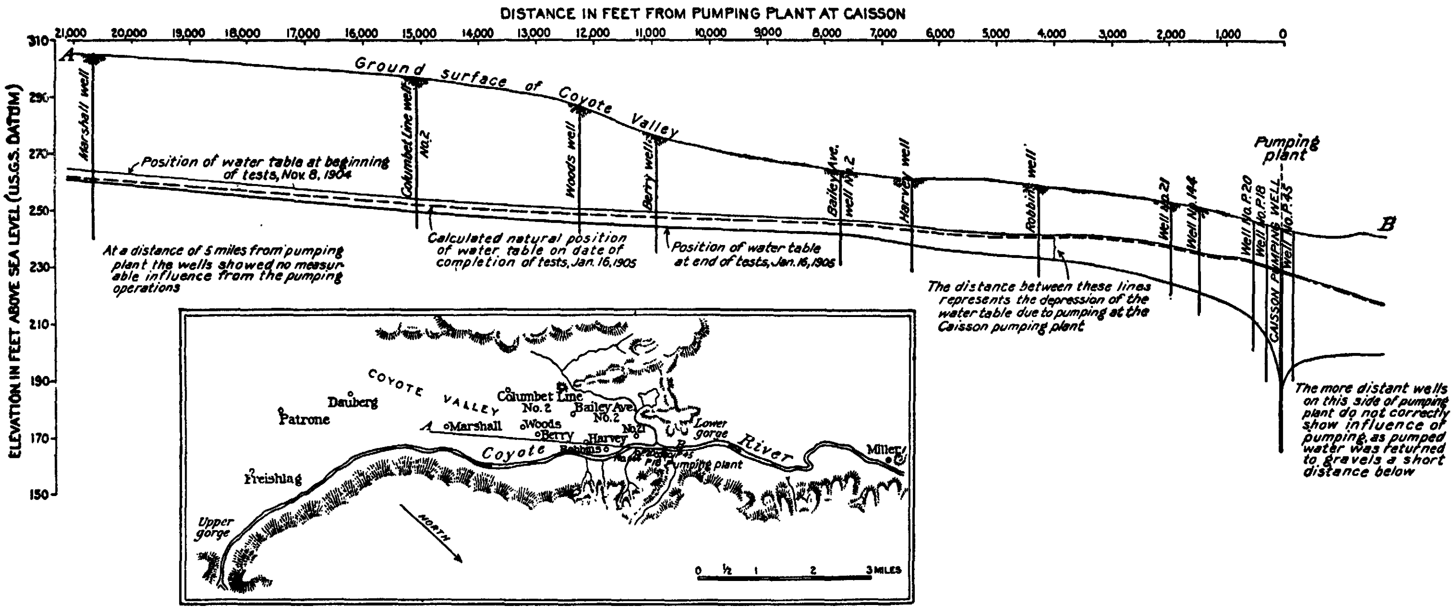


Figure 24.—Section and sketch map showing effect on water table produced by pumping test of Bay Cities Water Co. at the lower gorge of Coyote River, Morgan Hill area, Calif., Nov. 8, 1904, to Jan. 16, 1905. (Exhibit B, case of Miller *v.* Bay Cities Water Co.)

This method has the disadvantage of requiring heavy pumping operations, and it involves uncertainties due to percolation, during the period of the test, into and out of the area affected by the pumping. It has the great advantage of avoiding all the artificial conditions involved in laboratory experiments.

RECHARGE METHOD.

The fifth method is the converse of the fourth. It consists of observations on the amount of water that percolates from streams or canals into an aquifer and corresponding observations on the resulting rise of the water table, from which can be computed the volume of sediments saturated by the measured recharge. It involves several inaccuracies, chiefly those due to difficulties in making accurate measurements of seepage losses from streams and in making proper allowances for gains from precipitation and from percolation of water from other areas and for losses through percolation out of the area, evaporation, plant absorption, etc. It assumes that prior to the experiment the sediments contain water to the extent of their water-retaining capacity. The equation for specific yield is as follows:

$$y = 100\left(\frac{Y}{V}\right)$$

where y = specific yield.
Y = recharge.
V = volume of sediments saturated.

MOISTURE-EQUIVALENT METHOD.

The sixth method has not been perfected but has been suggested by the work of Briggs, Alway, Israelsen, and others. The term moisture equivalent was introduced by Briggs and McLane[29] to express the percentage of water retained by a sample of soil or other material when it is saturated and then subjected to a constant centrifugal force.

It seems theoretically possible to apply a centrifugal force of such magnitude that it would reduce the capillary fringe so much that this fringe could be ignored without introducing much error, even in small samples, and yet would not be strong enough to withdraw a large proportion of the water that is held more securely above the capillary fringe. Thus, if a material will lift water 100 inches by capillarity acting against gravity it will theoretically be able to hold it only 0.1 inch against a centrifugal force that is 1,000 times as great as the force of gravity. Experiment alone can determine to what extent such a force would remove water that is held above the capillary fringe against the pull of gravity.

---

[29] Briggs, L. J., and McLane, J. W., The moisture equivalents of soils: U. S. Dept. Agr. Bur. Soils Bull. 45, 1907.

Briggs and McLane made determinations of the moisture equivalents, under a centrifugal force 3,000 times the force of gravity, of more than 100 soils, of which they also made mechanical analyses. For a few soils they also made determinations of the moisture equivalent under centrifugal forces of several different intensities, as is shown in the following table. Unfortunately for the present purpose, the moisture equivalents are expressed in percentage by weight, and as the specific gravity of the soils is not given it is impossible to convert the values into percentage by volume.

Moisture equivalents of certain soils under different amounts of centrifugal force.

[Per cent by weight.]

Centrifugal force, in grams per cubic centimeter of water—that is, using the force of gravity as the unit	857	1,057	1,203	1,975	2,073	2,174	2,937	3,554
New Mexico dune sand	3.0	2.8	2.9	2.8	2.6			2.6
Sassafras loam, good	18.6	16.9	15.2	15.0	14.0			12.5
Leonardtown loam, good	18.0	16.5	15.2	13.6	14.2			12.1
Leonardtown loam, poor	12.0	10.3	9.6	7.7	7.4			6.3
Hagerstown stony loam						16.9	15.0	14.6
Hagerstown sandy loam						12.2	11.0	9.9
Hagerstown loam (1)						21.8	20.8	18.4
Hagerstown loam (2)						18.3	17.5	16.5
Hagerstown silt loam						17.9	16.5	15.8
Hagerstown shale loam						31.6	25.0	17.3
Hagerstown clay loam (1)						24.1	23.4	21.5
Hagerstown clay loam (2)						26.0	25.5	24.8

The following table gives the mechanical analyses of most of the soils whose moisture equivalents are given in the preceding table. It will be noted that the effective size of grain of practically all these samples is less than 0.005 millimeter.

Mechanical composition of certain soils.

[Per cent by weight for specified limits as to diameter of grain.]

	2 to 1 millimeters.	1 to 0.5 millimeter.	0.5 to 0.25 millimeter.	0.25 to 0.1 millimeter.	0.1 to 0.05 millimeter.	0.05 to 0.005 millimeter.	Less than 0.005 millimeter.	Organic matter.
Hagerstown stony loam	2.7	4.9	3.6	7.3	14.1	45.1	22.1	1.6
Hagerstown sandy loam	.4	5.0	8.8	23.4	20.2	33.0	9.4	1.0
Hagerstown loam (1)	2.1	3.4	3.4	6.8	12.4	57.2	14.9	1.4
Hagerstown loam (2)	1.0	1.8	1.4	7.4	18.6	49.9	19.7	1.0
Hagerstown silt loam	.3	.6	1.5	9.1	10.5	60.3	17.4	1.0
Hagerstown shale loam	13.1	5.1	2.0	3.8	7.9	55.5	11.7	2.6
Hagerstown clay loam (1)	1.0	2.7	2.6	6.7	10.6	61.7	14.3	2.2
Hagerstown clay loam (2)	1.9	1.8	1.2	2.5	6.3	69.6	17.0	1.3

The results obtained are summarized by Briggs and McLane as follows:

The moisture equivalents of over 100 samples of type soils have been determined, employing for this purpose a centrifugal force about 3,000 times the force of gravity. These moisture equivalents vary from 3.6 per cent in the coarser sandy soils to 46.5 per cent in a heavy clay subsoil [perhaps about 5 to 50 per cent by volume]

These observations were reduced by the method of least squares to determine the influence of the sand, silt, and clay groups and of the organic matter upon the retention of moisture. It was found for the whole series that each per cent of clay or organic matter in the soil corresponded to a retention of 0.62 per cent of moisture [by weight] when the soil was subjected to a force of 3,000 times that of gravity. Each per cent of silt, under similar conditions, corresponded to a retention of 0.13 per cent of moisture, and the coarser grades show practically no retentive action against this force. The probable error for these coefficients was rather high. * * * It is interesting to note that the organic matter, for the force employed, has a retentive power no greater than the clay group.

In these conclusions the term "clay" is used for sediments less than 0.005 millimeter in diameter, and the term "silt" for sediments between 0.005 and 0.05 millimeter in diameter. According to the results obtained each per cent of material between 0.05 and 0.25 millimeter in diameter had a retentive power of 0.002 per cent of water, and each per cent of material between 0.25 and 2 millimeters had a retentive power of 0.022 per cent of water. The apparent anomaly of the coarser sand having greater retention than the grade that is less coarse is explained as resulting from the fact that the soils vary greatly in character, so that the individual peculiarities of the soil tend to mask the true values of coefficients that are very small.

With respect to the relation of the moisture equivalent to the specific retention, Briggs and McLane[30] make the following suggestion:

It is possible to reduce the moisture content of a soil in this way so that it is no greater than the moisture content of the soil under favorable field conditions. By this method, then, it is possible to determine the retentive power of different soils for moisture when acted upon by the same definite force, comparable in magnitude with the pulling force to which the soil moisture is subjected in the field.

In a later publication Briggs and Shantz[31] developed the following equation:

$$\text{Moisture-holding capacity} = (\text{moisture equivalent} \times 1.57) + 21.$$

In this equation the "moisture-holding capacity" is the specific retention determined by the use of soil columns only 1 centimeter high and expressed in percentage by weight; the moisture equivalent is determined by the application of a centrifugal force of 1,000 times the force of gravity. Because of the low columns of material used the "moisture-holding capacity" of this equation is much greater than the true specific retention. For the purposes of hydrology the equation is therefore not directly applicable, but it is suggestive of the use that could perhaps be made of the moisture equivalent.

[30] Op. cit., p. 22.

[31] Briggs, L. J., and Shantz, H. L., The wilting coefficient for different plants and its indirect determination: U. S. Dept. Agr. Bur. Plant Industry Bull. 230, p. 73, 1912.

In figures 19, 20, and 21 (pp. 58–59), which show some of Israelsen's results, the moisture equivalents, expressed in percentages by volume, are shown in relation to the water content and porosity similarly expressed. In the coarser soils, such as the silt loams shown in figure 19, the values for the moisture equivalent are not very different from those for water content four days after irrigation, though the moisture equivalent averages slightly higher than the water content. For the more clayey soils there are larger differences. In the clay soils represented in figure 21 the moisture equivalent is shown to be much larger than the water content four days after irrigation and even greater than the porosity. Israelsen suggests that this may be due in part to difficulty in wetting the impervious clay soils, as a result of which the water content shown is less than the specific retention, and in part to differences in specific gravity of the soil in the field and in the perforated cups of the centrifuge. Israelsen[32] summarizes his conclusions as follows:

The comparisons made suggest that the moisture equivalent may be made a means of judging the maximum capillary capacity [specific retention] of soils in place. Though definite conclusions from so few correlations are not warranted, it seems that the moisture equivalent represents more nearly the maximum capillary capacity [specific retention] of the soil in place than do the ordinary laboratory determinations upon the disturbed soil, both in point of accuracy and of absolute value.

MECHANICAL-ANALYSIS METHOD.

As specific retention is related to texture a possible method of estimating the specific retention of an incoherent deposit is by making a mechanical analysis of the material. The specific yield would then be obtained by subtracting the specific retention from the porosity. The following statement is made by Briggs and Shantz[33] regarding the availability of this method:

Soil texture has been used for the quantitative description of soils more extensively than any other physical property, and unfortunately it has been one of the most difficult to interpret from the standpoint of moisture retentiveness. Texture is quantitatively expressed by means of the mechanical analysis, which shows the composition of the soil when the particles are separated into groups according to size. The accuracy with which the texture of the soil can be expressed by this means is dependent on the number of groups into which the particles are separated. But the difficulty of effecting a complete separation of the finer particles into the desired groups places a practical limit upon the number of groups, which is usually limited to seven.[34]

The use of mechanical analysis as a basis for determining the moisture retentiveness of a soil is further complicated by the fact that soils having a high clay content will show great differences in the amount of colloidal material, which greatly affects

[32] Op. cit., pp. 23-28.

[33] Op. cit., p. 68.

[34] Briggs, L. J., Martin, O. F., and Pearce, J. R., The centrifugal method of mechanical soil analysis: U. S. Dept. Agr. Bur. Soils Bull. 24, p. 33, 1904.

the moisture retentiveness. Furthermore, the particles constituting a given group may lie much nearer one limit of the group than the other, so that a given group does not always have the same properties. Consequently the particles constituting a given group in the mechanical analysis do not always have the same moisture retentiveness per unit mass. It is also possible that the specific retentivity of a group when measured alone is modified to some extent by admixture with particles from other groups.

The following equation for interpreting mechanical analyses of materials with respect to their water-retaining capacities was developed by Briggs and Shantz:[35]

$$\text{Moisture-holding capacity} = (0.03 \text{ sand} + 0.35 \text{ silt} + 1.65 \text{ clay}) + 21.$$

In this equation the term "sand" refers to the percentage, by weight, of the dry sample composed of particles between 2 and 0.05 millimeters in diameter, "silt" to the percentage between 0.05 and 0.005 millimeter, and "clay" to the percentage smaller than 0.005 millimeter. The term "moisture-holding capacity" has the same meaning as on page 74 and therefore indicates a larger quantity than the specific retention, as defined in this paper. The porosity minus this quantity would give a result that would be less than the actual specific yield of the material.

The specific retention and hence the specific yield could also be calculated by means of a curve based on the effective size of grain, such as is shown in figure 22 (p. 64), on the basis of Hazen's data. This method would require a determination of the porosity and a mechanical analysis or other means of ascertaining the effective size of grain. Some sort of results could be obtained by developing a curve to show the relation between porosity and the uniformity coefficient from data plotted as in figure 5 (p. 8). The specific yield could then be computed from the effective size of grain and the uniformity coefficient, and these two quantities could conveniently be derived by plotting a mechanical analysis as in figure 4 (p. 6). It is doubtful, however, whether the results derived in this manner would be accurate enough to be of practical value. At best this method is applicable only to incoherent materials.

ZONE OF AERATION.

DEFINITION OF TERMS.

The part of the solid earth lying above the zone of saturation may be called the "zone of aeration," because its interstices are largely filled with atmospheric gases. This zone also contains much water, and some of its smallest interstices may be completely filled with water. But the water in the zone of aeration is not, except temporarily, under hydrostatic pressure. It is for the most part held by molecular attraction, and if this force did not exist nearly all of this

[35] Op. cit., p. 73.

water would be drawn down by gravity to the water table. This water may appropriately be called "suspended subsurface water" because it is held up against the pull of gravity much as a body may be suspended by a visible string or cable, or as small solid and liquid particles are held in the atmosphere and small solid particles are held in a body of water through this same force of molecular attraction. It has also been called "vadose water." According to this classification there are two kinds of water in the interstices of the earth—suspended subsurface water, or vadose water, which is the water in the zone of aeration, and ground water, or phreatic water, which is the water in the zone of saturation.

In exceptional areas there are two zones of saturation, the upper one containing ground water that is supported at least temporarily by some relatively impervious bed at a level far above the water table of the main body of ground water. In such an area the unsaturated deposits between the upper and lower bodies of ground water may be regarded as a second zone of aeration.

Such conditions appear to prevail in the detrital fill of Sulphur Spring Valley, Ariz.,[36] where high-level water supported by calcareous hardpan occurs in many localities far above the main water table (fig. 25).

In the parts of the Tintic mining district,[37] in Utah, where igneous rocks rest on limestone and quartzite, there are two zones of aeration with an intervening zone of saturation. Springs and shallow wells obtain water from the decomposed igneous rocks and overlying rock waste, but wells and mine shafts sunk into the underlying limestone and quartzite lose their water and remain dry to depths of many hundred feet. Any water that reaches the limestone and quartzite sinks to great depths, where there is apparently a second zone of saturation.

On the island of Hawaii beds of dense volcanic ash are at several horizons interbedded with very permeable lava. Above some of these ash beds are found true zones of saturation, which will yield water to springs and tunnels. However, these perched water bodies are in some places more than 1,000 feet above the main zone of saturation and are separated from it by great thicknesses of very permeable but unsaturated lavas that yield no water. In figure 26 is shown a section on the Kapapala ranch, in the Kau district, in which there are two ash beds, at B and D, one about 400 feet above the other, each supporting a perched water body that constitutes a true zone of saturation and yields water supplies to springs and tunnels. The basal zone of saturation would doubtless be found near sea level, many

[36] Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, pp. 102–111, 1913.

[37] Meinzer, O. E., Ground water in Juab, Millard, and Iron counties, Utah: U. S. Geol. Survey Water-Supply Paper 277, pp. 29–31, 81–86, 1911.

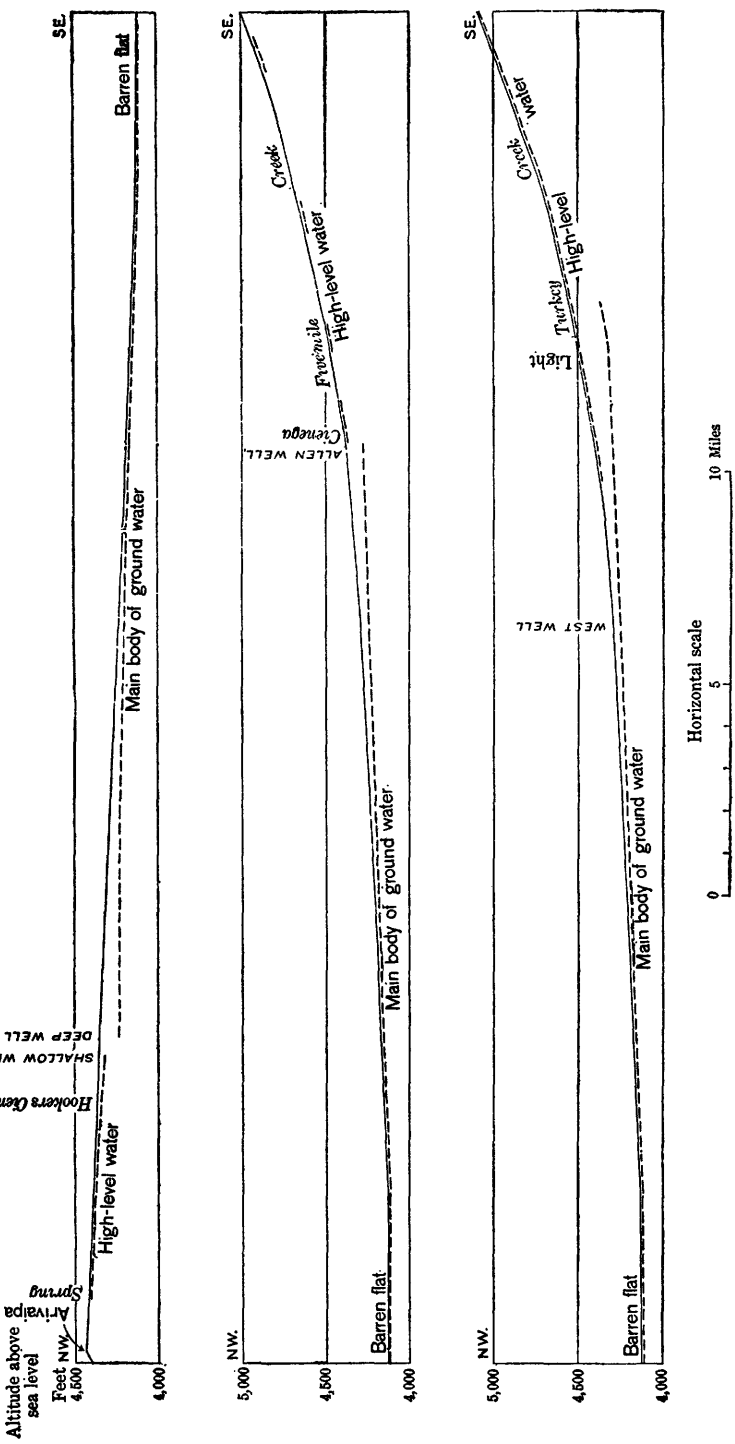


FIGURE 25.—Section showing relation of high-level water to main body of ground water in Sulphur Spring Valley, Ariz. Continuous lines show surface of land; broken lines show water tables.

hundred feet lower. In this locality there are therefore three zones of saturation alternating with three zones of aeration, A, C, and E.

A good example of a perched water body in Long Island is given by A. C. Veatch, as shown in figure 27. Unsaturated strata, comprising a second zone of aeration, intervene between the saturated zone that supplies the deep well and the saturated strata near the surface that supply the springs and shallow wells in the vicinity.

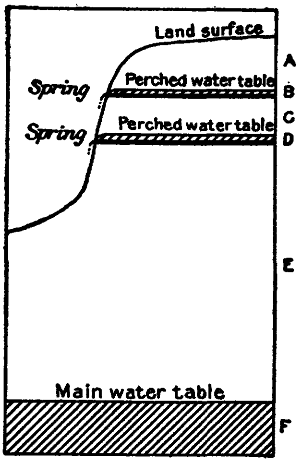


FIGURE 26.—Section at Kapapala ranch, Kau district, island of Hawaii, showing three zones of aeration, A, C, E, alternating with three zones of saturation, B, D, F. (Data furnished by W. O. Clark.)

Temporary zones of saturation are commonly found very near the surface after heavy rains, especially where the soil and subsoil are of clayey character, and in the spring before the deeper frost has left the ground. They produce conditions that are well known to farmers. Such a temporary zone of saturation may be far above the permanent zone of saturation and may be separated from it by unsaturated soil or rock. While it lasts, however, it has a true water table and in other respects behaves like a deeper permanent zone of saturation.

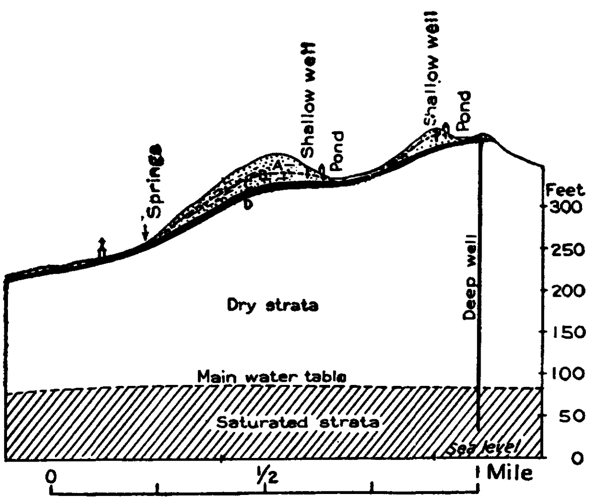


FIGURE 27.—Section on Long Island, N. Y., showing a body of perched water. A, Unsaturated strata; B, perched water table; C, saturated strata; D, nearly impermeable till. (After A. C. Veatch, U. S. Geol. Survey Prof. Paper 44, fig. 25, 1906.)

THICKNESS OF ZONE OF AERATION.

The zone of aeration varies in thickness from place to place according to the depth to the water table. In swampy tracts it is virtually absent, the zone of saturation being about at the surface. On elevated desert plains underlain by gravelly deposits it may be several hundred feet thick, and in mountains consisting of fissured or porous rocks in arid regions it may be more than 1,000 feet

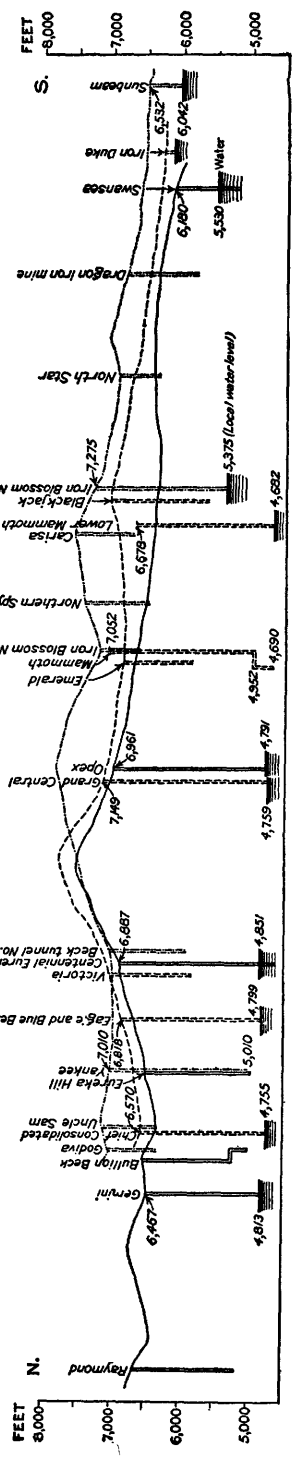


FIGURE 28.—Cross sections of Tintic mining district, Utah, showing shafts and water levels. (After Lindgren and Loughlin.)

thick. Over most of the humid portion of the United States and over large parts of the arid portion the thickness of the zone of aeration, or the depth to the water table, is less than 100 feet.

Data on 28,797 wells distributed throughout the United States were obtained through correspondence by McGee.[38] The average of the reported depths to the water level in all these wells is 37 feet. The actual average depth to the water level is doubtless considerably greater, because, obviously, wells are the most abundant where the depth to water is not great.

The mines at Tombstone, Ariz., were dry to a depth of about 500 or 600 feet, but deeper workings could be kept accessible only by pumping great quantities of water.[39] The mines at Bisbee, Ariz., are likewise dry to great depths, but heavy pumping is required from those which have been sunk deepest. Ransome[40] reports that in the Lowell mine the water level was encountered about 1,100 feet below the surface and that pumping was necessary after this depth was reached. In the Utah mine, which is situated near Fish Springs, Utah, and is developed chiefly in limestone, no water was found until a depth of 800 feet was reached. In the Tintic mining district, in Utah, a number of shafts sunk largely through limestone to depths of 1,500 to 2,390 feet are dry or receive water only near the bottom.[41]

[38] McGee, W J, Wells and subsoil water: U. S. Dept. Agr. Bur. Soils Bull. 92, pp. 161-163, 1913.

[39] Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, pp. 115-116, 1913.

[40] Ransome, F. L., U. S. Geol. Survey Geol. Atlas, Bisbee folio (No. 112), p. 16, 1904.

[41] Meinzer, O. E., Ground water in Juab, Millard, and Iron counties, Utah: U. S. Geol. Survey Water-Supply Paper 277, pp. 29, 80, 81, 1911. Lindgren, Waldemar, and Loughlin, G. F., Geology and ore deposits of the Tintic mining district, Utah: U. S. Geol. Survey Prof. Paper 107, pp. 122-125, 1919.

The Mammoth mine was still dry when it reached the depth of 2,360 feet. There is, however, a question as to whether this condition is due wholly to a very low water level or in part to the impervious character of the rock. The latest data on depths to the water level in the Tintic district are graphically shown in figure 28, which is taken from the paper by Lindgren and Loughlin.[42] In some of the high areas in the Hawaiian Islands, underlain by permeable lava, the water table is doubtless several thousand feet below the surface.

Extensive areas in which the zone of aeration is thin, the water table being near the surface, are by no means confined to the humid sections of the country but are found in many valleys in the arid and semiarid parts of the West. Sacramento Valley, Calif., which is 150 miles long and 40 miles wide, was found in a survey by Bryan[43] to have a depth to water of less than 25 feet throughout more than four-fifths of its area. The extent of shallow-water tracts in typical valleys in Arizona, New Mexico, and Nevada is shown in the following table:

Areas (in acres) having specified thicknesses of the zone of aeration (depths to water table).

	0–10 feet.	0–15 feet.	0–20 feet.	0–25 feet.	0–50 feet.	0–100 feet.	Authority.
Sulphur Spring Valley, Ariz.	....	96,000	....	141,000	262,000	432,000	U. S. Geol. Survey Water-Supply Paper 320, p. 96.
Tularosa Basin, N. Mex.	....	....	....	364,000	762,000	1,036,000	U. S. Geol. Survey Water Supply Paper 343, p. 104.
Big Smoky Valley, Nev.	130,000	....	....	....	240,000	335,000	U. S. Geol. Survey Water-Supply Paper 423, p. 105.
Steptoe Valley Nev.	95,000	....	135,000	....	185,000	....	U. S. Geol. Survey Water-Supply Paper 467, p. 38.

SUBDIVISIONS OF ZONE OF AERATION.

The zone of aeration may be divided with respect to the occurrence and circulation of its water into three belts—the belt of soil water, the intermediate belt, and the capillary fringe. The belt of soil water consists of soil and other materials that lie near enough to the surface to discharge water into the atmosphere in perceptible quantities by the action of plants or by soil evaporation and convection. The capillary fringe, as already explained (p. 31), is the belt immediately above the water table that contains water drawn up from the zone of saturation by capillary action. Where the water table is so far below the surface that the belt of soil water does not extend down to the capillary fringe there is an intermediate belt. This threefold subdivision of the zone of aeration and the relations of the three belts to each other are illustrated in figure 29. In accordance with this threefold subdivision of the zone of aeration, there may be said to be

[42] Op. cit., fig. 16.

[43] Bryan, Kirk, Ground water for irrigation in Sacramento Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 375, p. 19, 1915.

three kinds of suspended subsurface water, or vadose water—soil water, fringe water, and intermediate vadose water.

BELT OF SOIL WATER.

CHARACTER AND THICKNESS OF BELT.

Soil water may be discharged into the atmosphere by evaporation directly from the soil or by the action of plants.

Evaporation takes place only at the surface or in the interstices near the surface, except in clayey soils, which in drying form large sun cracks that permit evaporation at considerable depths, and except where there are caves with openings to the surface. The water that evaporates in the interstices is carried into the atmosphere by circulation of air through the upper layer of soil. Water is to some extent brought up to the evaporating surfaces by capillarity, but the total

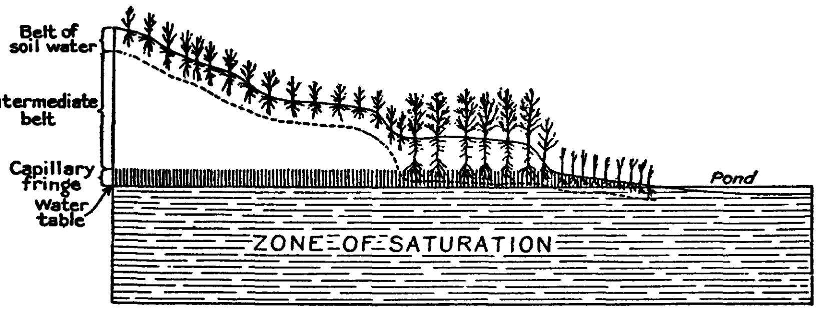


FIGURE 29.—Diagrammatic section showing the three belts of the zone of aeration.

depth below the surface from which water in appreciable quantities is removed by evaporation seldom exceeds a few feet.

The depths to which the roots of plants go for water varies greatly with different kinds of plants and with different kinds of soil and moisture conditions. Ordinary grasses and field crops do not draw from depths of more than a few feet, though Chilcott[44] cites an example of wheat in a semiarid region sending its roots to a depth of 6 feet and expresses the opinion that this depth of root penetration may not be unusual. Investigations by Burr[45] showed that in fine sandy loam, derived from loess, at North Platte, Nebr., corn, oats, spring wheat, and barley use water from a depth of 4 or 5 feet, and winter wheat from a depth of 6 or 7 feet; also that alfalfa, once well established in soil of this type, will obtain ground water where the water table is as much as 20 to 30 feet below the surface. Some of

[44] Chilcott, E. C., Some misconceptions concerning dry farming: U. S. Dept. Agr. Yearbook for 1911, p. 255, 1912.

[45] Burr, W. W., The storage and use of soil moisture: Nebraska Univ. Research Bull. 5, p. 9, 1914.

the relations of plant roots to the supplies of soil water are described by Kearney and Shantz[46] as follows:

Plants differ greatly in the characters of their root systems. Some species are characterized by roots which penetrate deeply into the soil, while others possess roots which lie near the surface. The root system can be more or less modified by environment and is particularly susceptible to the influence of changes in soil moisture and soil texture. Ability to evade drought is often due to having roots developed in such manner as to absorb water from an unusually large mass of soil. Whether a shallow or a deep root system is most effective depends largely upon the character of the soil and upon the distribution of the rainfall. If water penetrates readily to a considerable depth, plants having deep roots are obviously at an advantage as compared with shallow-rooting species. Such roots can push ahead into moist soil as fast as the surface layers dry out. In the virgin condition, soils which have this distribution of moisture are largely occupied by deep-rooting woody plants, such as the characteristic black sage (*Artemisia tridentata*) of the Great Basin region. Alfalfa with its long taproot is a good example of this adaptation among cultivated plants.

Large trees and certain types of deep-rooted desert plants draw water from considerable depths. There is evidence that a certain type of mesquite obtains water as much as 50 feet below the surface and that other perennials may send their roots to depths of 50 or even 60 feet.[47] This subject will be discussed more fully in a paper on the origin, discharge, and quantity of ground water now in preparation.

WATER-RETAINING CAPACITY IN RELATION TO AGRICULTURE.

Soil water is of great importance to the agriculturist because it is the water on which the crops depend and which in large measure determines their yield. Elaborate investigations have been made of the content of water in the soil, the conditions and rate of its discharge into the atmosphere, its consumption by plants, its upward and downward migration, the depth from which it is absorbed by different kinds of cultivated plants, and the behavior of different kinds of soil in all these respects. An extensive literature on these subjects has been produced by students of agriculture.

A high specific retention in a material—a large capacity for holding water against the pull of gravity—is detrimental to the material as an aquifer. It detracts from its value as a source of water for wells and springs. It measures to a considerable extent, however, the value of the material as a soil. The retained water is not available for wells and springs, but it is, for the most part, the water which supplies vegetation.

[46] Kearney, T. H., and Shantz, H. L., The water economy of dry-land crops: U. S. Dept. Agr. Yearbook for 1911, p. 356, 1912.

[47] Mendenhall, W. C., Some desert watering places in southeastern California and southwestern Nevada: U. S. Geol. Survey Water-Supply Paper 224, p. 20, 1909. Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, pp. 182–187, pls. 1–2, 1913. Brown, J. S., The Salton Sea region: U. S. Geol. Survey Water-Supply Paper 497 (in press). Rotmistrov, V. G., The nature of drought according to the evidence of the Odessa experiment field, Odessa, 1913.

497781 O–59–7

An excellent example of the importance to vegetation of the water-retaining capacity of a soil is afforded by the sand dunes in humid regions. For example, some of the dunes on the south and east sides of Lake Michigan are bare of vegetation or support chiefly cacti and other desert plants, and sand hills in parts of Florida where the average annual rainfall is about 48 inches support prickly pears and Spanish daggers. The sand in these humid regions is so coarse and clean that it has a high specific yield but a low specific retention. The rain percolates downward, out of the reach of plants, so rapidly and almost completely that the amount of water available for plant growth is no greater than it would be in a region of good soil and light rainfall. One of the most important properties of a good soil is a texture that will retain an adequate amount of water.

WATER AVAILABLE FOR GROWTH.

The root system of an ordinary plant includes a large number of fine rootlets that penetrate all parts of the soil from which the plant draws its water supply and dissolved mineral matter. These rootlets have the power of absorbing much but not all of the water that is retained by molecular attraction. To some extent the soil water is drawn to the rootlets by capillary action when they remove the water in their immediate vicinity. However, this capillary movement is sluggish, whereas water in adequate quantities is essential to the life and growth of the plants. Hence to a great extent plants send their rootlets to portions of the soil where water is available rather than wait for the water to migrate to the roots by capillarity.

The "wilting coefficient"[48] of a soil is defined as the ratio of (1) the weight of water in the soil when (with gradual reduction in the supply of soil water) the leaves of the plant growing in the soil first undergo permanent wilting to (2) the weight of the soil when dry. By permanent wilting is meant a reduction in water content from which the leaves can not recover in an approximately saturated atmosphere without the addition of water to the soil. As growth practically ceases when a plant reaches a permanently wilted condition, the wilting coefficient represents approximately the soil water that is not available for growth, and the excess of water in the soil at any given time over the wilting coefficient is the water available for growth at that time. The boundary between the water which is available and that which is unavailable for growth is doubtless somewhat indefinite, just as the boundary between gravity water and retained water is indefinite. The capacity of a soil for holding water available for growth is measured by the difference between its specific retention and its wilting coefficient.

---

[48] Briggs, L. J., and Shantz, H. L., The wilting coefficient for different plants and its indirect determination: U. S. Dept. Agr. Bur. Plant Industry Bull. 230, 1912.

The wilting coefficient differs greatly for different kinds of soil but is remarkably uniform for different kinds of plants growing in the same soil. This fact was demonstrated by Briggs and Shantz,[49] from whom the following is quoted:

The wide range in moisture content of different soils at the time of wilting of the plant cover appears to have been first clearly recognized by Sachs[50] in 1859. The differences which extreme types of soil exhibit in this respect are truly remarkable, ranging from 1 per cent in coarse dune sand to 30 per cent or more in the heaviest types of clay. Sachs's experimental work in this field was confined to a single plant. Later investigators in extending this work concluded that not only do soils show a wide range in moisture retentiveness, but that different groups of plants differ widely in their ability to reduce the moisture content of a given soil. Thus, the experimental work of Gain,[51] Heinrich,[52] Hedgcock,[53] and Clements,[54] all indicates considerable variation in the moisture content of the soil at the time of wilting of different plants, which has been interpreted to mean that some plants are capable of reducing the moisture content of a given soil to a lower point than others—in other words, that the nonavailable moisture varies according to the kind of plant used as an indicator. In fact, this view is the one usually presented in the standard works on plant physiology and plant ecology.

The difference exhibited by plants in this respect has also been considered to be an important factor in drought resistance, the additional supply of water thus made available to some plants being supposed to be sufficient to carry them through a dry period when other plants would succumb to drought. With this point of view in mind the present writers have made an extensive series of determinations with a number of plants, including native plants from semiarid and arid regions, to determine the variation exhibited in their ability to reduce the moisture content of the soil before permanent wilting takes place. The results of these investigations have led us to conclude that the variation exhibited by different plants is much less than has heretofore been supposed and that it is insignificant compared with the range in moisture retentiveness exhibited by different soils.

Wilting-coefficient determinations have been made in a series of 20 soils ranging from sands to clays. In this work, involving about 1,300 determinations, a large number of varieties of the different crop plants have been tested, as well as many native plants from the Great Plains.

The results obtained show that species differ only slightly as regards the soil-moisture content at which permanent wilting first takes place. Taking 100 to represent the average wilting coefficient, the different species tested (except *Colocasia* and *Isoetes*) give an extreme range from 92 for Japan rice to 106 for a variety of corn. Most of the species and varieties tested differ much less than this. On the same scale the great crop plants gave the following values, obtained by combining the different varieties: Corn 103, wheat 99, oats 99, sorghum 98, millet 97, barley 97, rye (one variety only) 94, rice 94, grasses 97, and legumes 101.

---

[49] Op. cit., pp. 7, 8, 75, 76.

[50] Sachs, J., Bericht über die physiologische Thätigkeit an der Versuchsstation in Tharandt, Landwirthschaftlichen Versuchs-Stationen, 1859, vol. 1, p. 235.

[51] Gain, E., Action de l'eau du sol sur la végétation: Rev. gén. botanique, vol. 7, p. 73, 1895.

[52] Heinrich, R., Zweiter Bericht über die Verhältnisse und Wirksamkeit der landwirtschaftlichen Versuchs-Stationen zu Rostock, p. 29, 1894.

[53] Hedgcock, G. G., The relation of the water content of the soil to certain plants, principally mesophytes—Studies in the vegetation of the State, pt. 2, pp. 5–79, 1902. In Botanical survey of Nebraska, vol. 6.

[54] Clements, F. E., Research methods in ecology, p. 30, Lincoln, Nebr., 1905.

The conclusion is thus reached that the differences exhibited by crop plants in their ability to reduce the moisture content of the soil before wilting occurs are so slight as to be without practical significance in the selection of crops for semiarid regions. Furthermore, it is believed that the slight differences which have been observed are largely due not to the ability of one variety to exert a greater attractive force upon the soil moisture than another but to the more perfect root distribution of one variety as compared with another. Drought resistance in certain plants can not, then, be attributed to their ability to exert a greater force upon the soil moisture and so gain an additional water supply.

The following equations developed by these investigators[55] show the relations between the wilting coefficient and other properties of soils:

$$\text{Wilting coefficient} = \frac{\text{Moisture equivalent}}{1.84}$$

$$= \frac{\text{Moisture-holding capacity} - 21}{2.90}$$

$$= 0.01 \text{ sand} + 0.12 \text{ silt} + 0.57 \text{ clay}.$$

In these equations the terms "moisture-holding capacity," "sand," "silt," and "clay" have the same meanings as are given on page 74. The authors also give estimates of the probable percentages of error that may be expected in each equation.

These equations are based in part on data given in the following tables:[56]

Relation of wilting coefficient to moisture equivalent of soils.

[From Briggs and Shantz. Wilting coefficient and moisture equivalent given in per cent by weight of the dry soil.]

No.	Type of soil.	Moisture equivalent.	Wilting coefficient.		Ratio of moisture equivalent to wilting coefficient.
			Number of determinations.	Mean.	
1	Coarse sand	1.55	11	0.86	1.81
7	....do	1.55	59	1.03	1.51
87	Sand	2.48	8	1.23	2.01
2	Fine sand	4.66	18	2.6	1.79
8	....do	5.5	42	3.03	1.82
9	....do	6.74	44	3.76	1.79
80	Sandy loam	....	15	4.2	....
3	....do	9.7	14	4.8	2.02
10	....do	12.0	45	6.3	1.91
82	....do	14.5	11	7.8	1.86
4	Fine sandy loam	18.1	36	9.3	1.95
30	....do	18.5	418	9.7	1.91
26	Sandy loam	18.6	64	8.84	2.10
12	Loam	18.9	45	10.4	1.82
86	Clay loam	23.3	9	13.4	1.74
78	Loam	23.8	34	12.7	1.87
5	....do	25.0	13	13.9	1.80
13	Clay loam	27.4	55	14.8	1.85
14	....do	29.3	33	17.1	1.71
6	....do	30.2	16	16.3	1.85
P	Heavy clay soils	31.9	3	16.8	1.89
Q	....do	40.2	2	22.2	1.82
R	....do	43.5	3	23.3	1.86
S	....do	44.9	2	24.2	1.85
T	....do	45.7	3	25.9	1.78
U	....do	48.8	3	25.7	1.90
V	....do	52.4	3	27.4	1.91
W	....do	56.2	3	30.4	1.84
X	....do	57.0	3	30.9	1.84

[55] Op. cit., p. 77.

[56] Op. cit., pp. 60, 68.

Relation of wilting coefficient to mechanical composition of soils.

[From Briggs and Shantz. Mechanical composition and wilting coefficient are given in per cent by weight of the dry soil.]

No.	Type of soil.	Mechanical composition.				Wilting coefficient.
		Coarse sand.	Fine sand.	Silt (0.05 to 0.005 millimeter).	Clay (less than 0.005 millimeter).	
7	Coarse sand	60.4	37.1	0.8	1.6	0.9
2	Fine sand	28.2	64.4	4.7	3.9	2.6
8	.....do	35.4	55.1	4.8	4.5	3.3
9	.....do	29.9	56.7	5.0	8.2	3.6
3	Sandy loam	33.1	50.0	8.6	7.5	4.8
4	Fine sandy loam	2.8	59.8	30.2	6.9	9.7
12	Loam	3.4	55.5	21.8	19.1	10.3
A	Sandy loam	32.4	28.8	26.7	11.8	9.9
B	Fine sandy loam	15.8	42.4	28.7	12.9	10.8
C	.....do	19.2	35.6	30.6	14.7	11.6
5	Loam	2.0	48.8	37.7	12.3	13.9
D	.....do	3.6	35.2	41.4	14.4	15.2
14	Clay loam	5.1	27.0	35.2	32.5	16.2
E	.....do	3.2	43.7	45.1	17.1	16.5
6	.....do	4.4	20.5	52.6	22.0	16.3

The relation between the wilting coefficient and the moisture equivalent for the wide range of soils given in the above table is shown by means of a straight-line curve in figure 30, and the relations between

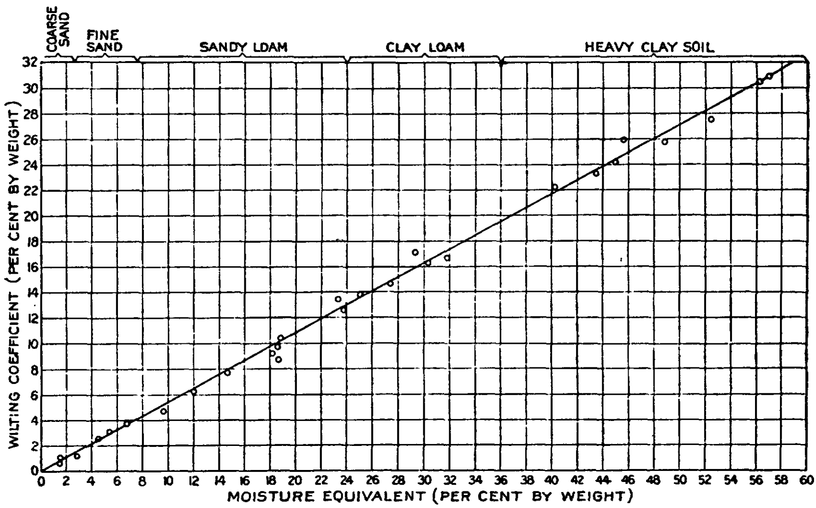


FIGURE 30.—Diagram showing relation between wilting coefficient and moisture equivalent for 28 types of soil ranging in texture from coarse sand to very heavy clay. (After Briggs and Shantz.)

the wilting coefficient and various other properties for a more limited range of soils are shown by similar curves in figure 31. These two figures also show the data on which the curves are based and thus exhibit the degree of accuracy of the curves and equations.

HYGROSCOPIC WATER AND OTHER WATER NOT AVAILABLE FOR GROWTH.

After permanent wilting has taken place the soil still contains some water. This remaining water is so firmly held that it is not only unavailable to wells and springs but also unavailable for the growth of plants. A part of the water that plants are unable to utilize for

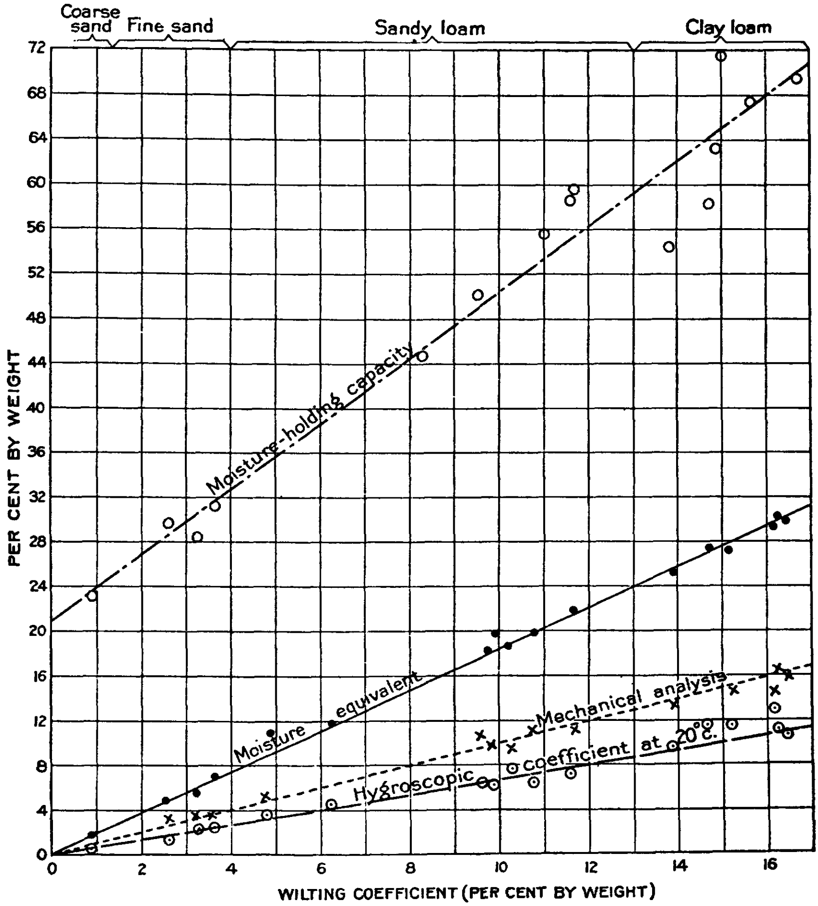


FIGURE 31.—Diagram showing relation between wilting coefficient and certain other properties of soils. The moisture-holding capacity is as defined on page 74 and represents a larger quantity than the true specific retention. The broken line labeled "mechanical analysis" shows the wilting coefficient as calculated from the equation for sand, silt, and clay on page 86. It is given merely to show the degree of accuracy that may be expected from this indirect method of determining the wilting coefficient.

growth can be removed by evaporation, but some water remains in a soil even after it has been fully exposed to evaporation. This last remnant is called hygroscopic water. It is in a sort of equilibrium with the water vapor of the atmosphere, for if a truly dry soil is brought into contact with the atmosphere it absorbs a certain amount of moisture, and this is hygroscopic water.

Briggs and Shantz[57] found that a plant may continue to absorb water from the soil even after permanent wilting has taken place, thereby protracting its life although not being able to grow. In fact, they show that this loss of water from the soil to the air goes on through the plant tissues even after the death of the plant and appears to be limited only by the establishment of a state of equilibrium between the soil and the air. The plant during the dying stage acts simply as a medium for the transfer of water, and, though the rate of loss is reduced, the final result is the same as if the air and soil were in direct contact. As to the functioning of plants during this dying stage, they make the following explanation:

Since growth practically ceases when the plants are in a permanently wilted state, any reduction of the soil moisture below this point constitutes an actual deficit which must be made up before the growth of any plant can be resumed. This deficit may be brought about either by direct evaporation from the soil to the air or by indirect evaporation through the plant when in a wilted or a dying condition. The permanent wilting of the plant does not then mark any limiting condition in the movement of water from the soil through the plant to the air. It is simply a point on the moisture curve corresponding to which the forces opposing the further removal of soil moisture exceed the osmotic force exerted by the cell contents of the plant. Under such conditions transpiration will exceed absorption—that is, a part of the water transpired will be supplied from that stored in the leaf tissues—and loss of turgor will result.

The following statement by Briggs[58] gives a good description of the hygroscopic state:

Most solid substances when exposed to ordinary atmospheric conditions condense upon their surfaces a slight amount of moisture. This moisture adheres with remarkable tenacity and can be completely driven off only by prolonged heating at temperatures above the boiling point of water. In some soils the presence of hygroscopic moisture is very marked on account of the large amount of surface presented by the soil grains. Air-dried samples, in which all visible evidences of moisture have disappeared, still contain under ordinary atmospheric conditions moisture in the hygroscopic form, amounting in some soils to 8 to 10 per cent of the dry weight. * * * [If a soil has been exposed to a saturated atmosphere] it is not improbable that water was condensed in some of the more minute capillary spaces. Lord Kelvin[59] has shown that such a minute capillary surface is capable of condensing moisture even when evaporation is taking place from a neighboring plane surface of water. Some capillary spaces might therefore be able to hold minute quantities of water under conditions which would remove the water from larger spaces. In this way we might have some water held in a soil by capillary action, under conditions which would seem to indicate that the water content must be purely hygroscopic in its nature.

The nature of this thin film which constitutes the hygroscopic moisture is not definitely known. It may extend uniformly over the surface of the grains independently of their form or nature, or it may be discontinuous, occurring only in spots on the surface and depending to some extent on the form and nature of the grain. It would seem justifiable to assume that the amount of moisture thus held is

[57] Op. cit., pp. 8-9.
[58] Briggs, L. J., The mechanics of soil moisture: U. S. Dept. Agr. Bur. Soils Bull. 10, pp. 11-12, 1897.
[59] Maxwell, J. C., Theory of heat, p. 287.

proportional to the surface of the grains, but this conclusion is supported only in a very general way by the results given in the table [on p. 91]. Loughridge remarks, in explanation of this, that the clays may be considered as very complex substances made up not only of particles in a very fine state of division but combined with ferric, aluminic, silicic, and humic hydrates existing in the soil in greatly varied amounts. Even if the presence of these hydrates did not directly influence the hygroscopic water of a soil their decomposition at the high temperature which it is necessary to maintain in order to drive off the hygroscopic moisture would introduce a disturbing factor in the value of the hygroscopic water content. On the other hand, it must be remembered that a mechanical analysis of a soil gives only in a very general way an idea of the surface area of the grains in a soil, and that a soil exposed to a saturated atmosphere is apt to acquire considerable moisture which is not strictly hygroscopic.

The term "hygroscopic coefficient" is used to express quantitatively the capacity of a soil for holding hygroscopic water It is the percentage of water in soil which, in a dry condition, has been brought into a saturated atmosphere and kept in that atmosphere at a constant temperature until it has absorbed all the atmospheric water vapor that it is capable of absorbing.[60] As soon as such a soil is placed in contact with an atmosphere having a lower relative humidity it will lose some of this hygroscopic water by evaporation. The term "hygroscopic coefficient" was introduced by Hilgard in 1874, but he had developed the method for determining this quantity in 1859. The conception of making such determinations, however, originated with Schuber as early as 1830. A good historical review of this subject and a description of Hilgard's method, together with a bibliography, are given by Alway, Kline, and McDole.[61]

The hygroscopic coefficient is regarded as significant in two respects. It provides in a general way an expression of the relative fineness of the material, in this respect having somewhat the same function as the effective size of grain (p. 7). It also provides some measure of the quantity of soil water that is available to plants, or, rather, of the capacity of a soil for holding available water. Thus, the specific retention minus the hygroscopic coefficient gives an approximation of the capacity of a soil for holding available water, although according to Briggs and Shantz this capacity is more nearly expressed by the specific retention minus the wilting coefficient.

The following table, taken from a paper by Loughridge,[62] gives the hygroscopic coefficient of soils of different texture. These values were obtained by exposing the soil in a very thin layer to a satu-

[60] Hilgard, E. W., Report on the geology and agriculture of the State of Mississippi, p. x, 1860; Methods of physical and chemical soil analysis: California Agr. Exper. Sta. Circ. 6, p. 243, 1903. Alway, F. J., and Russel, J. C., Use of the moisture equivalent for the indirect determination of the hygroscopic coefficient: Jour. Agr. Research, vol. 6, p. 833, 1916.

[61] Alway, F. J., Kline, M. A., and McDole, G. R., Some notes on the direct determination of the hygroscopic coefficient: Jour. Agr. Research, vol. 11, pp. 147-166, 1917.

[62] Loughridge, R. H., Investigations in soil physics: California Exper. Sta. Rept. for 1892-93, p. 70 (Copied from Briggs.)

rated atmosphere, kept at a constant temperature, for a period of 24 hours.

Hygroscopic coefficient of soils of different types.

Name and character of soil.	Hygroscopic coefficient (per cent by weight).	Mechanical analysis (per cent).		Chemical analysis (per cent).	
		Clay.	Clay to 0.25 millimeter.	Soluble silicates.	Ferric hydrate.
Sandy soil:					
Sandy soil	0.8	2.8	5.2	....	....
Do	1.2	2.6	8.9	....	....
Gila bottom soil	3.5	3.2	8.7	8.9	7.4
Loam:					
Plains soil	4.9	10.5	34.9	16.5	6.6
Granitic soil	5.9	11.9	32.8	21.0	6.2
Sediment soil	9.2	12.1	55.6	25.1	7.3
Clay:					
Alkali soil	2.6	26.1	54.0	....	....
Alluvial soil	10.3	31.5	76.8	20.7	9.1
Red volcanic soil	11.1	29.8	61.2	34.3	12.0
Red mountain soil	13.7	52.2	67.9	26.9	29.7
Red soil	14.2	24.8	57.1	54.0	9.5
Black adobe	14.5	32.6	74.0	23.3	7.7

The table shows, as has already been suggested, that the hygroscopic coefficient increases with the fineness of grain. It thus varies with the texture in the same manner as the specific retention. This is necessarily true because the hygroscopic coefficient forms a large part of the specific retention, the main force controlling both hygroscopic moisture and other retained water being the molecular attraction of the walls of the interstices. The important fact in this connection, however, is that the water available for growth does not increase to the same extent as the specific retention, because with increasing specific retention there is an increasing amount of unavailable water.

The method of Hilgard for the direct determination of the hygroscopic coefficient involves difficulties in maintaining a constant temperature in the room in which the absorption boxes are placed and in keeping the atmosphere in these boxes in a state of complete saturation. To simplify the determination of this quantity indirect methods were proposed by Briggs and Shantz[63] and have been tested by Alway and others. The following table gives results obtained by Briggs and Shantz on the moisture equivalent (p. 72) and the hygroscopic coefficient of various soils. The same data are shown graphically in figure 32.

[63] Briggs, L. J., and Shantz, H. L., The wilting coefficient for different plants and its indirect determination: U. S. Dept. Agr. Bur. Plant Industry Bull. 230, p. 73. 1912.

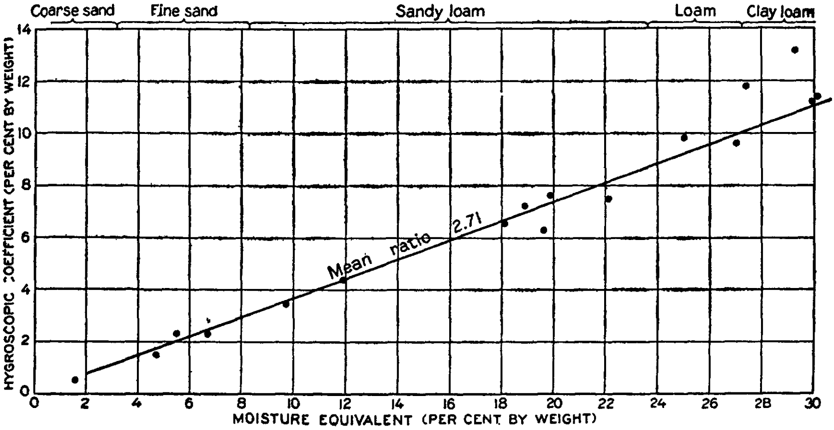


FIGURE 32.—Diagram showing relation between hygroscopic coefficient and moisture equivalent in soils of different textures. (Based on data by Briggs and Shantz.)

Relation of the moisture equivalent to the hygroscopic coefficient shown by data of Briggs and Shantz.[a]

No.	Type of soil.[b]	Moisture equivalent (per cent by weight).	Hygroscopic coefficient (per cent by weight).	Ratio of moisture equivalent to hygroscopic coefficient.	Difference between moisture equivalent and hygroscopic coefficient.
7	Coarse sand	1.6	0.5	3.20	1.1
2	Fine sand	4.7	1.5	3.13	3.2
8	.....do	5.5	2.3	2.39	3.2
9	.....do	6.7	2.3	2.91	4.4
3	Sandy loam	9.7	3.5	2.77	6.2
10	.....do	11.9	4.4	2.70	7.5
4	Fine sandy loam	18.1	6.5	2.78	11.6
12	Loam	18.9	7.8	2.42	11.1
A	Sandy loam	19.6	6.3	3.11	13.3
B	Fine sandy loam	19.9	6.6	3.01	13.3
C	.....do	22.1	7.5	2.94	14.6
5	Loam	25.0	9.8	2.55	15.2
D	.....do	27.0	9.6	2.81	17.4
13	Clay loam	27.4	11.8	2.32	15.6
14	.....do	29.3	13.2	2.22	16.1
E	.....do	30.0	11.2	2.68	18.8
6	.....do	30.2	11.4	2.65	18.8
	Mean[c]			2.71	

[a] Op. cit., pp. 57, 65.
[b] For mechanical analyses of these soils see table on page 87.
[c] Omitting 7 and 2.

On the basis of their experiments these authors[64] derived the following equations, in which the terms "moisture-holding capacity," "sand," "silt," and "clay" have the meanings given on page 74:

Hygroscopic coefficient = wilting coefficient × 0.68
= moisture equivalent × 0.37
= (moisture-holding capacity − 21) × 0.234.
= 0.007 sand + 0.082 silt + 0.39 clay.

[64] Op. cit., p. 73.

After testing these equations with other soils, Alway and Russel[65] came to the following conclusion:

The hygroscopic coefficient may in most cases be calculated from the moisture equivalent with sufficient accuracy to permit its use in soil-moisture studies. For certain types of soil, however, the ratio departs so widely from that assigned by Briggs and Shantz that the indiscriminate use of the latter value does not seem permissible. Before employing this indirect method for the determination of the hygroscopic coefficient in connection with soil-moisture studies the ratio should be experimentally established for each of the particular types of soil involved. The effect of considerable quantities of organic matter is, in general, to give the ratio of the moisture equivalent to the hygroscopic coefficient a higher value.

In figure 33 the same data are used as in figure 28, but they are plotted in such a manner as to show the relation of the difference between moisture equivalent and hygroscopic coefficient to the

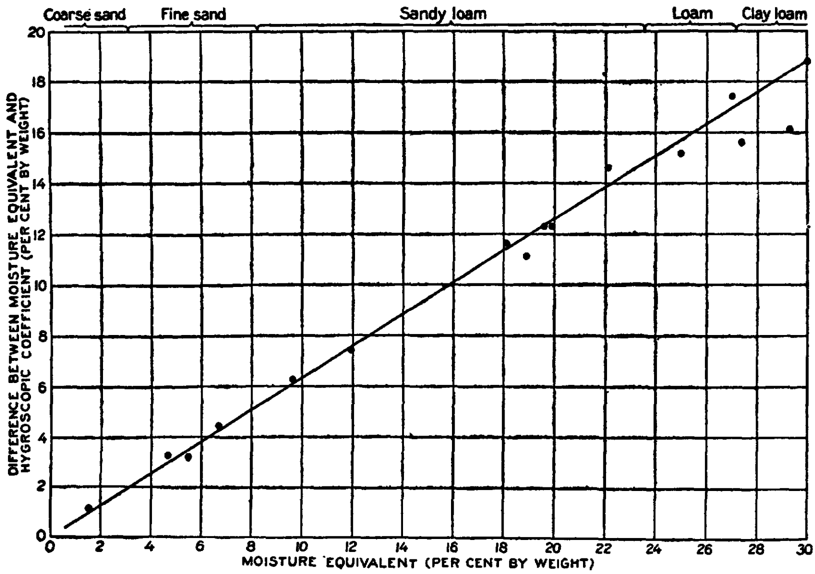


FIGURE 33.—Diagram showing relation of moisture equivalent to difference between moisture equivalent and hygroscopic coefficient in soils of different textures. (Based on data by Briggs and Shantz.)

moisture equivalent and to the texture of the soil. This diagram has significance in furnishing a rough approximation of the capacity of soils of different degrees of fineness to hold water available for growth. To the extent that the moisture equivalent represents the specific retention and the hygroscopic coefficient represents the unavailable water the difference represents the capacity for water available for growth. Although, as has been seen, these assumptions may be far from the truth, they are doubtless accurate enough to permit the general conclusion that, until the fineness of clay loam is

[65] Alway, F. J., and Russel, J. C., Use of the moisture equivalent for the [illegible] the hygroscopic coefficient: Jour. Agr. Research, vol. 6, p. 845, 1916.

reached, the capacity of soils to hold water available for growth increases with fineness of grain. Of course, other factors of practical importance enter into the problem of the water supply of plants, such as the rate at which rain or irrigation water will seep into the soil and the ability of the rootlets to penetrate small interstices.

INTERMEDIATE BELT.

The space between the lower limit of the belt in which water can be withdrawn by evaporation or plant action and the upper limit of the capillary fringe forms an intermediate belt that is thick where the depth to the water table is great but thin where the water table is near the surface—where, indeed, such a belt may be entirely lacking. Both the belt of soil water and the capillary fringe are limited in thickness by definite local conditions. Thus, the belt of soil water is limited by both the character of the vegetation and the texture of the rock or soil, and the capillary fringe is limited by the texture of the rock or soil. The intermediate belt, however, is not thus limited. It is the residual part of the zone of aeration.

When in any locality more water seeps into the earth than can be retained by the belt of soil water the surplus is drawn down by gravity to deeper levels, and some of it may reach the water table and be added to the supply of ground water. A part of the water, however, is likely to be held in the intermediate zone by molecular attraction. According to the laws of capillarity, as shown in figure 34, water that enters this belt is likely to be drawn into the smallest openings and held there secure from being pulled downward by the force of gravity. It is theoretically improbable that water which is at a considerable depth below the level reached by roots can be drawn up within their reach, even in periods of intense drought, although some writers have held the belief that water is drawn up by some sort of capillary action from indefinite depths. (See references on pp. 34, 35.) As water can probably not be drawn back to the surface from the intermediate belt it would seem that all parts of this belt through which descending waters percolate would eventually become filled with water to the limit of their water-retaining capacity.

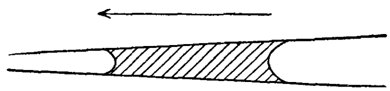


FIGURE 34.—Diagram of a funnel-shaped capillary tube, showing direction of resultant capillary attraction.

As the water retained in the intermediate belt is not available either to supply wells and springs or for plant growth it is of no value to either well drillers or farmers, and it has consequently received very little attention from hydrologists or students of agriculture. Where water is used in drilling operations there is no opportunity to observe the water content of this intermediate belt. Some general observations have been made in digging or boring rather deep wells and in sinking shafts for other purposes where water is not used in the excavating process, and more specific tests could easily be made of samples taken from such excavations.

In regard to rocks excavated above the water table for the manufacture of cement, Eckel[66] states that the water content of hard limestones usually ranges from one-half of 1 per cent to 3 per cent, by weight, but rarely exceeds 3 per cent; that of chalky limestones may be 5 per cent, except in prolonged wet weather, when it may be as high as 20 per cent. He states further that the water content of clays may range from about 1 per cent in clays that have been air dried to 30 per cent in fresh clays, and that the water content of shales is rarely more than 10 per cent. All these values are stated in per cent by weight of the dry material. The fact seems to be that the materials of the intermediate belt are generally somewhat moist but do not contain as much water as they are capable of holding by molecular attraction.

RELATION OF BELT OF SOIL WATER TO ZONE OF SATURATION.

Where the water table is so near the surface that certain kinds of plants can send their roots down to the capillary fringe these plants absorb and utilize its water (fig. 29, p. 82). As soon as some of the fringe water is removed water from the zone of saturation is drawn up by capillary action to take its place. Thus there may be a continuous process by which plants are supplied with water from the zone of saturation, and great quantities of ground water are discharged into the atmosphere. Certain species of plants habitually send their roots to the capillary fringe and feed on ground water.[67] For plants of this kind the writer has proposed the name "phreatophyte,"[68] which is taken from Greek roots meaning a "well plant." A phreatophyte is a plant which, like a well, taps the ground-water supply. These plants are much more conspicuous and more distinct from other plants in arid regions, where water supplies are scarce, than in humid regions, where the soil, even far above the water table, generally contains considerable available water. Some of the most common phreatophytes of the arid regions of the western United States are salt grass (*Distichlis spicata*), big greasewood (*Sarcobatus vermiculatus*), a certain type of mesquite (*Prosopis*), buffalo-berry bush (*Shepherdia*), rabbit brush (*Chrysothamnus graveolens*), yerba mansa (*Anemopsis californica*), samphire (*Spirostachys occidentalis*), giant

[66] Eckel, E. C., Portland-cement manufacture: U. S. Geol. Survey Water-Supply Paper 93, pp. 291-292, 1904.

[67] Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring valleys, Nev.: U. S. Geol. Survey Water-Supply Paper 423, pp. 95-100, 1917.

[68] Meinzer, O. E., Quantitative methods of estimating ground-water supplies: Geol. Soc. America Bull., vol. 31, p. 333, 1920.

reed grass (*Phragmites communis*), giant rye grass (*Elymus condensatus*), and alkaline sacaton (*Sporobolus airoides*). Among trees that live largely on ground water in the arid regions are birch, willow, cottonwood, sycamore, and some kinds of palms. The wild rose in arid regions also depends largely on ground water. Most of these plants will also thrive under other conditions of ample water supply, as in irrigated tracts, but many of them have adaptations for reaching ground water, and where conditions have not been modified by man they are almost invariably associated with ground water.

Where the water table lies at a very shallow depth the ground water is lifted by capillarity so near the surface that evaporation takes place from the soil and ground water is discharged into the atmosphere without the agency of plants. Where the zone of aeration is very thin plants must either extend their roots into the zone of saturation or confine their activities to a very narrow belt (fig. 29, p. 82). Only certain kinds of plants can thrive under such conditions. Where the zone of saturation reaches the surface ground water seeps out and forms streams or ponds.

SUBSURFACE ICE.

In extensive Arctic and sub-Arctic regions the water in the interstices of the soil and rocks is frozen to great depths and in summer thaws to a depth of only a few feet. Numerous bodies of clear ice of various sizes and shapes also occur within this zone of frozen ground.[69] The following statements in regard to the distribution and depth of frozen ground in Alaska are made by Brooks:[70]

> The wide distribution of ground frost is even more typical of this subpolar region than is the dearth of erosion. In numerous excavations made in placer mining the ground is permanently frozen to great depths, beginning 18 inches or 2 feet below the surface, and the alluvium is frozen down to hard rock. In the Klondike the alluvium is frozen to a depth of about 200 feet. At Fairbanks permanent ground frost has been found at many places to a depth of more than 200 feet and the deepest shaft sunk there penetrated 318 feet of frozen alluvium. In Seward Peninsula many holes in permanently frozen alluvium are more than 75 feet deep, and one is nearly 200 feet deep. These shafts are all in flood plains, but at many places on north-facing hill slopes ground ice can be found within a foot or two of the surface. Some ground in the province is not frozen, for causes not determined. Underground channels of water have been encountered in some mine workings and have played havoc with the operations, but these appear to be exceptional.

In 1828 a shaft was sunk by a man named Schergin at Yakutsk, Siberia, in latitude 62°, into frozen ground to a depth of about 100 feet, in an unsuccessful attempt to find a water supply for the village. Later excavation was resumed with the purpose of determin-

---

[69] Leffingwell, E. de K., The Canning River region, northern Alaska: U. S. Geol. Survey Prof. Paper 109, p. 179, 1919.

[70] Waring, G. A., Mineral springs of Alaska: U. S. Geol. Survey Water-Supply Paper 418, p. 9 (preface by A. H. Brooks), 1917.

ing the depth of frost. The hole was carried to a depth of 384 feet, where it was still in frozen ground. In 1844 to 1846 a series of observations was made in this shaft by A. T. von Middendorff, on the temperature of the frozen ground at different depths. The details of the methods used and the results obtained are described and discussed by Leffingwell,[71] who plotted the temperatures as shown in figure 35.

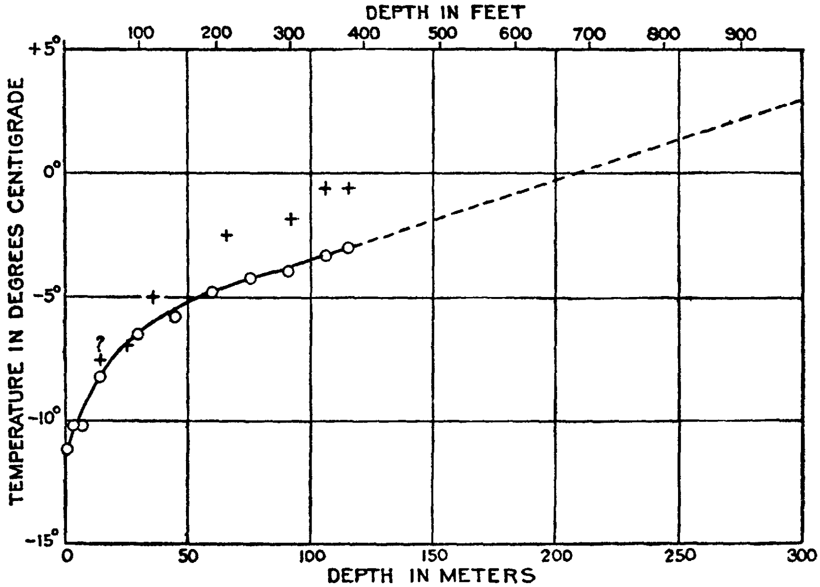


FIGURE 35.—Curve showing variation of temperature with depth in the 384-foot shaft at Yakutsk, Siberia. (After Leffingwell.) The continuous line is drawn through temperatures observed by Middendorff; the broken line is a prolongation of the curve below the shaft. Circles show temperatures according to Middendorff; crosses show temperatures according to Schergin.

Leffingwell[72] comments on Middendorff's results as follows:

The curve [fig. 35] shows that the temperatures change rapidly at first and then much more slowly. The first 50 feet and the last 200 have nearly constant gradients of 4.4 and 30.8 meters, respectively, per degree centigrade. Between these two straight portions of the curve the gradient changes from depth to depth in an orderly manner. As the ground is frozen, the circulation of ground water can not be the cause of the difference in gradient in the two portions. The diffusivity of the ground can hardly vary greatly enough to cause the observed effect. Any variations of the diffusivity due to the presence of different kinds of rocks ought to produce angular variations in the curve. The possible cooling of the upper portion of the shaft by penetration of the outer air can hardly amount to more than the half degree observed by Middendorff, but the curve indicates a lowering of about 5° C. for the temperature of the surface ground. The most favorable hypothesis seems to be that the mean temperature of the air has been lowered about 5° C. in comparatively recent times.

---

[71] Op. cit., pp. 184–194. Includes reference to publication by Middendorff.
[72] Op. cit., pp. 185–187

Erman states that the mean annual temperature of the air at Yakutsk was −7.4° C. in 1827, and Middendorff gives −12.2° C. for 1845. A lowering of the temperature of about this amount was deduced from the shape of Middendorff's curve, but as the cooling of the shaft may have disturbed the original distribution of ground temperature, all the deductions from it are thrown into doubt.

If the curve from 7 to 50 feet is prolonged, it will reach the freezing point, 0° C., at about 170 feet; the curve from 200 to 382 will reach it at about 680 feet. If the excavation had stopped at 50 feet, there would have been every reason for expecting to reach the frost limit at less than 200 feet. The gradient is so constant for the lower 180 feet of the shaft that we should be justified in placing the limit of frost at about 680 feet. Middendorff's calculations place it at 612 feet, with 670 feet as a maximum. Dr. Peter assumes that the gradient becomes progressively lower and calculates that 1,000 feet is the depth of frost.

Leffingwell considers that the weight of the overlying ground will depress the freezing point somewhat and concludes, on the basis of Middendorff's observations, that the lower limit of frozen ground in that locality is at a depth of about 650 feet. He then discusses the observations made by Schergin at the time the shaft was sunk (see fig. 35), which are considerably different from those of Middendorff and would lead to the conclusion that the bottom of the frozen ground is only about 400 feet below the surface.

As to the cause of the deep freezing Leffingwell[73] makes the following statement:

Three hypotheses have been suggested as to the origin of the deep freezing of the ground in the Arctic regions. Russell[74] came to the conclusion that deposition and freezing went on at the same time, so that the present thickness of the frozen layer is the result of successive additions of frozen material. Brooks[75] has suggested that the frozen ground of the Yukon Valley is the result of a colder Pleistocene climate, and that at present the ground is thawing. The third and usual hypothesis is that the ground has been frozen to the present depth under temperatures which now prevail.

In regard to the evidences that the frozen ground is due to a colder climate in the past, Brooks[76] says:

When the moss is stripped the ground thaws, and with open-cut mining or cultivation the upper level of permanent ground frost seems gradually to descend. It therefore appears that this ground frost is a survival of a climate colder than the present and is preserved by the nonconducting mat of moss and other vegetation. It is natural to attribute it to the climatic conditions that brought about the last glacial advance in Alaska, during which but little of the central region was ice covered, though glaciers advanced into it from the higher mountains on the north and south.

In general, the deep frost consists of water in the ordinary interstices of the soil or rock which has been frozen. Many bodies of ice of considerable extent, however, occur in the frozen zone, resulting

[73] Op. cit., p. 187.
[74] Russell, I. C., Surface geology of Alaska: Geol. Soc. America Bull., vol. 1, pp. 129–130, 1889.
[75] Brooks, A. H., communication. See also Antimony deposits of Alaska: U. S. Geol. Survey Bull. 649, p. 27, 1916.
[76] Op. cit., pp. 9–10.

either from the freezing of water in openings in the rocks or from the burial of surface ice. Leffingwell treated this subject at length and included in his paper a valuable bibliography and digest of the literature on the subject. On the basis of his own extensive observations on the north coast of Alaska, he describes in detail the vertical wedges of ice which, according to his investigations, have grown in place. He classifies as follows the different kinds of ice bodies that occur beneath the surface in the frozen zone:[77]

Careful examination has revealed the existence of the following kinds of ground ice: (1) Grains of clear ice, the largest an inch in diameter, mixed with earth; (2) thin undulating sheets or ribbons of ice alternating with thin beds of earth; (3) heavy horizontal beds of clear ice; (4) heavy beds of ice alternating with beds of earth; (5) heavy deposits of ice with isolated earth inclusions; (6) a network of vertical wedges of ice surrounding polygonal bodies of earth.

The first two kinds are of minor importance, and no satisfactory explanation of their origin has been given. The third kind is met with chiefly upon flood plains of rivers and is best explained as resulting from the burial of the ice on flood plains by spring floods. The fourth kind is not common. It may represent a building up of the surface of the ground by successive deposits of ice like the third kind. No satisfactory explanation has been given for the fifth kind of ice, the New Siberian type. The writer thinks that the wedge theory may furnish the best explanation. The sixth kind of ice is of widespread occurrence upon the coast of Arctic Alaska; it probably exists also in Spitzbergen and Siberia.

WATER IN SOLID SOLUTION AND IN CHEMICAL COMBINATION.

In the preceding pages attention has been confined to the interstitial water—that is, the water which occurs in the interstices of the rocks. This includes the water imprisoned in inclusions, such as are abundant in quartz—some of them so small that they can be seen only with the aid of a microscope. It includes theoretically the water that is firmly held by adhesion in the minute subcapillary pores. It also includes most of the hygroscopic water, as is indicated by the fact that the hygroscopic coefficient varies approximately as the aggregate wall space of the interstices. However, water occurs in rocks in still more intimate relation to the mineral matter.

The most intimate relation is that of a chemical combination, in which the water loses its identity as water and becomes a part of the substance of another mineral but is readily reconverted into water by application of heat to the mineral. According to chemical theory, the molecules of water (H_2O) become parts of more complex molecules. Thus, the formula for a molecule of gypsum is considered to be $CaSO_4+2H_2O$, the two molecules of water ($2H_2O$) being not water at all but parts of the gypsum molecule. The gypsum ($CaSO_4+2H_2O$) is a different mineral from anhydrite ($CaSO_4$) and has distinctly different optical properties. When the gypsum is heated, this chemi-

[77] Op. cit., pp. 241-242.

cally combined water, which is called water of crystallization, is given off as ordinary water. Many minerals contain water of crystallization. (See any textbook on mineralogy.)

The concept of water in solid solution is a product of the modern science of physical chemistry.[78] In this state the molecules of water are regarded as retaining their identity but as being separated from one another and distributed through the intermolecular spaces of certain minerals. A mineral containing water in solid solution is a homogeneous substance just as one containing water in chemical combination is, but the water in solid solution may be contained in varying proportions up to a certain limit, whereas water in chemical combination occurs in a fixed proportion to the mineral. The characteristics and importance of water in solid solutions are indicated by the following summary statement of results obtained by Allen and Clement:[79]

> A study of five different specimens of natural tremolite, two of them of exceptional purity, proves that all contain water ranging from 1.7 to 2.5 per cent. This water is lost gradually with rising temperatures without any loss in homogeneity and with very slight change in the optical properties. The water is therefore not chemically combined, although the mineral in the powdered state is not completely dehydrated under 900° centigrade. It is to be regarded as dissolved water, and tremolite as a solid solution. A diopside from a metamorphosed limestone contained 1 per cent of water and behaved in practically the same way, though presumably the diopside of eruptive rocks is anhydrous. The amphibole kupfferite and a specimen of beryl contained, respectively, 3.8 per cent and 2.5 per cent of water, which they lost very slowly at comparatively high temperatures (400°–800° centigrade) and still retained their homogeneity. * * * All these minerals show important points of resemblance to the zeolites, with which they may broadly be classed. * * * Recent analyses indicate that all the amphiboles contain water. Actinolite, glaucophane, and pargasite contain 1.3 to 3 per cent, mostly retained above 100° centigrade. The hornblendes also contain water, though usually in smaller quantity. These facts, taken in connection with the above work on tremolite and kupfferite, lead to the suspicion that the amphiboles generally contain dissolved water as a characteristic constituent and are solid solutions.

Natural glasses, such as obsidian and pitchstone, also contain considerable quantities of water, apparently not in minute cavities in the glass but in a sort of molecular mixture. Various mixtures of glass and water have been artificially produced. The water in this state is not interstitial water nor water of crystallization. Moreover, it does not have the same relation to the mineral matter as water that is in solid solution in crystallized minerals.

The foregoing statements show that in addition to the water that occurs in the interstices of the rocks, very large quantities in the aggregate occur in solid solutions and molecular mixtures and as water of crystallization.

---

[78] Findlay, Alex., The phase rule and its application (Textbooks of physical chemistry), London, Longmans, Green & Co., 1917.

[79] Allen, E. T., and Clement, J. K., The rôle of water in tremolite and certain other minerals: Am. Jour Sci., 4th ser., vol. 26, pp. 101-118, 1908.

INTERNAL WATER.

Deep down in the earth, in what Van Hise has called the zone of rock flowage (p. 40), interstices are presumably absent, and there is therefore no room for water to exist in its ordinary condition, but some evidence that water is derived from the zone of rock flowage is afforded by volcanoes, hot springs, and the structure and composition of intrusive rocks. Rock magmas, or masses of molten rock, are believed to be solutions in which the constituent minerals are dissolved in one another. Water is believed to be a common constituent of these solutions in either a molecular or a dissociated condition. Water is yielded by volcanoes in great quantities, and there is not much question that this water is derived from the ejected lavas. If water in some miscible condition forms a constituent part of the material of the interior of the earth the total quantity of such internal water may be very large, and this water may be making substantial contributions to the water supply of the exterior. This difficult subject will be more fully discussed in another paper, now in preparation, on the origin, discharge, and quantity of ground water.

SUMMARY.

The occurrence of water below the surface of the earth is briefly summarized in the following classification:

I. Interstitial water:
- A. Suspended subsurface water (vadose water)·
  - 1. Soil water:
    - (*a*) Water available for growth.
    - (*b*) Water not available for growth.
      - Water that can be removed by evaporation.
      - Water that can not be removed by evaporation (hygroscopic water).
  - 2. Intermediate vadose water.
  - 3. Fringe water.
- B. Ground water (phreatic water):
  - 1. Gravity ground water.
  - 2. Ground water not under the control of gravity.
- C. Subsurface ice (interstitial ice).

II. Water in the mineral matter forming solid rocks (water in solid solution, water of crystallization, etc.).

III. Internal water (and magmatic water above the zone of rock flowage).

Chapter II. KINDS OF ROCKS AND THEIR WATER-BEARING PROPERTIES.

ORIGIN AND CLASSIFICATION OF ROCKS.

PRINCIPAL CLASSES AND THEIR ORIGIN.

The materials penetrated in sinking wells consist in part of incoherent materials, such as clay, sand, and gravel, and in part of consolidated rocks, such as granite, limestone, and sandstone. For convenience the geologist calls all these materials, "rocks," whether they are firm and hard, like granite, or loose and soft, like sand.

At considerable depths the rocks are generally consolidated and hence relatively difficult to penetrate in sinking wells. Commonly they are broken by a few fractures or joints, such as can be seen in rock quarries, but are otherwise coherent and firm. Near the surface the rocks become broken and decomposed by various mechanical and chemical processes, collectively called "weathering," which are described in all textbooks on geology. In some places the weathering processes extend so deep that for many feet below the surface there are thoroughly soft and incoherent materials derived from the decomposition of hard rocks. Thus, in certain localities crystalline rocks, such as gneiss, remain so completely in place that they preserve almost every detail of their structure and yet are so thoroughly rotted that even many feet below the surface they can be excavated like loose sand.

However, the loose materials near the surface are so easily washed away by the surface water, blown away by the wind, or, in cold regions, carried away by glacial ice that the hard rocks have in many places been stripped of their mantle of weathered débris and exposed at the surface. On the other hand, the transporting agencies—water, wind, ice, etc.—have laid down their loads in certain areas, thus producing deposits of gravel, sand, clay, and other fragmental materials to depths that may reach hundreds or even thousands of feet. Consequently, as every well driller knows, there is great irregularity in the amount of loose material that must be penetrated before hard rock, often called "bedrock," is reached. In certain places materials violently ejected from volcanoes have solidified in fragments and have also been deposited at the surface as loose, incoherent materials.

In the course of time loose materials at considerable depths generally become more or less consolidated, partly through the compacting caused by the weight of the overlying sediments, partly through cementation of the fragments to one another with mineral matter precipitated out of solution by percolating waters, and partly through other processes, such as chemical changes and recrystallization resulting from heat and pressure.

It is evident from the foregoing discussion that the rocks of the earth can be divided into two large classes—the consolidated rocks, or bedrocks, and the unconsolidated materials. It is also evident that these two classes grade into each other because of the indefinite depths to which the weathering processes extend and at which the consolidating processes begin, also because of the very slow operation of most of these processes.

With respect to their origin, the rocks can be divided into three great classes—(1) igneous rocks, which are produced by the cooling and solidification of molten materials; (2) sedimentary rocks, which are produced by the deposition of materials weathered from older rocks, derived from the remains of animals and plants, or precipitated out of solution in water; and (3) metamorphic rocks, which are produced by the profound alteration of other rocks, chiefly through the agencies of heat and pressure. Sedimentary rocks may be derived from the decay or disintegration of igneous, metamorphic, or sedimentary rocks; metamorphic rocks may be derived from either igneous or sedimentary rocks. There is a sharp distinction between igneous and sedimentary rocks, except for the fragmental materials produced by volcanic eruptions, such as volcanic ash and cinders, which may be handled more or less by water and wind before they are deposited. These deposits of volcanic sediments grade into lava beds, on the one hand, and into true sedimentary beds on the other. There is no sharp distinction between metamorphic rocks and the sedimentary and igneous rocks from which they are derived, generally by slow and gradual processes.

The differences in character of these three classes of rocks, due to differences in origin, are of great and fundamental importance in the occurrence of ground water. Pronounced differences in texture and structure, and hence in water-bearing qualities, are produced by the three radically different modes of origin.

IGNEOUS ROCKS.

Igneous rocks are produced by the cooling and solidification of molten material derived from great depths below the surface, where the earth is very hot. Molten material rises through fissures or other weak parts of the solid rocks, and some of it reaches the surface in volcanic eruptions. That which solidified without reaching the surface is called "intrusive rock"; that which crystallized in large bodies at considerable depth is called "plutonic rock"; that which solidified after being ejected from some volcanic vent is called "extrusive rock" or "volcanic rock."

Igneous rocks differ widely in texture, and some of these differences have an important influence on their water-bearing properties. Coarse-grained igneous rocks, such as granite, which consists of crystals that can readily be seen without a magnifying glass, are said to have a granitic texture; fine-grained igneous rocks are said to have a stony or felsitic texture; fine-grained igneous rocks with embedded large crystals are said to have a porphyritic texture; and igneous rocks that consist of natural glass or slag are said to have a glassy texture. These differences are due chiefly to differences in mode of origin and to some extent to differences in composition. Molten material that cools very slowly forms large crystals, and that which cools rapidly forms minute crystals or glassy rock that is not crystalline. Molten material that remains deeply buried in large masses solidifies very slowly, whereas that which is brought to the surface cools and solidifies rapidly. Hence, an igneous rock with granitic texture can confidently be classed as an intrusive or plutonic rock, and one with glassy texture as an extrusive or volcanic rock or a rock from a small intrusion. There is, however, no sharp distinction in texture between intrusive and extrusive rocks, for molten material deep within a thick lava flow may cool as slowly as some that has been intruded into small cracks where it is surrounded by cold rocks.

A lava flow, especially in its upper parts, is likely to contain numerous large openings of sorts not found in intrusive rocks. It may be vesicular—that is, full of holes caused by the escape of gases from the material as it cooled; it may contain caverns and tunnels formed by molten lava flowing out from beneath a solidified crust, or by related processes; and it may be traversed by large joints produced by shrinkage during rapid cooling. Volcanic material that is violently expelled may solidify in fragments that range from fine dust to large boulders. Deposits of such fragmental material may form beds of tuff or agglomerate that are very porous.

Igneous rocks are composed of many different kinds of minerals, which can easily be seen in rocks of granitic texture but can be discerned only with a microscope, if at all, in fine-grained rocks. They are described in textbooks on geology and mineralogy. These minerals are important in relation to ground water in several ways: they affect the chemical composition of the water; in the fine-grained and glassy rocks they have an important relation to the water-bearing properties of the rocks; and in the coarse-grained rocks they largely determine the kinds of materials that are produced when the rocks weather, and hence the water-bearing properties of the sedimentary deposits derived from them.

The principal minerals found in fresh igneous rocks are quartz, feldspar, mica, hornblende, pyroxene, and olivine.

Quartz, which forms the glassy-appearing grains in granite, is a crystalline form of silica. It is hard and strong, so that it is not easily broken or worn; it is also chemically very stable and therefore is not decomposed when the rest of the rock weathers, and it is not dissolved by percolating waters except to a very small extent. When all the other minerals of a granitic rock are broken down to form clay or other fine material, the grains of quartz persist. Hence it is, for the most part, the grains of quartz that form the deposits of sand and sandstone, whereas the decomposed residuum of the other minerals forms the deposits of clay.

There are several kinds of feldspar. This mineral forms light-colored crystals which are conspicuous in granite and commonly give it a pink or light-gray appearance. Feldspar constitutes more than one-half of the substance of an average igneous rock.

Mica is characterized by remarkably perfect cleavage, as a result of which it can easily be split into very thin flexible plates. There are several kinds of mica, but the most common are muscovite and biotite. Muscovite is a white, nearly transparent mica which affords the isinglass that is used in stove windows. Biotite is a dark mica that chemically belongs to the ferromagnesian group of minerals. Mica can readily be recognized by its flaky appearance. Like feldspar and ferromagnesian minerals, it produces a residuum of clay when it is thoroughly decomposed. However, it breaks down very slowly and consequently is found in undecomposed remnants in many deposits of clay and sand, giving them a silvery appearance and making them especially slippery. The slippery, incoherent character of the quicksands that cause well drillers so much trouble is often due in part to the presence of particles of mica.

Hornblende, pyroxene, olivine, and other ferromagnesian minerals are generally black or dark green and are most abundant in the dark varieties of rocks, whether of coarse-grained, fine-grained, or glassy texture.

On the basis of their composition igneous rocks may be divided into three very indefinite classes according to their contents of silica. These classes have commonly been called "acidic," "basic," and "intermediate," but the terms "acidic" and "basic" are misleading because they do not have the same meaning as in chemistry. Instead the names "persilicic," "mediosilicic," and "subsilicic" have been suggested by Clarke.[1] The acidic or persilicic rocks are rich in quartz, certain kinds of feldspar, and mica; the basic or subsilicic rocks are rich in ferromagnesian minerals and in other kinds of feldspar. The

[1] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 420-421, 1920.

persilicic rocks are generally relatively light in color, whereas the subsilicic rocks are dark. Under ordinary circumstances the lavas of the persilicic rocks are likely to be more viscous and to solidify more readily than those of the subsilicic rocks. Hence when persilicic lavas are erupted they are often piled up to form high, steep volcanic peaks, whereas the subsilicic lavas often flow out over the surface for many miles, producing extensive sheets of lava rock, which usually contains numerous caverns and joints. Hence also the persilicic lavas are likely to be erupted with explosive violence, producing much fragmental material, whereas the subsilicic lavas flow out of their vents more quietly and with the production of less cinders, ashes, and dust. There are, however, important exceptions to these generalizations, for rhyolite, which is a fine-grained persilicic rock, may occur in series of thin and very persistent beds. The most common subsilicic extrusive rock is basalt, which covers large parts of the northwestern United States and nearly all of the Hawaiian Islands and is an important water bearer.

In summary, it may be said that igneous rocks can be divided in three ways—according to origin, into plutonic, intrusive, and extrusive; according to texture, into granitic, porphyritic, felsitic, and glassy; and according to composition, into persilicic, mediosilicic, and subsilicic. It will be seen that each of these classifications has some significance with respect to the occurrence of ground water.

SEDIMENTARY ROCKS.

The sedimentary rocks may be grouped according to origin into three classes—clastic deposits, organic deposits, and chemical deposits. The clastic deposits are composed of fragments derived from the weathering and erosion of older rocks. They include beds of gravel, sand, silt, and clay and various mixtures of these materials, also the rocks produced by the consolidation of such materials. The organic deposits include chiefly the calcareous and siliceous remains of animals, such as shells and the skeletons of corals and sponges, and the carbonaceous remains of plants. The calcareous materials form limestone, chalk, marl, and related rocks; the carbonaceous materials form peat, coal, and related materials. The chemical deposits consist of substances precipitated out of solution in water. They include deposits of silica, such as flint, some kinds of chert, vein quartz, and siliceous sinter; ferruginous deposits, such as some kinds of iron ore; calcareous deposits, such as caliche and travertine; gypsum; and common salt and other very soluble alkali salts.

The clastic deposits may be subdivided with respect to the kinds of materials which they contain, the agencies and processes involved in their production, and the degree of consolidation they have undergone since they were laid down.

The boulders and pebbles of gravel beds are more or less rounded by having been tumbled about by the water prior to their deposition. They consist of various kinds of rock, but most of them are made of some hard and durable rock, for boulders or pebbles of soft material are soon worn and broken into small fragments, and those made of unstable minerals will in relatively short time decay and fall apart. Rocks composed of silica, such as flint, chert, vein quartz, and quartzite, though not in themselves of much consequence as water bearers, are very important in supplying the most durable material for the production of gravel, which is the best of all water-bearing materials. Pebbles of limestone are rather stable but may dissolve and be worn away; those of granite or other igneous rock ultimately decay and fall to pieces, and those of softer material disappear still more rapidly; but the pebbles of flint, chert, and other siliceous materials do not decay, are nearly insoluble, are very resistant to wear, and therefore constitute a very large proportion of the material of gravel beds. The glacial gravels of the United States also contain much material derived from hard limestone.

Sand may also consist of fragments of various materials, but even more largely than gravel it is composed of fragments of silica. The great majority of the grains of sand doubtless came originally from quartz crystals weathered out of granitic rocks and later more or less rounded by wear. Coarse sand is probably derived largely from the quartz crystals of coarse-grained igneous rock and fine sand or silt from igneous rocks of finer grain.

Pure clay consists of such impalpably small particles that it feels smooth and slippery when moist. It is derived from the thorough decay of feldspar and other minerals of igneous rocks. However, much of the material commonly called clay is finely ground rock flour or not wholly decomposed mineral matter, and it generally contains large amounts of coarser material. "Loam" and "adobe" are other names for clayey mixtures.

The fragmental materials that form the clastic rocks have been transported and deposited chiefly by surface water, wind, and glacial ice. The work of the water is by far the most important. It may be accomplished wherever water is in motion, whether in streams or in waves and currents of lakes or ocean. Both water and wind tend to assort the débris which they handle—a process which is of very great importance in the development of water-bearing formations. Thus, a stream with a certain current may separate the clay and sand from the gravel by carrying away the clay and sand but leaving the gravel in the bed of the stream. Farther on its current may slacken somewhat so that it will drop the sand but will still continue to carry its load of clay. Glacial ice has none of this assorting power. It carries fragments of all sizes and deposits them together in a mixture, except as the fragments are assorted by the waters that issue from the ice.

The materials resulting from the assortment of rock débris are gravel, sand, silt, and clay. The more nearly complete the assorting process has been the more nearly uniform in size are the constituent grains or pebbles. Because a well-assorted gravel or sand does not contain much fine material it is said to be a clean gravel or sand. Two important types of unassorted or poorly assorted clastic materials are (1) till, or boulder clay, which is laid down by glacial ice, and (2) the type of alluvium formed under very changeable conditions, especially on the alluvial fans close to mountains in arid regions.

Clastic deposits of every type may occur in any stage of consolidation, from those whose individual fragments are wholly free from one another and rest only lightly upon one another to those whose original fragments have become so firmly attached to one another that they rank among the hardest and strongest of all rocks. Thus, by imperceptible differences, gravel grades into conglomerate, and conglomerate may grade into quartzite; likewise, sand grades into sandstone, and sandstone into quartzite; or clay grades into shale, and shale into slate. The unassorted clastic deposits also exist in various stages of consolidation and are called by various names such as "sandy shale" or "shaly sandstone." Consolidated unassorted materials that contain pebbles or boulders are called "conglomerate." Degree of consolidation, like degree of assortment, is a very important factor with respect to the occurrence of ground water.

METAMORPHIC ROCKS.

The principal metamorphic rocks are quartzite, slate, marble, schist, and gneiss, each of which occurs in numerous varieties.

Quartzite is a nearly solid mass of quartz, commonly produced by very thorough cementation of quartzose sandstone or conglomerate. It is the hardest and most durable of all common rocks but is generally broken to some extent by joints.

Slate is derived from shale or related clayey materials by pressure and other metamorphic processes. It has a well-marked cleavage, so that it splits readily into thin layers. This cleavage is produced by pressure and shearing, and the cleavage planes are not the same as the bedding planes of the clay or shale from which the slate was derived and may not be parallel to them. Slate is much harder than shale and weathers less readily, but it is not nearly so hard or so durable as quartzite and some of the other indurated rocks. In addition to its cleavage it is likely to be broken by joints.

Marble is produced by the induration and crystallization of limestone. It is a dense rock, but, like limestone, it can be slowly dissolved by water percolating through its joints or other openings.

Schist is produced by the profound alteration of shale, slate, or other rock, largely through intense pressure and deformation. It has an irregular foliated structure known as schistosity, which is due largely to the development of flakes of mica parallel to the planes of shearing. This gives the rock a silvery appearance.

Gneiss is a banded granular rock, and except for its banded structure it resembles crystalline igneous rock. Much of it is derived from and grades into granite and other crystalline igneous rocks, but some is derived from sedimentary or other rocks.

INTERSTICES OF ROCKS.

CLASSIFICATION OF INTERSTICES.

The interstices or open spaces in rocks are the product of the processes which, through the long ages of geologic time, have been at work on the materials of the earth, forming and altering the rocks. Through many processes, working in different ways on rock materials of various kinds, interstices have been produced that differ greatly in size, shape, and relation to one another. Thus, some knowledge of the origin and subsequent history of rocks is essential to an understanding of their interstices, just as a knowledge of their interstices is essential to an understanding of their characteristics as sources of water.

The interstices of rocks can be divided into two classes—original and secondary. The original interstices were created when the rock came into existence as a result of the processes by which it was formed; the secondary interstices were developed by processes that affected the rock after it had been formed. The original interstices can be subdivided into two groups—those of sedimentary origin and those of igneous origin. The secondary interstices comprise joints and other fracture openings, solution openings, and openings produced by several processes of minor importance, such as the work of plants and animals, mechanical erosion, and recrystallization. The most important interstices with respect to ground-water supplies are the original sedimentary interstices; next to them are the fracture and solution openings.

The following table outlines the principal groups of interstices, as given in the previous paragraph. A more detailed classification of interstices has been made by Fuller.[2]

Types of interstices.

1. Original interstices:
   (a) Sedimentary interstices.
   (b) Igneous interstices.
2. Secondary interstices:
   (a) Joints and other fracture openings.
   (b) Solution openings.
   (c) Openings of minor importance, such as those produced by the work of plants and animals, mechanical erosion, and recrystallization.

[2] Fuller, M. L., Summary of the controlling factors of artesian flows: U. S. Geol. Survey Bull. 319, pp. 8-15, 1908.

ORIGINAL SEDIMENTARY INTERSTICES.

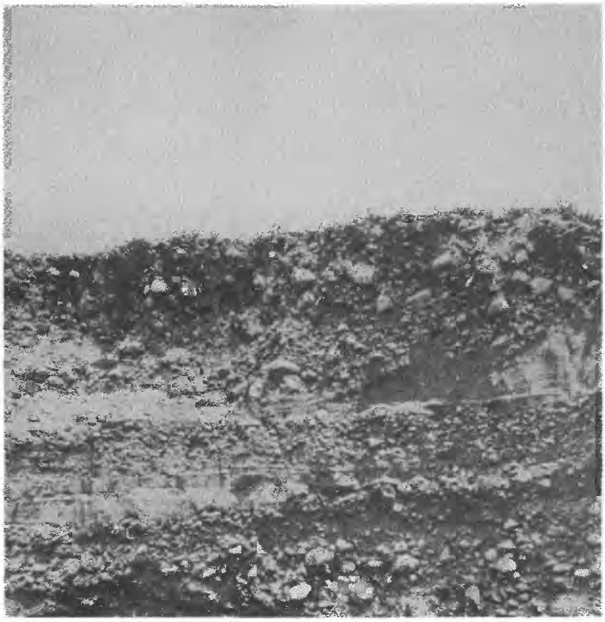
Original sedimentary interstices consist of the spaces between adjacent fragments of a sedimentary rock. As most of these fragments have been tumbled about by water, wind, or other agencies, they are generally more or less rounded. Hence, when they were deposited, open spaces remained between them, and these are the most important sources of ground water. The nature of these interstices has already been described (pp. 4–8). They characterize the rocks shown in Plates III, *A* and *B*, IV, *A*, and V, *A*. Well-assorted uncemented gravel, sand, or silt have a large porosity, but in poorly assorted materials small particles occupy the spaces between the larger ones, with the result that their open spaces are greatly reduced. (See p. 129 and Pl. VIII, *A* and *B*.) Material composed of uniform grains of small size has as great porosity as one of uniform grains or pebbles of large size; but that composed of large grains or pebbles is a better source of water because its interstices are larger, and they consequently convey and yield their water more freely. In poorly assorted or unassorted material the interstices are also relatively small, and hence they do not yield their water freely. The interstices of a sedimentary rock may gradually become filled with mineral matter deposited out of solution from percolating waters, until finally the rock may become practically solid throughout (fig. 1, p. 3).

The interstices of this type range from minute pores of microscopic dimensions that yield virtually no water to openings several inches wide that allow water to percolate very freely. Most of the sedimentary rocks are so fine grained that their interstices are not more than a small fraction of an inch in width; yet, as is shown on pages 117–131, unless the grains are very small indeed the rocks yield considerable water. Though the interstices of this type are generally small they are generally very abundant and evenly distributed, and as a rule they open freely into one another. Because of these characteristics they produce high porosity, permeability, and specific yield in many of the sedimentary rocks, and, on the whole, they are the most valuable class of interstices for producing water.

ORIGINAL IGNEOUS INTERSTICES.

Several kinds of interstices are developed in igneous rocks during the process of solidification. They comprise small cavities, or inclusions, within some of the crystals, small intercrystal spaces, vesicles produced by steam or other gaseous material escaping from extruded lava, and cavities produced in lava flows by the movement of the lava while it is congealing.

Cavities within the crystals are very numerous in some minerals, especially in quartz, in which they may comprise a considerable percentage of the total volume. Many of them contain minute quanti-

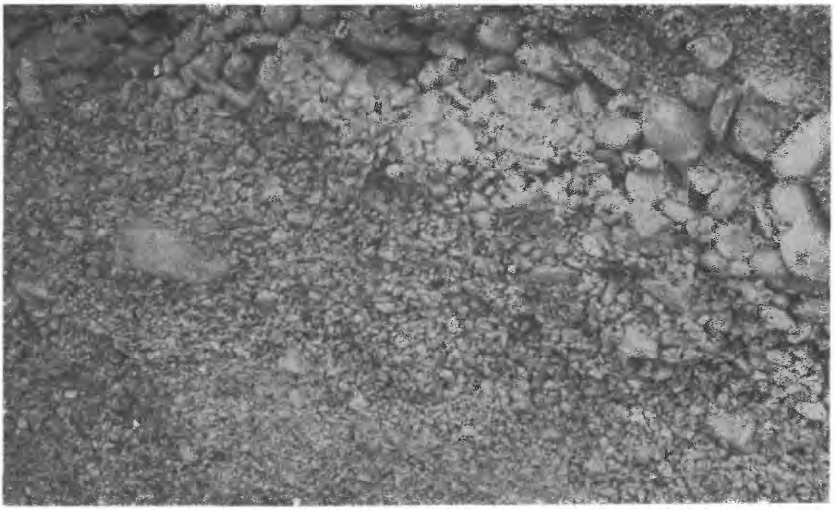


A. GLACIAL OUTWASH GRAVEL.

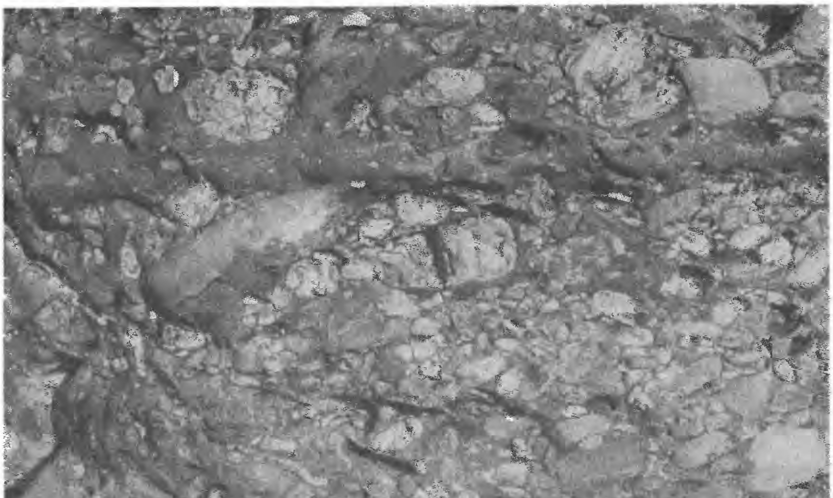
Yields water freely if wells are thoroughly cleaned out to remove fine material. Photograph by A. J. Ellis.

B. CLIFFS FORMED BY LOESS.

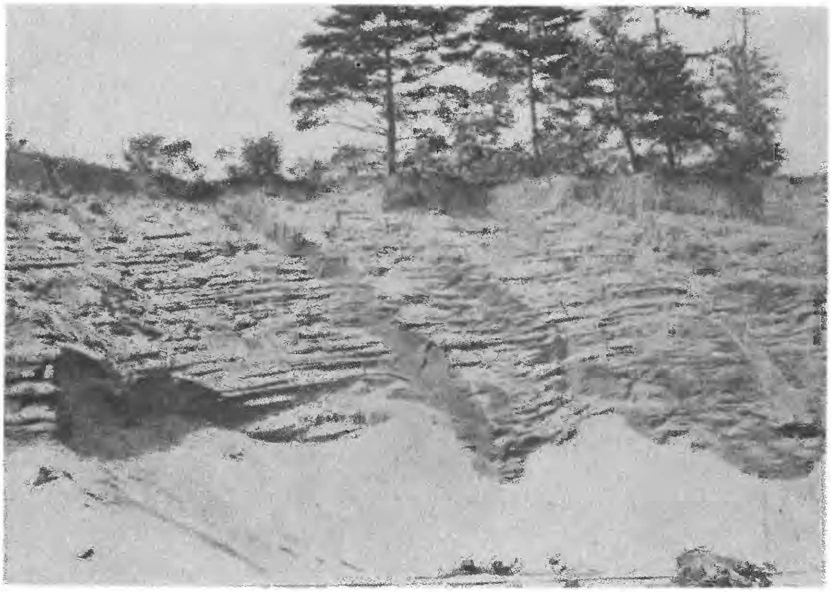
Photograph by A. F. Crider.



A. CLEAN GRAVEL THAT WILL YIELD WATER FREELY.
Photograph by G. K. Gilbert.



B. COMPACT CONGLOMERATE THAT WILL YIELD LITTLE OR NO WATER EXCEPT FROM JOINTS.
Photograph by C. D. Walcott.

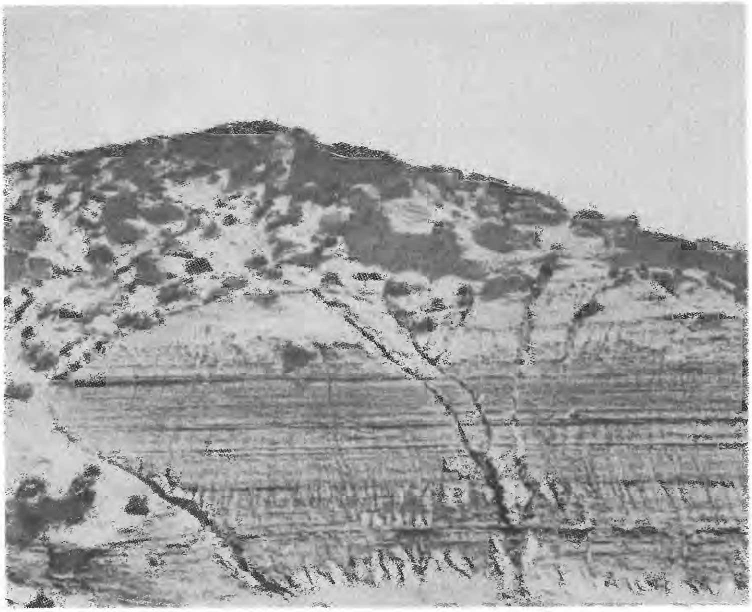


A. DUNE SAND THAT IS COARSE ENOUGH TO YIELD WATER FREELY BUT IS SO INCOHERENT THAT IT MAY CAUSE TROUBLE BY ENTERING WELLS.

Photograph by A. J. Ellis.

B. HARD SANDSTONE CONTAINING JOINTS THROUGH WHICH WATER CAN PERCOLATE.

Photograph by A. J. Ellis.



A. LAMINATED CLAYEY DEPOSIT THAT WILL YIELD LITTLE OR NO WATER.
Photograph by O. E. Meinzer.

B. STRATIFIED CLAY THAT WILL NOT YIELD WATER.
The superficial cracks become sealed when water is absorbed. Photograph by A. J. Ellis.

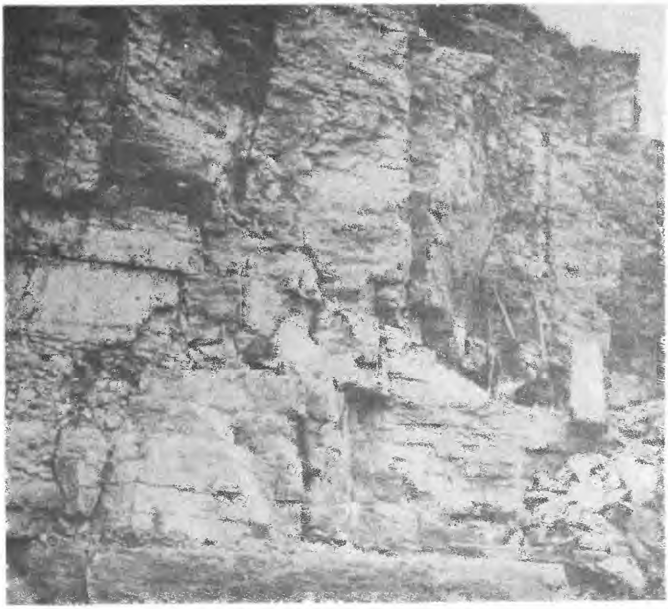
A. SLATY SHALE, SHOWING CLEAVAGE.
Photograph by C. D. Walcott.

B. LIMESTONE, SHOWING SOLUTION CHANNELS ALONG JOINTS.
Photograph by A. J. Ellis.

497781 O–59–9

A. TILL OR BOULDER CLAY, SHOWING ITS UNASSORTED CHARACTER.
Photograph by W. C. Alden.

B. PARTLY STRATIFIED BUT POORLY ASSORTED ALLUVIUM IN A DESERT BASIN.
Photograph by O. E. Meinzer.



A. LIMESTONE, SHOWING JOINTS AND BEDDING PLANES ALONG WHICH SOLUTIO CAN TAKE PLACE.

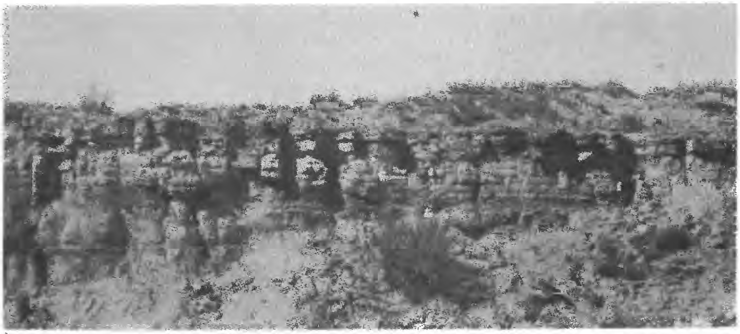
Photograph by W. C. Alden.

B. COMPACT BEDDED LIMESTONE WITH PARTINGS FROM WHICH WATER IS SEEPING.

Photograph by S. R. Capps.

A. CAVE IN LIMESTONE WHICH IS YIELDING GROUND WATER.
Photograph by V. H. Barnett.

B. CAVE IN GYPSUM WHICH IS YIELDING GROUND WATER.
Photograph by W. D. Johnson.



A. SOFT GYPSUM, SHOWING BEDDING PLANES AND JOINTS.
Photograph by O. E. Meinzer.

B. SINK HOLE IN GYPSEOUS SOIL EXTENDING BELOW THE WATER TABLI
Photograph by O. E. Meinzer.

C. SINK HOLE IN GYPSUM.
Photograph by O. E. Meinzer.

ties of water, but as they are of only microscopic size and do not open into one another they yield no water to wells or to the roots of plants, and they are not generally taken into account in making determinations of porosity. Original intercrystal spaces are also very small and unimportant with respect to water supply.

Rounded vesicles of considerable size are commonly produced near the top of a lava flow by the expansion of steam or other gas when the pressure is removed. These vesicles may be so large and so abundant that they give the rock a very high porosity. They are of some value as water producers, but their value is limited by the fact that they are largely isolated or communicate with one another only very imperfectly.

The more fluid lavas, such as basalt, produce numerous caverns and tunnels during the process of congealing. A surficial crust may form, after which the liquid lava beneath may drain away, leaving cavernous spaces, or a new supply of liquid lava may inundate the crust or break it up in such a way as to form large, irregular cavities. Openings of this type are also somewhat isolated from one another but are generally connected by the numerous large joints that commonly form in such lava beds as a result of shrinkage produced by cooling. These irregular cavities, together with the joints, are of great importance as sources of ground water and give rise to some of the largest springs and strongest wells in the world. The irregular surfaces and the broken character of typical beds of extrusive basalt are shown in Plate XIV.

JOINTS AND OTHER FRACTURE OPENINGS.

Nearly all consolidated rock formations are broken by cracks, as can be seen in quarries and in natural outcrops. These cracks are called joints. They are very narrow in some places where the rock surfaces press against each other, but in other places they are wide open, forming reservoirs of considerable capacity. Some joints do not reach very far; others extend for long distances and to great depths. They commonly run in various directions and hence intersect one another, thus not only breaking up the rock into blocks convenient for quarrying but also providing good channels of communication for the ground water. They are produced by various causes—chiefly by shrinkage, pressure, and deformation. Where there has been extensive deformation the rocks may have been displaced along the fractures, producing faults that extend far into the earth and that are of special significance as reservoirs and conductors of water or producing shear or breccia zones that are also likely to yield unusual amounts of water. In stratified sedimentary rocks the successive strata may break apart more or less extensively, and these partings may yield considerable water.

Daubrée[3] applied the name "lithoclases" to fracture openings and divided them into three classes—"leptoclases," or minor joints, "diaclases," or major joints, and "paraclases," or large faults. The leptoclases, which break up the rocks into minute fragments, he divided into two subclasses—"synclases" and "piésoclases." The "synclases" are caused by internal forces, generally shrinkage due to cooling or drying; they have somewhat of a geometric regularity—for example, the prisms of basalt and the polyhedrons of dried mud. The "piésoclases," like the "diaclases" and "paraclases," are produced by external forces, commonly pressure. They are irregular, minute fractures that are especially abundant near the surface but are also found far below the surface. The "diaclases" are the large joints, many of them nearly vertical, that are especially common in sedimentary rocks. They generally occur in two or more systems, the joints of each system being oriented in approximately the same direction and perhaps nearly at right angles to the joints of the other system. The "paraclases" are even larger than the "diaclases" and extend deeper into the earth.

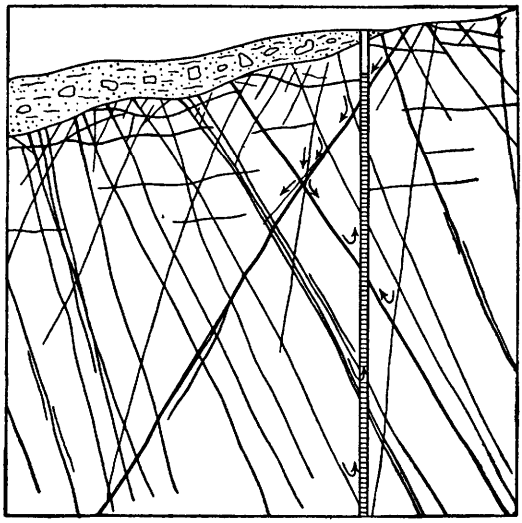


FIGURE 36.—Diagram showing how a well obtains water by cutting joints. (After E. E. Ellis.)

Joints are of great importance as sources of ground water, especially because they occur in practically all the hard, dense formations, such as granite and quartzite, which would otherwise be devoid of available water but which may thus afford supplies of much value throughout extensive regions. Many of the supplies obtained from jointed rocks are not large but yet are ample for domestic use. The manner in which joints contribute water to wells is illustrated by the diagrammatic section in figure 36. Joints in various rocks that may yield water are shown in Plates V, *B*; IX, *A* and *B*; XIII, *B*; XVII, *B*; and XVIII, *A* and *B*.

A very careful study of joints in the crystalline rocks of Connecticut in relation to ground water was made by E. E. Ellis. The following statement by him is based on this study:[4]

[3] Daubrée, A., Les eaux souterraines à l'époque actuelle, vol. 1, pp. 129–145, Paris, 1887.

[4] Ellis, E. E., Occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 160, pp. 21–23, 1906.

Joints are the more or less extensive and generally smooth and straight planes cutting the rock in various directions and are the result of fracturing forces which have split it into blocks of different shapes and sizes, although usually without any appreciable separation or movement of the rocks.

TYPES OF JOINTS.

Vertical joints.—The most common type of joint is that having an approximately vertical position (70°–90°), but joints with many other inclinations occur. The mean inclination of joints observed in 75 localities in the region investigated was 74°. The inclination of the joints is shown in the following table.

Inclination of joints in Connecticut rocks.

Inclination.	Number of localities observed.
80°-90°	40
70°-80°	17
40°-70°	14
Below 40°	4

The joints are mostly straight, but a few that were curved or showed other irregularities were observed.

Horizontal joints.—In many of the rocks there is another class of joints which are very different from the vertical type, both in their degree of inclination and in their general nature. These occupy an approximately level position, rarely more than 20° from the horizontal and usually much less than this. In general this joint structure follows the surface configuration of the rock, but occasionally it is found to pitch at a low angle in a direction opposite to the slope of the hillside.

Fissility and schistosity openings.—The porosity of schist, while probably greater than that of slate, is too small to admit artesian circulation through the pores. In the crumpled schists there appear to be openings between the laminae, but they probably do not permit sufficient rapid circulation for well supplies. It is upon the more or less pronounced fracture planes parallel to schistosity, especially those near the surface, that the wells depend.

Faults.—Faults may be considered as extreme types of joints in which there has been movement of one wall of the joint plane past the other. The work of Hobbs, Davis, and others has shown that there has been a considerable amount of faulting in Connecticut, while it is not uncommon to find strongly marked shear zones, indicating slipping in the crystalline rocks. They are comparatively rare phenomena, however, and are seldom encountered in well drilling and accordingly will be treated simply as special cases of jointing. They are possibly important as sources for springs, although it is extremely difficult and generally impossible to ascribe any particular spring to a fault plane.

SPACING AND CONTINUITY OF JOINTS.

Vertical joints.—The vertical joints, which are the important water carriers, have no regularity of spacing, even for the same rock. From a large number of observations it appears that at the places where jointing is well developed the spacing of all joints is commonly between 3 feet and 7 feet to a depth of 50 feet; the average spacing, however, between vertical joints of the same series for the crystalline rocks, excluding trap and limestone, is more than 10 feet for this depth, while the study of well records indicates that this is not far from the average spacing for all joints to a depth of 100 feet.

Although there are many exceptions, joints of this type are generally continuous for considerable distances both along the line of outcrop and that of dip. Faults, however, have the greatest continuity and frequently extend for several miles across the country, occasionally for tens of miles. The sheeted zones of close jointing are probably nearly as continuous as faults, and their dimensions should be measured in hundreds of feet. Where there is a well-defined parallel joint series the prominent joints may extend several hundred feet, while the minor intersecting joints will be much shorter.

Horizontal joints.—There is much greater regularity of spacing in the horizontal joints than in the vertical joints. They are apparently surface phenomena and diminish in number rapidly with depth, and it is probable that they do not exist as fractures at 200 feet below the surface. In the first 20 feet below the surface these horizontal joints average 1 foot apart, in the next 30 feet they average between 4 and 7 feet, and in the next 50 feet they are much more widely spaced, running from 6 to 30 eet or more apart.

The continuity of individual horizontal joints rarely exceeds 150 feet, but owing to their intersection of each other a continuous opening might be formed of several hundred feet which would be in the form of a curved sheet approximately parallel to the hill slope, each lower sheet having less curvature than the other. They are probably better developed on the hills than in the valleys, as the pitch of the joints is usually less than the slope of the surface, which consequently cuts across the joints; and as they are wider spaced with depth the horizontal joints which cross the valleys will be widely spaced.

DEPTH.

Not only do joints become tighter with depth, but they are farther apart. The application of this principle in the drilling of wells is of the utmost importance, as it is frequently asserted that water can always be obtained by going deep enough, whereas, in fact, the deeper the well the less the chance of striking fractures, which are the only passages permitting water transmission in crystalline rocks. It is further evident that owing to the closing of joints with depth, there will be a much greater circulation in the upper half than in the lower half of any individual joint.

The number of fractures supplying water varies greatly in different wells. In some cases the greater part of the water appears to come from a single opening; while in others the water comes in slowly from a large number of openings. In the average well there are from 1 to 4 horizons from which the principal supplies of water come, although the yield from one of them is usually greater than from all the others together. This is particularly true of the deeper wells (from 200 to 300 feet), in which the principal source is usually very close to the bottom of the well.

If an average inclination of 70° from the horizontal and an average spacing of 10 feet be assumed for the vertical joints for the upper 200 feet of rock, each well 200 feet in depth will intersect 7 joints. This is probably not far from the average for all the wells, the small and discontinuous fractures near the surface being neglected. Below 200 feet the average number of joints intersected would be somewhat decreased for the next 100 feet, and greatly decreased at depths greater than 300 feet.

INTERSECTION OF JOINTS.

The intersection of joints with one another is very important in determining the nature of the underground circulation. While all joints intersect, the circulation is greatest where the joints of the principal systems meet and where, in addition to the vertical joints, horizontal fractures occur.

WIDTH OF OPENINGS.

At the immediate surface joints often have an opening of one-half inch to 2 inches, and occasionally much greater. This wide opening is due to various weathering and mechanical agencies, which act only near the surface, and consequently is not found at depths below which these agencies act. In an artificial cut, such as a quarry wall, joints which may be open one-half inch at the surface are often found to be too tight to admit a knife blade at 25 feet below the surface.

While the joints at 30 feet below the surface may have only one-twentieth the opening that they have at the surface, the same proportionate tightening will not continue at lower depths, although it is certain that the greater the depths the greater must be the tendency of joints to close, owing to increased pressure and the smaller opportunity for lateral expansion below the level of minor topographic relief.

SOLUTION OPENINGS.

Solution openings are produced chiefly by the water that penetrates preexisting interstices. They are of two kinds—those due to the chemical decomposition of rocks and the solution and subsequent removal of the soluble products, and those due to the solution and removal of soluble rocks.

Interstices produced by decomposition are found in igneous rocks and in the metamorphic rocks that contain abundant complex minerals, particularly in granitic rocks. The decayed residue is clayey, and hence the interstices are not large and do not yield much water; yet in many places they afford large enough supplies to be of considerable practical value. In fault zones and shear zones the decomposition generally extends to greater depths than elsewhere, and water-bearing material may be encountered at depths of more than 100 feet. Slaty cleavage and schistosity also favor rock decay and the formation of small interstices.

Openings produced by the dissolving of soluble rocks may be regarded as of two kinds—those produced by the removal of a soluble cement from an otherwise nearly insoluble rock, as a sandstone whose original interstices had become filled with a calcareous cement, and those found in rocks that are composed mainly of soluble material, such as limestone, gypsum, and salt. Where there is free circulation of water through joints or other openings in limestone, solution of the rock material may progress until the formation is ramified by a network of caverns, some of which may grow to great size. A single passage in the Mammoth Cave of Kentucky is more than 8 miles long. Many such passages are 20 feet high, a few as much as 75 feet high, and some are as much as 50 to 150 feet wide. The great vertical wells of the Mammoth and other caves have diameters of 10 feet or more and depths of more than 200 feet.[5] In Plate X, *A*,

[5] Fuller, M. L., Summary of the controlling factors of artesian flows: U. S. Geol. Survey Bull. 319, p. 11, 1908. See also Keilhack, Konrad, Lehrbuch der Grundwasser- und Quellenkunde, pp. 231–246, Berlin, 1912; Katzer, Fr., Karst und Karsthydrographie, Sarajewo, Daubré, 1909; Martel, E. A., Nouveau traité des eaux souterraines, Paris, 1921.

is given a view of a huge elongated opening in limestone from which a subterranean stream is flowing; in Plate X, *B*, is shown a similar opening in gypsum from which a stream is also issuing. (See also Pls. VII, *B*; XI, *B* and *C*; and XII, *A* and *B*.) In figure 37 is shown a diagrammatic section of a system of solution openings.

The following additional information regarding this type of openings is given by Fuller:[6]

Many of the channels of this type have resulted from the enlargement of joints, the action being especially marked near the intersection of two or more planes, the great irregularity of some of the openings being accounted for by the complexity of the joint or fracture systems. This appears to be the case in the Joplin zinc district. Elsewhere, however, many of the largest passages follow bedding planes without reference to jointing, apparently having developed from one of the many meandering and branching passages that characterize such planes at many points. The small chan-

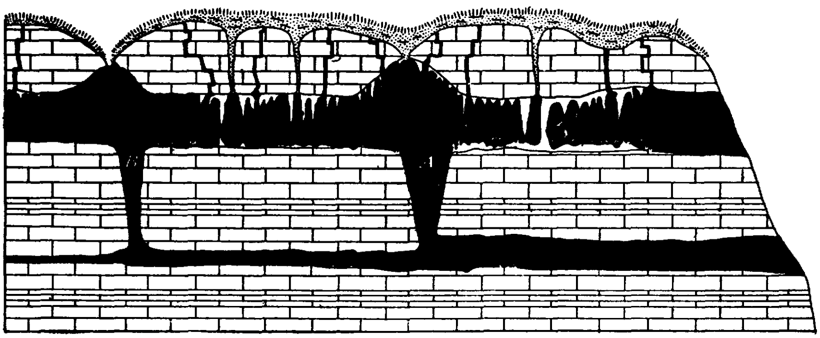


FIGURE 37.—Diagram showing system of solution openings. (After G. C. Matson.) The black spaces represent subterranean openings from which limestone (represented by rectangular pattern) has been dissolved by solution. *A*, *B*, Pits leading from upper to lower caverns. The white spaces represent stalactites and stalagmites.

nels are gradually enlarged and tend to coalesce and form a single large channel, which by continued solution is gradually widened until a cave results. A few small tubular channels that pass diagonally through the rock without apparent connection with joints or bedding planes have been noted. The determining causes of such passages are not known, but it seems certain they represent simply the enlargements of some preexisting line of easy water movement.

The sheet form of solution passage is the first stage in the enlargement of joints, faults, or other planes. The secondary pores first formed eventually unite into an exceedingly narrow sheetlike opening. In crystalline and other insoluble rocks these may persist indefinitely, but in limestones differential solution soon develops the characteristic irregular cavities.

On account of their large size solution passages yield water freely and are among the most important of water bearers.

[6] Op. cit., p. 12.

WATER-BEARING PROPERTIES OF ROCKS.

GRAVEL AND CONGLOMERATE.

Gravel is the best kind of formation to yield water. In the United States it supplies most of the strong wells and furnishes more water to wells than all other materials taken together. A coarse clean gravel has a high porosity, high permeability, and high specific yield. It absorbs water readily, stores it in large quantities, and yields it to wells freely. A well only a foot in diameter ending in a good bed of gravel may supply more than 1,000 gallons a minute. In Plate IV, *A*, is shown a clean gravel which would yield water very freely if it lay in the zone of saturation. Clean gravel is deposited chiefly by large swift streams whose velocity decreases downstream. It was formed extensively by the waters that issued from the great ice sheets that once covered the northern part of the United States (Pl. III, *A*), and by the streams that still flow from the mountains of western United States upon the Great Plains or into the numerous intermontane basins (Pl. VIII, *B*). Such gravel is also formed on shores which receive coarse débris and whose wave action and shore currents are competent to remove the finer materials (Pl. IV, *A*).

Most of the water supply for the city of Brooklyn was formerly pumped from wells ending in glacial outwash gravel on Long Island. About 100 million gallons a day was pumped from wells in a catchment area of about 160 square miles in the western part of the island.[7] Examples of strong wells supplied from gravel deposits of intermontane basins are afforded by the wells in San Bernardino Valley, Calif., reported by Mendenhall.[8] A group of three wells, all less than 200 feet deep, in 1892 flowed about 4,000 gallons a minute each. Four others, ranging in depth from less than 300 feet to 582 feet, are reported to have yielded about 3,000 gallons a minute each. Two others flowed between 1,500 and 2,000 gallons a minute. In 1904 the aggregate yield of all wells in this valley was about 144 second-feet (about 65,000 gallons a minute or 93 million gallons a day).

There is, however, a great range in the water-bearing properties of the various kinds of gravel, conditioned mainly by the degree of assortment and the degree of cementation. Some deposits consist largely of pebbles and boulders and yet have a matrix of such dense and compact material that they are worthless as producers of water. Others have become transformed into hard conglomerate, with the interstices so completely filled with cement that they will not yield water (Pl. IV, *B*). However, conglomerates may be fractured, like

---

[7] Spear, W. E., Report on water supply, Long Island sources, vol. 1, pp. 56-66, Board of Water Supply of the City of New York, 1912.

[8] Mendenhall, W. C., The hydrology of San Bernardino Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 142, pp. 52, 53, 63, 1905.

most other consolidated rocks, and may yield some water from their joints.

The kind and abundance of gravel in a sedimentary deposit depend largely on the kinds of rocks from which the sediments were derived. Thus, in a débris-filled intermontane basin much can be predicted in advance of drilling as to the yield of the underlying gravels by noting the character of the rocks in the adjacent mountains from which the débris was washed. Shale, marl, soft shaly sandstone, or fine-grained volcanic ash will not produce gravel. In arid regions rocks may disintegrate without being chemically decomposed, and the resulting débris may form a good gravel, but in time the pebbles are likely to decay and fall apart, rendering the formation compact. This is probably one reason why the deeper fill of many of these basins fails to yield much water. Slate or hard limestone may yield fairly good gravel, but it is likely to be somewhat cemented. Quartzite does not yield much débris, but such as it supplies is excellent material for gravel. The best and most permanent gravel beds are produced from materials that have been transported long distances and have passed through many vicissitudes, so that the soft and unstable materials have disappeared and only the hard, insoluble, and durable materials remain.

As a rule the water from gravel beds is of good quality unless it was mineralized before it entered the gravel. The water receives relatively little mineral matter from the gravel because the gravel is commonly composed of stable materials and, moreover, its interstices are so large that the water does not come into very close contact with the rock material.

SAND, SILT, SANDSTONE, AND QUARTZITE.

Sand and sandstone rank next to gravel as water bearers. They comprise some of the great aquifers of the United States, such as the well-known St. Peter and Dakota sandstones. A sand or sandstone formation is as a rule more continuous and widespread than a bed of gravel or conglomerate. It has a comparable porosity for the same degree of assortment and cementation, reaching 30 to 40 per cent or even more in clean uncemented sands of uniform grain. It compares unfavorably with gravel, however, in having smaller interstices and hence in conducting water less readily and giving up a smaller proportion to wells. It also compares unfavorably in consisting of smaller particles, which are more readily carried by the water into the wells, thus producing some of the most difficult problems in connection with drilling and pumping (Pl. V, *A*). A good sandstone well may yield a few hundred gallons a minute, but on an average sandstone wells furnish distinctly less water than wells supplied by gravel.

There is great variety in the formations that are properly called sand or sandstone, and a correspondingly wide range in the water-bearing characteristics of these formations. This range is determined by several factors, chiefly size of grain, degree of assortment, degree of cementation, and amount of jointing.

The size of grain is very important. A coarse sand if well assorted yields freely, whereas an equally well assorted silt holds a large part of its water and surrenders the rest very slowly. A fine, incoherent sand is not only unsatisfactory or worthless as a source of water supply but it is one of the most serious hindrances in recovering ground water. In sinking wells it causes trouble by running into the wells and filling them and by pressing so hard upon the outside of the casing that it becomes impossible to drive the casing down. By coming into wells after they are finished it damages the pump, sometimes erodes the casing, and frequently clogs the wells.

Deposits of sand are as a rule assorted better than deposits of gravel because they are generally laid down by streams or currents that are less turbulent and erratic. However, many sand deposits do not consist of clean sand but contain a clay matrix that spoils them as water bearers. The "Red Beds," such as are extensively developed in the Permian and Triassic formations and underlie large areas in the western United States, include much sandstone that is poorly assorted and clayey and hence is unsatisfactory as a source of water.

Numerous mechanical analyses were made by Dake[9] of sandstones in the Mississippi Valley region, including such well-known and productive water-bearing formations as the Cambrian ("Potsdam") sandstone in Wisconsin, the Jordan sandstone in Iowa, and the St. Peter sandstone in Missouri. Two analyses of the Cambrian sandstone of Wisconsin showed effective sizes of grain (see p. 7) of 0.16 and 0.17 millimeter and uniformity coefficients of 1.6 and 1.9, respectively. Both samples consisted chiefly of medium and fine sand with small portions of coarse and very fine sand, as these terms are defined on page 17. One analysis of the Jordan sandstone showed an effective size of grain of 0.21 millimeter and a uniformity coefficient of 2.5. The sample consisted largely of medium and coarse sand. Seventeen analyses of St. Peter sandstone showed effective sizes ranging from 0.12 to 0.24 millimeter and averaging 0.17 millimeter. They showed uniformity coefficients ranging from 1.4 to 2.6 and averaging 1.9. These samples, like those of the Cambrian sandstone of Wisconsin, consisted chiefly of medium and fine sand, only a few per cent, as a rule, being larger than 0.5 millimeter or less than 0.1 millimeter. These quantitative data give some idea of size of grain

[9] Dake, C. L., The problem of the St. Peter sandstone: Missouri Univ. School of Mines and Metallurgy Bull., August, 1921, pp. 152-177.

and degree of assortment that is requisite for satisfactory yields. These rather fine-grained but clean sandstones are widely regarded as good aquifers and are believed to yield their water from the interstices between the grains rather than from joints. Probably, however, they are not far from the limit of fineness for material that will yield water freely. Figure 38 shows the mechanical composition of one of the samples of Cambrian sandstone and of a sample of St. Peter sandstone which is about average in effective size and uniformity coefficient among the seventeen samples shown by Dake. A

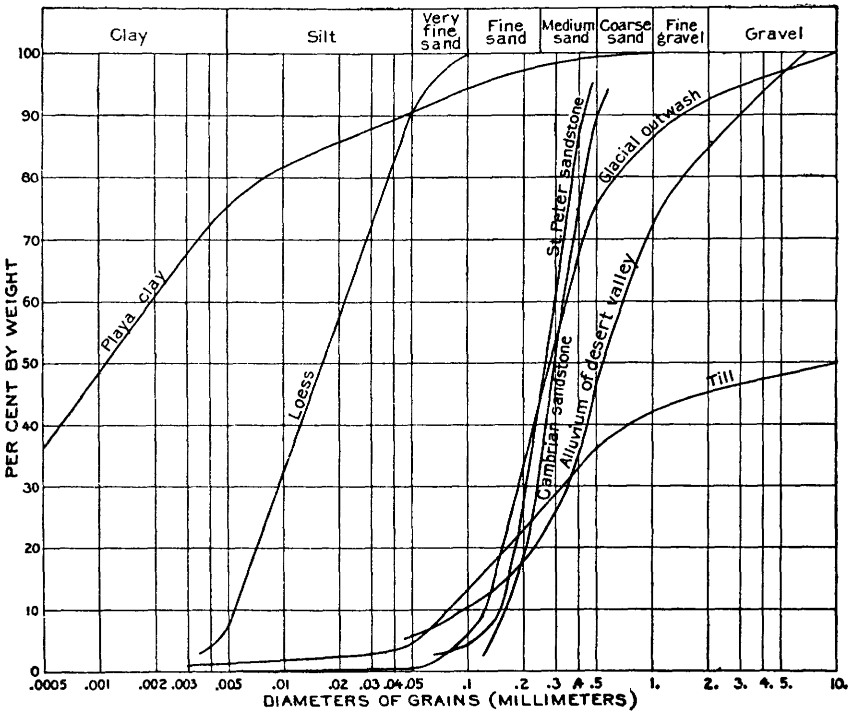


FIGURE 38.—Diagram showing mechanical composition of six water-bearing materials and of non water-bearing playa clay. The Cambrian and St. Peter sandstones are well enough assorted and coarse enough to yield water freely. The glacial outwash and alluvium of a desert valley are also good water bearers, but the alluvium suffers from its large content of silt and fine sand. The till is unassorted but yields water slowly. The loess is fine grained but rather well assorted and yields water very slowly. The playa clay is too fine grained to yield water in appreciable quantities.

sample of the Catahoula sandstone, a good water-bearing formation in Texas, was analyzed by Goldman.[10] He found that 10.4 per cent of the sample consisted of coarse sand (0.9 to 0.45 millimeter), 53.4 per cent of medium sand (0.45 to 0.26 millimeter), and 34.1 per cent of fine or very fine sand (0.26 to 0.04 millimeter). This gives a probable effective size of more than 0.1 millimeter and a uniformity coefficient of perhaps 3.

[10] Goldman, M. I., Petrographic evidence on the origin of the Catahoula sandstone of Texas: Am. Jour. Sci., 4th ser., vol. 39, p. 263, 1915.

The interstices of sandstone are more readily closed by precipitates from percolating water than the interstices of gravel, because they are smaller. Many of the more indurated sandstones are too thoroughly cemented to yield much water from the original openings between their grains. In quartzites these interstices have been almost completely closed by cementation. A moderate amount of cementation may, however, improve a sand as a water bearer by making it more coherent and less likely to run into wells. Cementation and resulting consolidation also produce conditions favorable for the development of joints (Pl. V, *B*). In quartzites and the more indurated sandstones the joints have a very important function. Where the original interstices have been entirely closed the joints may be the only sources of water, and where the cementing process is less complete they serve the function of receiving supplies from the minute pores of the rock by slow percolation and delivering it freely to wells by which they are penetrated. In such a formation the success of a well depends on the number and size of the joints that it encounters and the extent to which these joints persist and intersect others. Success in penetrating joints is largely a matter of chance but can sometimes be achieved by a careful study of the joint systems where the rocks crop out.

One of the hardest and most firmly cemented of quartzite formations is the Sioux quartzite, in southwestern Minnesota and adjacent parts of South Dakota and Iowa. In pioneer days of the region it was not considered a possible source of water, but the great dearth of water in some localities compelled the experiment of drilling into it. Almost everywhere it was found to yield some water, and it is now depended on as a reliable source of supply. The water percolates chiefly through the joints by which the rock is broken. Although the amount furnished by any single joint is usually small the effect is accumulative, and as drilling is continued the well becomes connected with more and more of these water-bearing joints. The yield is usually very small as compared with that of wells in more porous formations. It is customary for drillers to guarantee only 100 gallons an hour in farm wells, though the actual yield is often much greater. The two city wells at Pipestone, Minn., which are respectively 6 and 8 inches in diameter and 200 and 350 feet deep, together deliver 140 gallons a minute.[11]

In Connecticut an altered quartzite consisting largely of quartz grains apparently yields very little water. Information was obtained by Gregory and Ellis[12] regarding five wells drilled into it, three of

[11] Hall, C. W., Meinzer, O. E., and Fuller, M. L., Geology and underground waters of southern Minnesota: U. S. Geol. Survey Water-Supply Paper 256, especially pp. 295-297, 332-334, 1911.

[12] Gregory, H. E., and Ellis, E. E., Underground water resources of Connecticut, with a study of the occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 232, p. 99, 1909.

497781 O-59-10

which are more than 300 feet deep and one more than 200 feet. In each well the supply was very small and unsatisfactory. Though the number of wells is too small for conclusive generalization, the evidence indicates that the rock is a very unreliable source of water supply and that the fractures are few and poorly developed.

Four drill holes are reported by Miss Bascom[13] in the Chickies quartzite, a hard, resistant, somewhat conglomeratic formation near Philadelphia. One hole is 570 feet deep and yields no water, one is 132 feet deep and yields 5 gallons a minute, one is 64 feet deep and yields 10 gallons a minute, and one is 780 feet deep and yields 100 gallons a minute.

LOESS.

Loess is a fine, homogeneous, nearly structureless silt, usually buff in color and regarded by most people as a kind of yellow clay. It is soft and easily excavated and yet has a remarkable capacity for standing in vertical walls (Pl. III, *B*). Much of this material was deposited by the wind during one or more of the intervals between the several advances of the great ice sheets into the northern part of the United States. It mantles slopes and crests and upland areas, and the fact that it is thickest near the principal streams, as in the uplands bordering the valleys of Missouri and Mississippi rivers, suggests that it was largely blown up as dust from the bottom lands.

Loess is a porous material that has interstices of such a size that it has a high water-retaining capacity but still permits slow percolation. It therefore has the hydrologic properties for making an excellent soil but only a poor aquifer. It supplies wells in but relatively small areas in the United States. In most places it forms only a veneer of a few feet, and even where it attains a thickness of 50 to 100 feet it is likely to be in elevated positions some distance above the water table. It yields water very slowly but may supply enough for domestic or farm use. Some wells in southwestern Iowa are supplied from loess, but on the farms it is generally necessary to bore several wells, usually connected by drifts, in order to get enough water for the live stock.[14] The loess is too soft to develop joints that are important in supplying water, and it apparently yields water by seepage directly from the minute pores between the individual grains. For this reason it is necessary to provide wells with extensive surfaces for infiltration.

The more or less typical loess from the Mississippi Valley region, of which mechanical analyses are given in the following table, consists chiefly of silt, as defined by the United States Bureau of Soils (p. 17),

[13] Bascom, Florence, Water resources of the Philadelphia district: U. S. Geol. Survey Water-Supply Paper 106, p. 49, 1904.

[14] Norton, W. H., Hendrixson, W. S., Simpson, H. E., Meinzer, O. E., and others, Underground water resources of Iowa: U. S. Geol. Survey Water-Supply Paper 293, p. 917, 1912.

and has an average effective size of grain not far from 0.005 millimeter. The analyses show that the loess is fairly well sorted, but they do not give sufficient data for making close estimates of the uniformity coefficients. The coefficients of the Arkansas and Wisconsin samples (Nos. 1–8) may be as low as 2 and are probably not over 5, but that of the composite Nebraska sample (No. 9) may be somewhat higher. The data given indicate that the effective size of grain of the loess of the Mississippi Valley region is only about one-thirty-fifth that of the St. Peter sandstone and yet is many times the size of a subcapillary opening as defined on pages 26–27. The mechanical composition of No. 2 is shown graphically in figure 38.

Mechanical analyses of loess in Arkansas, Wisconsin, and Nebraska.

[Percentage, by weight, of total sample.]

	Diameter (millimeters).	1	2	3	4	5	6	7	8	9
Fine gravel	2 to 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Coarse sand	1 to 0.5	.0	.0	.0	.0	.2	.0	.0	.1	.2
Medium sand	0.5 to 0.25	.1	.0	.1	.1	.1	.0	.2	.1	.4
Fine sand	0.25 to 0.1	.2	.1	1.1	.1	.2	.7	1.0	1.7	1.7
Very fine sand	0.1 to 0.05	3.8	9.5	9.4	5.6	4.8	19.6	5.1	18.2	26.7
Silt	0.05 to 0.005	84.2	83.2	82.3	85.5	84.7	64.8	81.5	63.1	59.7
Clay	Less than 0.005	11.4	7.0	6.9	8.6	10.0	14.7	12.2	16.4	11.3

NOTE.—Nos. 1 to 5 are samples of loess from Arkansas, studied by E. W. Shaw and L. W. Stephenson, of the U. S. Geological Survey, and analyzed by the U. S. Bureau of Soils. (See U. S. Geol. Survey Water-Supply Paper 399, pp. 103–104, 1916.) Nos. 6 to 8 are samples of loess from Wisconsin, studied by W. C. Alden, of the U. S. Geological Survey, and analyzed by the U. S. Bureau of Soils. (See Water-Supply Paper 399, p. 105.) No. 9 represents loess soil from Nebraska from depths of 1 to 6 feet, collected and studied by F. J. Alway and C. O. Rust for the Nebraska Agricultural Experiment Station. The figures are averages of the analyses of 36 samples, each of which was a composite of 50 individual samples. (See Soil Science, vol. 1, pp. 405–436, 1916.)

The water in loess is likely to be somewhat hard but otherwise of good quality. The danger of contamination of the water in the loess is diminished by the fact that the material is very fine grained and rarely contains crevices that are connected with the surface.

Brief descriptions of the occurrence of water in loess deposits are given in several of the publications of the United States Geological Survey.[15]

CLAY, SHALE, AND SLATE.

True clay is aluminum silicate formed by the decomposition of the more complex silicates found in igneous and metamorphic rocks. It consists of such exceedingly minute particles that it is plastic and feels smooth. To a large extent it is a colloidal substance. In the process of assortment of fragmental material by water the clay is in general held longest in suspension and is the last to be deposited. In many places it occurs in very finely laminated beds which are quite impervious (Pl. VI, *A* and *B*).

[15] See Water-Supply Papers 159, 164, 256, 259, and 293; and Geologic Folios 105, 156, 188, and 195.

Among all deposits true clay is the most hopeless as a source of water supply. This is not because it contains no water. The porosity of nine samples of clay ranged, according to Ries,[16] between 17.3 and 30.1 per cent. As quoted by Warington,[17] Meister gives the porosity of clay as 50 per cent and Schwartz gives it as 52.7 per cent. But as the constituent particles of clay are impalpably small the interstices between the particles are so minute that they hold tenaciously to all their water, rendering the clay impervious under ordinary hydrostatic pressure. Moreover, clay is so soft and plastic when wet that any joints or other larger openings formed in it are closed completely under even slight pressure.

Most of the numerous deposits that are called clay by well drillers are in fact mixtures of clay with coarser materials. Such clayey mixtures are deposited by sheet floods and by rapidly subsiding streams after they no longer carry much coarse material. They are the finest phases of unassorted or poorly assorted clastic deposits. These clayey mixtures are regarded in drilling as non water-bearing, but they furnish small domestic supplies to many shallow dug wells that have large infiltration areas and considerable storage capacity. The water may come into the well from relatively sandy or gravelly lenses in the clayey deposit or it may trickle out of small crevices that are formed in various ways. As the material is less plastic than true clay and perhaps somewhat consolidated, it may have sufficient strength to keep open such crevices under the small pressures existing near the surface.

The following table, based on the work of David G. Thompson, of the United States Geological Survey, shows the mechanical composition of the fine sediments deposited in the beds of temporary lakes, or playas, in the desert region of California. These sediments consist chiefly of silt and clay and are made up largely of fine colloidal clay. They are only moderately well assorted. However, No. 4, at least, has a high porosity. They are too fine grained to be sources of water supply. The mechanical composition of No. 3 is shown graphically in figure 38, in comparison with certain recognized water-bearing materials.

[16] Ries, Heinrich, Clays: their occurrence, properties, and uses, p. 163, New York, John Wiley & Sons, 1906.

[17] Warington, Robert, Physical properties of soils, p. 67, Oxford, Clarendon Press, 1900.

Mechanical composition of playa deposits in the Mohave Desert region, Calif.

[By David G. Thompson. Percentage, by weight, of air-dried sample after removal of water-soluble constituents.]

	Diameter (millimeters).	1	2	3	4
Gravel	More than 1	2.4	0.1	0.2	0.02
Coarse sand	1.0 to 0.5	2.3	.7	.8	.2
Medium sand	0.5 to 0.25	4.0	1.6	1.4	1.1
Fine sand (0.25 to 0.1 millimeter)	0.25 to 0.125	5.7	1.5	1.7	2.3
Very fine sand (0.1 to 0.05 millimeter)	0.125 to 0.074	5.1	1.7	3.1	2.4
	0.074 to 0.050	8.5	3.1	5.1	1.0
Silt[a]	0.050 to 0.020	20.0	8.0	2.0	.01
	0.020 to 0.005	42.0	14.4	10.2	2.3
Clay[a]	0.005 to 0.002	8.5	25.1	15.2	4.7
	0.002 to 0.0005	1.4	20.3	24.5	19.5
	Less than 0.0005	.3	23.5	35.8	66.6
Effective size (millimeter)		.005	(b)	(b)	(b)
Uniformity coefficient		6	(c)		
Porosity (per cent by volume)[d]					38.3 37.8

[a] The sizes smaller than 0.05 millimeter were determined by a method described by E. C. J. Mohr (Die mechanische Bodenanalyse: Dépt. agr. Indes Néerlandaises Bull. 41, 1910), in which the material in suspension in water is allowed to settle through definite distances for periods of different lengths. The material in suspension at the end of a given period is decanted and allowed to settle for the next longer period. The limits of the sizes separated in this way are doubtless less definite than those of the larger sizes separated by sieving.

[b] Less than 0.0005 millimeter.

[c] More than 7; probably between 10 and 15.

[d] Porosity determined by A. F. Melcher.

1. Hard, smooth material at surface of playa in Superior Valley, 25 miles north of Barstow, Calif. Microscopic examination of the material between 0.02 and 0.005 millimeter in diameter showed that a large part of it was composed of aggregates of fine particles, many of which showed typical Brownian movement. It is probable that if the material were carefully treated these aggregates would disintegrate. In the separation without special treatment, however, the aggregates acted as definite particles of the size given.
2. Soft, powdery, moist, and highly alkaline material at surface of playa in Harper Valley, near Hinkley, Calif.
3. Hard mud-cracked material about 50 feet from No. 2.
4. Material at surface of hard, smooth playa called Rogers " Dry Lake," near Lancaster, Calif.

Shale is formed by the induration of either true clay or one of the clayey mixtures. It is a poor kind of formation from which to get water, but in a few localities where good aquifers are lacking it furnishes meager supplies for some wells. Its available water is found in joints and along bedding planes. Joints are as a rule best developed near the surface, in the hardest shales and in the more brittle varieties derived from the less plastic mixtures. An example of a thick formation of dense shale that offers very unfavorable ground-water conditions is afforded by the Pierre shale, which underlies large parts of the Great Plains. An example of a shaly formation that is better than the average as a water producer is the Brule clay, which also underlies parts of the Great Plains. This somewhat gritty and brittle formation is broken, especially in the weathered parts, into small cubical blocks and seems to contain some large openings near the surface. It supplies small quantities of water to many wells, and under certain conditions it seems to supply very large quantities from its fissured upper portion.[18]

[18] Meinzer, O. E., Ground water for irrigation in Lodgepole Valley, Wyoming and Nebraska: U. S. Geol. Survey Water-Supply Paper 425, pp. 56, 62, 63, 1919. Brief statements regarding water in shale are also given in Water-Supply Papers 110, 232, 233, 254, 257, and 259.

Slate is likewise not a satisfactory water bearer, but in places where there are no other sources it furnishes small though perhaps very valuable supplies. The rock itself is too dense to yield water, but some water may percolate through its joints and cleavage planes, especially near the surface, where the crevices have been enlarged by weathering (Pl. VII, *A*). In mountainous areas underlain by slate ground water is generally scarce.

At the mining town of Manhattan, Nev., where water is very scarce, most of the public supply is derived from slate. One well, 4 by 8 feet in cross section and 60 feet deep, all except the top 6 feet of which is in slate, yields in different seasons from 5,000 to 10,000 gallons a day.[19]

In southern Maine, according to Clapp,[20] slate produces more water than granite, and few wells in slate are absolute failures. In that region most slate wells less than 100 feet deep yield between 1 and 10 gallons a minute, but many of the deeper wells yield as much as 30 gallons a minute, and a few yield more than 50 gallons a minute. In the large slate areas of Maine drilling to depths of 400 or 500 feet is advised unless sufficient supplies are obtained nearer the surface.

In Connecticut Ellis[21] noted that five wells drilled into a slaty rock to an average depth of 94 feet yield very little water. The cleavage of the rock is nearly vertical, causing difficulty in drilling, and most of the fractures appear to be filled by some cementing mineral matter.

TILL.

Glaciers carry rock débris of all sizes from fine rock flour to huge boulders, mixed promiscuously. The deposits of this débris are called "glacial drift." The drift is in part deposited directly by the ice and in part carried farther by the waters resulting from the melting of the ice or by the wind. That which is deposited directly by the ice forms heterogeneous unassorted mixtures called "till" or "boulder clay" (Pl. VIII, *A*); that deposited by escaping streams forms chiefly water-bearing "outwash gravel" (Pl. III, *A*); that deposited by lakes impounded by ice or till forms chiefly impervious clay beds (Pl. VI, *B*); and that deposited by the wind forms accumulations of loess (Pl. III, *B*) or dune sand (Pl. V, *A*). Extensive deposits of all kinds of glacial drift were laid down by successive continental ice sheets that invaded the northern part of the United States in late geologic time—shortly before the dawn of human history.

---

[19] Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring valleys, Nev.: U. S. Geol. Survey Water-Supply Paper 423, p. 127, 1917.

[20] Clapp, F. G., Underground waters of southern Maine: U. S. Geol. Survey Water-Supply Paper 223, pp. 33-34, 1909; Occurrence and composition of well waters in the slates of Maine: U. S. Geol. Survey Water-Supply Paper 258, pp. 32-39, 1911.

[21] Ellis, E. E., Occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 160, p. 27, 1906. Gregory, H. E., and Ellis, E. E., Underground water resources of Connecticut, with a study of the occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 232, p. 99, 1909.

As till is unassorted it commonly has a low porosity and a low specific yield. However, there are great variations in the composition and texture of the till in different places, depending largely on the kind of rocks that supplied the débris of which it consists. Some till is compact, with clayey materials predominating; some have only meager amounts of fine material, being mainly sandy or stony. The clayey till is so nearly impervious that it yields little or no water; the sandy or stony till is somewhat more porous and permeable and may be a fairly good water producer.

Intermingled and interbedded with the till in the most intricate, chaotic, and varied manner, and also in many places lying beneath or above it, are beds and lenses of water-laid sand and gravel. In some places these deposits lie between two till sheets of distinctly different ages and represent an interglacial epoch, but many of them do not have this significance. In most localities where the drift is thick, beds of water-bearing sand and gravel are encountered by wells, but these beds vary greatly, even in the same locality, in thickness, coarseness of material, and depth. Only rarely can a particular bed be traced by means of well sections for more than a few miles. The ground moraine, which was laid down over wide areas at the base of the ice sheet, is generally more compact and contains fewer sandy and gravelly beds than the terminal and recessional moraines, deposited at the margins of the melting ice sheets.

Glacial drift covers a large part of the northern United States. It commonly lies at the surface and is spread over the older formations as a mantle, ranging in thickness from only a few feet to a few hundred feet. On account of its low permeability the till tends to become saturated nearly to the surface, even on hilltops and hillsides. As it is usually the first formation penetrated throughout the large region in which it occurs and as it usually yields some water, it has become the source of supply for a very great number of wells in the United States—chiefly domestic wells that are not subject to heavy demands. Because of the comparative ease with which the till can be excavated, the shallow depth to water in it, and the need for large infiltration surfaces in order to get adequate supplies for even domestic uses, a large proportion of the till wells are dug wells a few feet in diameter. Till seldom yields enough for public waterworks or large industrial plants, but in places considerable water is recovered from it by excavating extensive systems of infiltration tunnels.

Many dug wells supplied by till have exceedingly small yields but may nevertheless be considered satisfactory for domestic use. A well of this type in Connecticut, 24 feet deep and 3¼ feet in diameter, tested by Palmer[22] was found, with a drawdown of 3½ to 4 feet, to

[22] Palmer, H. S., Ground water in the Southington-Granby area, Conn.: U. S. Geol. Survey Water-Supply Paper 466, pp. 49-50, 1921.

have an inflow of only 37 gallons in 2¾ hours, which was less than a quart a minute and only a third of a gallon an hour for each square foot of seepage surface (fig. 39). Yet this well is pumped with a small gasoline engine and supplies a small private system of waterworks that includes an air-pressure tank. Its yield and storage capacity are sufficient to supply the small demands made upon it by the family, and consequently the well is considered entirely satisfactory.

In recent years many of the shallow dug wells in the areas of deep glacial drift have been abandoned for deeper drilled wells which are only a few inches in diameter but which extend to gravel beds associated with the till. These drilled wells generally yield supplies that are larger, more reliable in time of drought, and less liable to pollution. They generally yield as much as 5 gallons a minute, and many that tap sand or gravel beds associated with the till will yield as much as 100 gallons a minute.

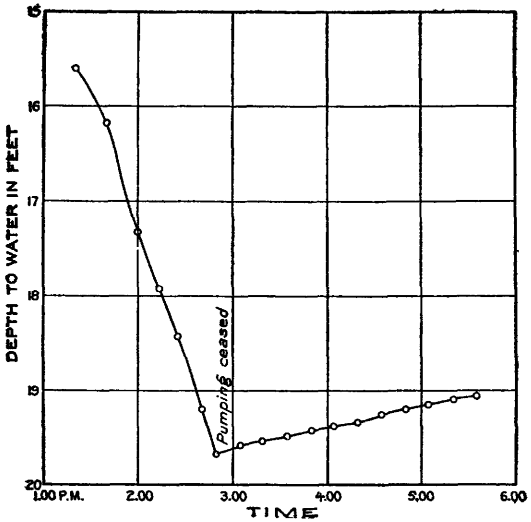


FIGURE 39.—Diagram showing the very small yield of a satisfactory domestic well, 3½ feet in diameter, ending in till in Connecticut. (After H. S. Palmer.) From 1.30 p. m. to 2.50 p. m. the well was pumped at about 2¾ gallons a minute. From 2.50 p. m. to 5.35 p. m. no water was withdrawn, but the water level in the well rose only 0.59 foot, indicating an inflow of only 37 gallons in 2¾ hours.

The following table gives the mechanical composition and porosity of seven samples of glacial drift in Connecticut, which is being studied by Norah E. Dowell, of the United States Geological Survey, and shows the difference between the till and the outwash deposits in both assortment and porosity. Some of the beds of outwash are much coarser than the samples of outwash shown in the table, but these coarser beds are equally well sorted. The till is derived chiefly from gneiss and schist and is of a stony type, poor in clayey materials. Samples 3 and 5 are shown in figure 38.

Mechanical composition and porosity of glacial drift in Pomperaug Valley, Conn.

[By Norah E. Dowell. Mechanical composition in percentage, by weight.]

	Diameter (millimeters).	Glacial outwash.			Till.			Glacial lake deposit.
		1	2	*3	4	5	6	7
Gravel to boulders	More than 10	....	....	....	50.0	50.0	75.0	....
Gravel	10 to 2	....	13.8	7.3	8.7	4.7	5.9	1.5
Fine gravel	2 to 1	22.2	6.9	6.3	5.2	3.0	2.9	1.7
Coarse sand	1 to 0.5	26.9	19.4	10.8	6.4	6.1	2.7	1.6
Medium sand	0.5 to 0.25	33.9	28.2	31.0	7.7	10.3	4.0	2.0
Fine sand (0.25 to 0.1 millimeter).	0.25 to 0.125	13.5	22.6	35.2	7.0	9.5	3.7	21.9
Very fine sand (0.1 to 0.05 millimeter).	0.125 to 0.074	2.2	6.4	6.8	4.2	4.8	2.1	40.3
	0.074 to 0.05	1.0	2.2	2.3	7.0	7.4	2.9	29.9
Silt	0.05 to 0.005	.3	.4	.3	3.8	2.9	.8	1.0
Clay	Less than 0.005	.1	.1	.0	.0	1.3	.0	.1
Effective size (millimeter)		.13	.13	.13	.07	.07	.27	.06
Uniformity coefficient		4.9	3.8	2.8	150+	150+	....	1.9
Porosity (per cent by volume)		31.8	37.1	38.5	16.3	15.8	8.7	41.9

The occurrence of water in the till is described in many of the publications of the United States Geological Survey.[23]

UNASSORTED OR POORLY ASSORTED ALLUVIUM.

Although running water is a great assorting agency and is thus perhaps the most important agency for the production of water-bearing formations, yet not all deposits made by running water are well assorted. The arid intermontane basins of the western part of the United States are underlain in most places by several hundred feet of rock waste washed from adjacent mountains, most of which was deposited by running water. These stream-made deposits include numerous beds of excellent water-bearing gravel, but the bulk of the material is not well assorted, consisting of pebbles and boulders embedded in a matrix which itself is a mixture of gritty and clayey débris (Pl. VIII, *B*). Such poorly assorted deposits are probably the result of very erratic conditions of stream flow, whereby an area may at one moment receive coarse material carried by a raging flood and soon after receive only the clayey sediments of a dissipated stream, which fill the spaces between the coarser débris. The well-assorted gravels are probably deposited in definite stream channels leading out from the canyons that discharge the surface waters from the mountains. The poorly assorted deposits are probably formed in the areas between these principal channels that are also occasionally flooded. As stream deposition proceeds the courses of the principal channels are shifted many times, and the gravel beds of the abandoned channels gradually become covered with the more poorly assorted alluvium. Hence the deposit as a whole ultimately develops into a

[23] See Water-Supply Papers 114, 232, 254, 255, 256, 257, 293, 374, and 400, and Geologic Folios 96, 97, 100, 113, 114, 149, 156, 188.

thick mass of ill-assorted alluvial material ramified by numerous stringers of well-assorted gravel. These ramifying stringers form ground-water arteries. Each alluvial fan has a system of such arteries, all branching out from the mouth of the parent canyon and hence very favorably situated for receiving water from the canyon. The ground-water arteries function very much like the arteries of the human body, and the interstices of the poorly assorted matrix function like the capillaries of the body. The hydrostatic pressure at the principal point of recharge at the mouth of the canyon sends the water through the arteries as fast as it can ooze out through the capillaries of the clayey matrix.[24]

The poorly assorted alluvium of the fill of intermontane basins has some resemblance to the till of glacial deposits, both in its texture and in its water-bearing properties, although on an average it is more porous and permeable. Like the till, it lies immediately below the surface throughout extensive areas and is penetrated by numerous dug wells that receive enough infiltration for domestic and livestock supplies but generally not enough for larger requirements, as for public waterworks or irrigation. Where large supplies are needed wells are drilled deep into the fill in order to penetrate the interbedded deposits of clean gravel, which are quite as erratic in their occurrence as the gravel deposits of glacial drift but which are commonly encountered by drilled wells and furnish very copious supplies of water.

The alluvium of large perennial streams is better assorted than that of the erratic intermittent and ephemeral streams of arid regions, but it also generally includes much poorly assorted material that yields water in only meager amounts. As a rule a drilled well in alluvial deposits derives most of its water from one or more definitely recognized gravel beds that form only a small part of the total well section. The bulk of the material penetrated is likely to be a more or less heterogeneous mass, often called clay by the driller, which may yield considerable seepage to a well of large diameter but is ignored by drillers in search of strong water-bearing beds. Even the good water-bearing gravels of alluvial deposits are likely to contain much intermingled fine material that must be cleaned out before a well will yield freely.

The following table shows the mechanical composition and porosity of several samples of alluvium in the fill of desert valleys in California, which are being studied by David G. Thompson. All the materials shown in the table would probably yield water, and some would doubtless yield enough for irrigation. Nos. 1, 2, and 3 are rather fine grained and well assorted. The porosity of Nos. 1 and 2 and doubtless also of No. 3 is high. Nos. 4 and 5 are not so well assorted,

[24] The conception of ground-water arteries was suggested to the author by Mr. Paul Bailey, of the California State Water Commission.

but, like Nos. 2 and 3, they contain enough gravel and coarse or medium sand to be developed as sources of water by pumping out the fine material through wells that are sunk into them. This method of development is, of course, possible only in materials that are incoherent, so that the small grains are free to be carried by the percolating water. No. 4, which is graphically shown in figure 38, probably has the best possibilities as a water bearer because of its large contents of gravel and coarse sand. Many of the water-bearing beds in alluvium consist of coarser material than any shown in this table and will yield water more freely without special development.

Mechanical composition and porosity of alluvium in Mohave Desert region, Calif.

[By David G. Thompson. Mechanical composition in percentage, by weight, of air-dried sample.]

	Diameter (millimeters).	1	2	3	4	5
Gravel	More than 4			3.3	5.3	0
	4 to 2	0.1	2.5	1.6	6.9	0.7
Fine gravel	2 to 1	.2	3.9	1.1	15.6	3.4
Coarse sand	1.0 to 0.5	.4	8.7	5.1	24.7	7.5
Medium sand	0.5 to 0.25	3.0	17.0	19.0	25.8	15.0
Fine sand (0.25 to 0.1 millimeter).	0.25 to 0.125	12.4	19.1	49.0	9.4	18.9
Very fine sand (0.1 to 0.05 millimeter)	0.125 to 0.074	15.8	17.4	15.2	4.5	15.7
	0.074 to 0.05	44.3	19.2	4.4	2.2	16.8
Silt [a]	0.05 to 0.005	23.1	11.0	.9	5.5	16.7
Clay [a]	Less than 0.005	3.6	1.1	.5		5.2
Effective size (millimeter)		.02?	.045	.09	.10	.02?
Uniformity coefficient		3.5?	4	2.5	7	8?
Porosity [b] (per cent by volume)		43.1	35.7			

[a] The sizes smaller than 0.05 millimeter were separated by allowing the material to settle in water as explained on p. 125.
[b] Porosity determined by A. F. Melcher.

1. Pleistocene alluvium from alluvial fan of ancient Mohave River, near Yermo, Calif. Now dissected by present river.
2. Pleistocene alluvium lying about 5 feet below No. 1, and separated from it by gravel.
3. Alluvium deposited in recent flood by Mohave River on fan near lower end of the river.
4. Alluvium near Newberry Spring in Lower Mohave Valley, Calif., probably deposited by ancient Mohave River.
5. Alluvium in lowest part of alluvial slope about 10 miles from base of Sierra Nevada, built by small streams, Indian Wells Valley, Calif.

LIMESTONE AND RELATED ROCKS.

No rock differs more radically with respect to yield of water than limestone. Some limestone formations rank among the best aquifers; others are as unproductive as shale. These differences are due only in part to the original texture of the rock; they are chiefly the result of differences in the extent to which it has been subjected to the solvent action of percolating waters.

Newly formed limestone may contain abundant interstices between the calcareous fragments of which it is composed. However, on account of the ease with which the calcareous materials are compacted or are dissolved and again precipitated, the original interstices tend to close up or to become filled. Hence, the older limestones are generally compact and impervious except in bedding planes and joints (Pl. IX, *A* and *B*) and in passages developed by solution, generally along bedding planes or joints (Pl. VII, *B*). If the formation has always lain at considerable depths, under conditions of sluggish water circulation, it is likely to be a poor source of water. If it has been in a topographic or structural position that induced active circulation of water it is usually cavernous and is likely to be a good aquifer (Pl. X, *A*).

The limestone is dissolved most rapidly above the water table, where there is abundant and rapid percolation and where the percolating waters contain carbon dioxide, which is necessary for dissolving limestone. However, the crevices that occur above the water table are not available as reservoirs of ground water; only those below the water table can yield permanent supplies to wells. Obviously an ideal sequence of events has occurred where a limestone was exposed to leaching until it became cavernous and was then subjected to changes that raised the water table and immersed the cavernous part in the zone of saturation. This sequence of events has occurred in the north-central United States and has made excellent aquifers out of some of the prominent limestones of that region, such as the Galena limestone and the Niagara limestone. Before the glacial epoch these limestones lay at the surface over wide areas and were subjected to extensive weathering. Then they were overridden by successive ice sheets and became covered with glacial drift. To-day the water table in most places passes through the drift mantle, leaving the underlying cavernous limestone within the zone of saturation. In these areas limestone is considered an excellent water bearer, and many limestone wells will yield from 100 to several hundred gallons a minute. Where these same formations are so deeply buried that they have never been leached they are often not regarded as aquifers by deep-well drillers, who search for the water-bearing sandstones between the limestones.

A similar sequence of events has rendered some of the limestones of Florida cavernous. The region was uplifted and the limestones were leached until many large solution openings were developed. Then it subsided several hundred feet, bringing the cavernous limestone below the water. These submerged caverns have become great water conduits from which issue some of the largest springs in the United States.[25]

Not only is there a wide range in the yield of different formations of limestone and of the same formation in different localities, but there is also great diversity in the yield of similar wells in the same locality and ending in the same limestone. The reason is obvious. The search for water in a creviced formation involves a large element of chance. One well may hit a large cavern with an almost inexhaustible supply of water; another well, only a few feet

[25] Matson, G. C., and Sanford, Samuel, Geology and ground waters of Florida: U. S. Geol. Survey Water-Supply Paper 319, pp. 207–210, 1913.

away, may miss all the large openings and may consequently receive but little water. These differences are illustrated in figure 40.

Limestone formations give rise to large springs. Their waters occur in large, definite openings and are generally discharged to the surface from such openings. One of the largest springs in the United States is Silver Spring, in Florida, which flows from a single large opening in limestone. According to measurements made by the United States Geological Survey, it yields from 342 to 822 cubic feet a second, or from 153,000 to 368,000 gallons a minute.[26] The water emerges from a basin over 35 feet deep in a stream that is reported to be about 50 feet wide and 10 feet deep, and the water is so clear that objects lying on the bottom are distinctly visible.[27] About 15 to 20 other limestone springs in the United States are known to yield more than 100 cubic feet a second (chiefly in Florida and in the Ozark region of Missouri and Arkansas); and springs yielding as much as 1 cubic foot a second (about 450 gallons a minute) are fairly abundant.

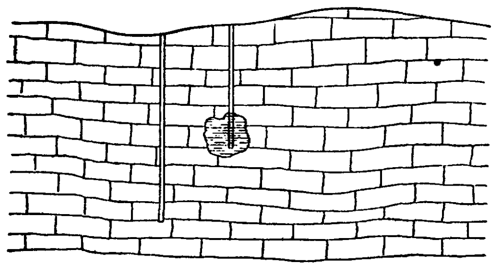


FIGURE 40.—Diagram showing difference in conditions in wells in limestone not far apart. (After G. C. Matson.)

Many regions underlain by limestone have no surface run-off; all their surface water passes through sink holes into subterranean passages in the limestone. Thus, streams of considerable size may pass beneath the surface, flow for miles through subterranean passages, and eventually reappear at the surface. On plateaus and mountains composed of limestone the ground water is generally far below the surface, and it is usually difficult or impossible to develop ground-water supplies. Good examples of such conditions are afforded by the Tintic mining district in Utah (see pp. 80–81 and fig. 28) and by the plateau country of central New Mexico.[28]

As a rule, the boundary between the zone of saturation and the zone of aeration is about as definite in limestone as in other rocks. The joints and solution passages, both great and small, generally form a network of connected openings that are filled with water up to a certain level, which is the water table. In some places, however, a well will pass through limestone and will not strike a water-bearing crevice until it has been drilled a considerable distance below the water table. When it strikes the water-bearing crevice, the water will gen-

[26] U. S. Geol. Survey Water-Supply Paper 27, p. 45, 1899; also Water-Supply Paper 452, p. 61, 1920.
[27] Matson, G. C., and Sanford, Samuel, op. cit., p. 29.
[28] Meinzer, O. E., and Hare, R. F., Geology and water resources of Tularosa Basin, N. Mex.: U. S. Geol. Survey Water-Supply Paper 343, pp. 170–175, 1915.

erally rise in the well about to the level of the water table. Some of the large caverns contain streams that do not differ greatly from surface streams. Like the surface streams, they generally flow about at the level of the water table. As the result of a heavy rain or the rapid thawing of snow they may receive great quantities of surface water directly through sink holes and may, like the surface streams, become greatly enlarged. In these times of flood they may lose some of their water by percolation into the smaller crevices, but at low stages they are fed by the body of ground water that occupies all crevices below the water table. Rarely there is a passage through the limestone that leads from a sink hole, where water is taken in, to a point of discharge at a lower level, without extending down to the water table. Such a subterranean passage is essentially a dry wash that is arched over by a natural bridge. Its discharge is extremely irregular and ceases as soon as the flood water has disappeared. Subterranean streams that do not extend to the water table are rare because the water entering a sink hole will follow any available opening down to the water table, and if its channel is above the water table it will tend to wear it down to that level. These processes are well illustrated by the following description of the occurrence and work of water in the limestone that underlies the Shenandoah Valley, in Virginia:[29]

The caverns of the Shenandoah Valley are far more numerous than the casual visitor would be likely to imagine. The rocks in which this broad trenchlike valley has been excavated by water are mainly limestone, and wherever these rocks occur the existence of caverns is indicated by two unfailing signs—the presence of innumerable water sinks and the absence of brooks tributary to the rather regularly spaced creeks. The brookless tracts receive a due share of rainfall and must obviously contribute water to maintain the flow of the creeks and rivers, but their contributions are not delivered by way of the surface drains but through underground channels that supply copious springs in the deep valleys. The sinks are rude funnels, by means of which surface waters are diverted to the subterranean waterways.

The development of extensive underground waterways in limestone formations like those of the Shenandoah Valley hinges upon the two geologic facts that large masses of rock are always cut by joints and that limestone is dissolved by rain water, which always contains more or less carbon dixoide. Surface water entering fissures, joint cracks, and bedding planes attacks the limestone walls and thus by a process of etching converts close fractures and joints into relatively open crevices. As this process of solution goes on lateral connections will be made from crevice to crevice, and the downward etching of the linked openings will be halted only when the subsurface water channels have become closely adjusted to the water table controlled by surface streams.

Marble does not differ essentially from hard limestone in so far as its water-bearing properties are concerned.

Dolomite, or magnesian limestone, is somewhat less soluble than true calcareous limestone, but it also becomes cavernous when it is subjected to weathering.

[29] U. S. Geol. Survey Press Bull., July 17, 1922, based on investigations by A. C. Spencer.

Chalk, which is a soft, fine-grained, friable limestone, is abundant in Europe, where it forms an important source of water,[30] but it is scarce in the United States. It occurs in the Upper Cretaceous of the Great Plains, where it furnishes water to some wells. It yields water in moderate amounts from joints and solution passages, which are open near the surface but tend to close under pressure at considerable depths.[31]

Shaly limestone, calcareous shale, and marl are formations intermediate in composition between limestone and shale. These formations are also intermediate as producers of water. They are generally softer and less cavernous than limestone but somewhat more friable and brittle and hence more jointed than shale.

Caliche occurs in the fill of desert basins. It consists of this fill so extensively cemented and perhaps in part replaced by a calcareous precipitate that it has the appearance of a massive, conglomeratic limestone. It is formed near the surface and does not generally attain a depth of more than a few feet.[32] Layers of caliche may, however, become deeply buried by sediments deposited later, and several such layers may be encountered in drilling.[33] Caliche is too compact to yield much water, and where it lies near the surface it retards the downward percolation of water from the surface. It is, however, not entirely impervious. It contains some crevices and may become soft and fairly permeable when thoroughly wet.

The following description of the occurrence of water in the Highbridge and Lexington limestones in Kentucky, by Matson,[34] affords a good illustration of the character of cavernous limestone and dolomite aquifers:

The Highbridge limestone contains but few large underground streams; most of the water channels in it are small. Along Kentucky River gorge, however, some of the channels form good-sized caverns.

The Lexington limestone, except in the vicinity of large surface streams, occupies areas having gently rolling topography and a heavy deposit of porous soil. These conditions favor the occurrence of a large amount of underground water and the development of extensive systems of underground drainage, and the formation contains innumerable small channels and many large caverns. Indeed, most of the counties in which this limestone covers a large area can boast one or more caverns. The best known and probably the largest of these is the Russell Cave, in Fayette County, which is reported to have been explored for nearly a mile. Several of the other caverns in the Lexington limestone have been explored shorter distances. Most of these caverns contain streams, many of which give rise to large springs. Few of the caverns are accessible except in dry weather. The small underground chan-

---

[30] Woodward, H. B., The geology of water supply, pp. 158-169, London, Edward Arnold, 1910.

[31] See U. S. Geol. Survey Geol. Atlas, Folios 100, 113, 114, and 156, which contain short descriptions of water in chalk.

[32] Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, pp. 65-66, pl. 10, 1913.

[33] Idem, p. 55, pl. 9.

[34] Matson, G. C., Water resources of the Blue Grass region, Ky.: U. S. Geol. Survey Water-Supply Paper 233, pp. 46-49, 1909.

nels that lie above the level of surface drainage also give rise to many springs. Below the level of the surface drainage the underground channels in the Lexington limestone are apparently small, but most of them seem to be full of water, while the channels nearer the surface are practically never entirely filled.

The Highbridge limestone is penetrated by but few shallow wells, and most of the deep wells sunk in it obtain mineral water. More than 95 per cent of the drilled wells of the upland obtain water from the Lexington limestone. The possibility of procuring water depends entirely on the chance of encountering one of the underground channels. In some localities few wells fail to procure an adequate supply; in others many failures are reported.

The occurrence of water in the Galena and Niagara dolomites in Iowa is described by Norton[35] as follows:

Sealed between two shales, the Galena dolomite forms a water bed of no little value. Where dolomitized and nonargillaceous it is porous—not, indeed, sufficiently to permit free percolation but enough to give rise to incipient waterways along joints, bedding planes, and specially porous layers, and these have developed by solution into definite channels capable of a large yield to wells. Though no assurance can be given that the drill will strike one of these channels, it has done so in a good many of the Iowa wells. The yield from the Galena and Platteville is in some places abundant, amounting in some of the wells in Davenport and Rock Island to 300 or 400 gallons a minute. At Mason City the entire city supply is drawn from these formations. In shallow wells the Galena affords excellent water throughout its area of outcrop. Its base at least is saturated, and southward and westward, where it dips under the Maquoketa shale, it continues water-logged. Thus it remains the chief source of farm wells in large areas where wells penetrate the Maquoketa shale and are drilled to depths of 300 to 400 feet to reach it. In West Dubuque there is an area so cut up by labyrinthine passages underground and so full of water that it is known as the Poland Pond. On one occasion a small skiff was taken down a shaft and used in exploring this ground. The springs issuing from the Galena dolomite are among the most copious in the State. This is a direct result of the many channels, some cavernous in size, that have been opened by solution along bedding planes and intersecting joints. The chief horizon is that at the base of the formation, immediately above the impervious Decorah shale. Over the wide areas where the Galena is the country rock, large numbers of sink holes pit the surface and lead the storm waters directly into the fissures and thus furnish a ready supply of water. In some places storm waters are led so directly to a near-by valley that they form a large part of the supply of some spring, which readily responds to every rainfall by showing a proportional increase in volume and turbidity. Such springs, however, should be avoided, as they are very liable to pollution by organic impurities washed into the sink holes with the water.

The Niagara transmits water very freely, not only through many small cavities but especially through a large number of joints, cracks, bedding planes, and open crevices formed by solution in the soluble rock, through which an active circulation obtains. In number and size, however, the open cavities are small compared with those of the Galena. The water absorbed over the large intake area of this formation is held by the impervious shale beneath from passing downward, so that at least the base of the limestone is waterlogged and the contact with the shale forms a strong well and spring horizon. The margin along the bold eastern escarpment is so well drained that in many places it is difficult to secure good wells. Farther back the ground-water level rises until along the margin of the overlying Devonian the forma-

[35] Norton, W. H., Hendrixson, W. S., Simpson, H. E., Meinzer, O. E., and others, Underground water resources of Iowa: U. S. Geol. Survey Water-Supply Paper 293, pp. 103-106, 1912.

tion is almost entirely saturated and wells obtain an abundance of water soon after penetrating it. Though rarely dry at the base, it is subject to the disadvantage common to other limestones—the possibility that the drill may go a long distance, even through the formation to the shale, without striking one of the crevices or water passages. Perhaps the most constant water-bearing bed of the formation is an especially porous, granular stratum lying some distance above the base. The water from the Niagara is usually copious enough for the public supply of towns of 1,000 or 2,000 population or for minor industrial purposes, though in some places it may be unsatisfactory as a boiler water on account of its hardness. Springs are very numerous along the base of the Niagara escarpment and in the heads of the narrow ravines which deeply notch it. Owing to the numerous thin shaly layers interbedded with the limestone, springs are abundant well up within the formation.

GYPSUM AND SALT.

Gypsum is most commonly found as an impurity in shale and limestone, but in places it forms beds as much as 100 feet thick.[36] It is softer and more soluble than limestone. It allows slow general percolation and readily develops sink holes and solution passages, which, however, do not remain open under much pressure (Pls. X, *B*; XI, *A*, *B*, and *C*; and XIII, *A* and *B*). In a few places in the United States, mostly in the Southwest, there are wells that end in deposits consisting chiefly of gypsum. The yield of these wells is small unless they strike a solution passage, in which case it may be large. The water is highly mineralized.[37]

Wind-blown deposits of gypsum are of two kinds—(1) granular gypsum sand, which is at first very porous but soon becomes somewhat more compact through recrystallization, and (2) impure gypseous dust, which somewhat resembles loess and which becomes compact and clayey but apparently yields small quantities of poor water to a few wells.[38]

Beds of rock salt and other saline deposits are very soluble and hence generally contain water, which, however, has so much salt in solution that it can not be used for ordinary purposes.

PEAT AND COAL.

Deposits of both peat and coal generally contain some available ground water where they lie below the water table. Coal beds supply many springs and wells in Pennsylvania, and they constitute an important source of water for wells in eastern Montana and adjacent

[36] Meinzer, O. E., Geology and water resources of Estancia Valley, N. Mex., with notes on ground-water conditions in adjacent parts of central New Mexico: U. S. Geol. Survey Water-Supply Paper 275, p. 13, 1911.

[37] See U. S. Geol. Survey Water-Supply Papers 148, 154, and 343, which contain a few data on water in gypsum formations.

[38] Meinzer, O. E., Geology and water resources of Estancia Valley, N. Mex., with notes on ground-water conditions in adjacent parts of central New Mexico: U. S. Geol. Survey Water-Supply Paper 275, 1911. Meinzer, O. E., and Hare, R. F., Geology and water resources of Tularosa Basin, N. Mex.: U. S. Geol. Survey Water-Supply Paper 343, 1915.

497781 O-59-11

regions. In some parts of the arid West coal beds form good water bearers. In many places they are underlain by nearly impervious clays or shales, which help to retain the water. Some of the coal beds can be traced from a distance by the verdure of vegetation along their outcrops. The water from coal beds is generally clear but may be brown or nearly black. It is generally wholesome and not highly mineralized but may be sulphurous. As the coal is brittle and does not have much strength it is readily fractured. The water is probably obtained largely from joints.[39]

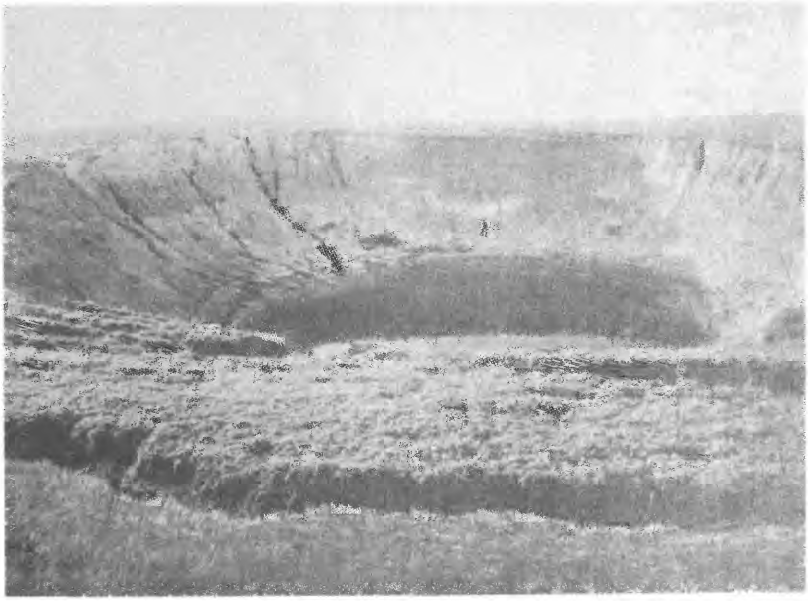
BASALT.

Basalt ranks among the important water-bearing rocks in the United States. Spread out in successive sheets over extensive areas, it forms the only source of supply throughout large sections of the Northwest and in the Hawaiian Islands. The water occurs in large joint openings (Pl. XIII, *B*) and in other cavities (Pl. XIV, *A* and *B*); it also occurs in the zones of vesicular and fragmental material between successive lava sheets (Pl. XV, *A* and *B*). This rock is so generally traversed by large openings that it takes in surface water very readily. Many surface reservoirs that have been constructed where it crops out are failures because the water sinks into the rock. Not all basalt, however, yields water. The interior parts of large lava flows are likely to be very unproductive except where they are jointed, and the openings in ancient basalts may have become sealed. Thus the so-called traps of eastern United States and the ancient basalts of northern Michigan yield only meager quantities of water.

Wells drilled into basalt in the Northwest are generally successful. As in limestone, the openings vary in size and are irregularly distributed, but in most wells drilled a considerable distance below the water table some water-bearing crevices are encountered. Yields of as much as 100 gallons a minute are not uncommon. In Quincy Valley, Wash., one drilled well was found to deliver between 900 and 1,000 gallons a minute during long periods of pumping. In Hawaii there are many strong wells supplied from basalt. Of the flowing wells on the Island of Oahu measured by the United States Geological Survey many yield more than 1 cubic foot a second (450 gallons a minute), some yield more than 2 cubic feet a second (900 gallons a minute), and one yields about 4.5 cubic feet a second (about 2,000 gallons a minute).[40]

[39] Brief descriptions of water in coal beds are given in the following publications of the U. S. Geol. Survey: Bull. 300, pp. 133–134, 1907; Bull. 447, pp. 135–136, 1911; Bull. 627, p. 12, 1916; Folio 174, p. 15, 1910.

[40] Martin, W. F., and Pierce, C. H., Water resources of Hawaii, 1909–1911: U. S. Geol. Survey Water-Supply Paper 318, pp. 188–191, 1913.



A. SALT WELL, A SINK HOLE NEAR MEADE, KANS.

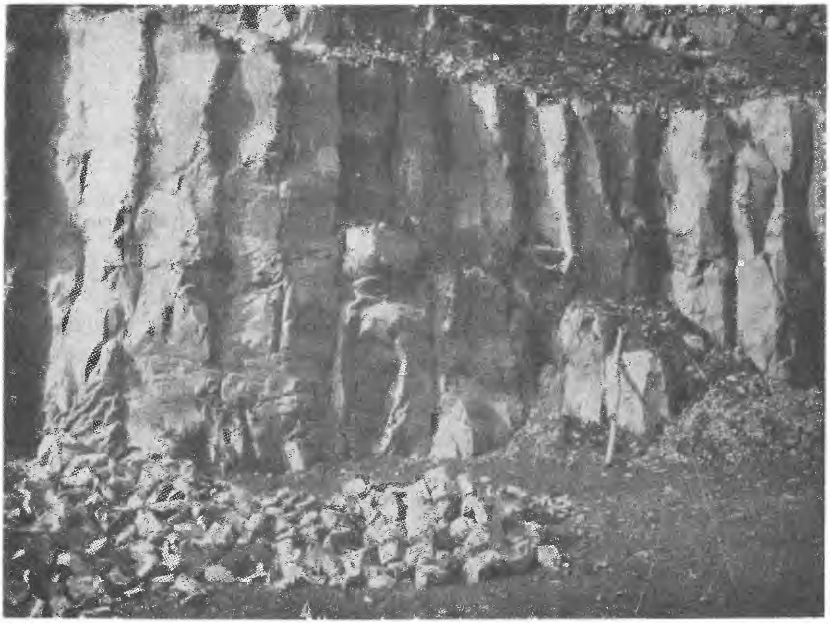
This sink hole was formed in 1879 by the collapse of the surface caused by the remova lof salt through solution in ground water. The water shown at the bottom is on a level with the water table. Photograph by W. D. Johnson.

B. ST. JACOBS WELL, A SINK HOLE IN CLARK COUNTY, KANS.

This sink hole extends down to the water table. Photograph by W. D. Johnson.

A. BIG SPRINGS, IDAHO.

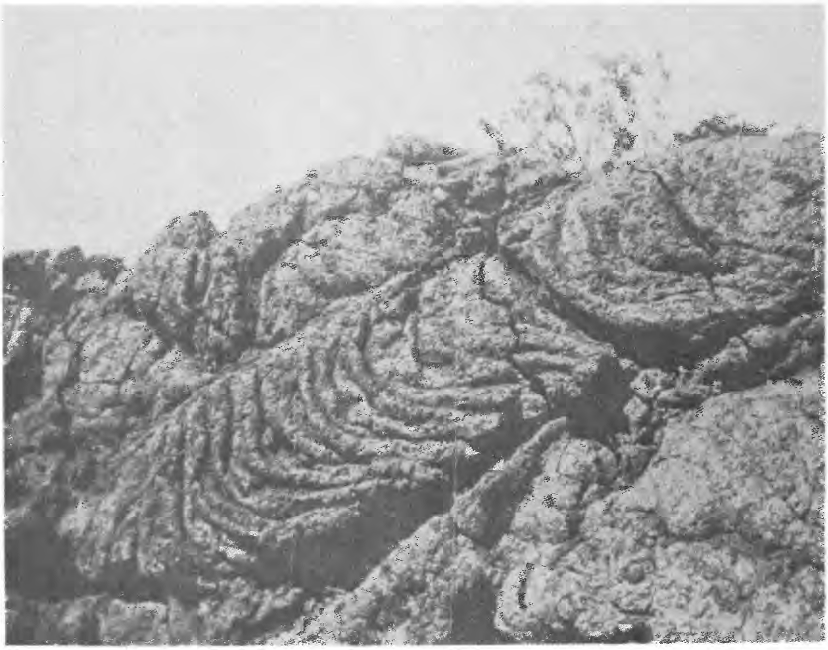
These springs flow from obsidian and yield about 190 cubic feet per second. Photograph by O. E. Meinzer.



B. BASALT WITH COLUMNAR JOINTING.

Photograph by J. P. Iddings.

A. EDGE OF LAVA BED, SHOWING FISSURE.



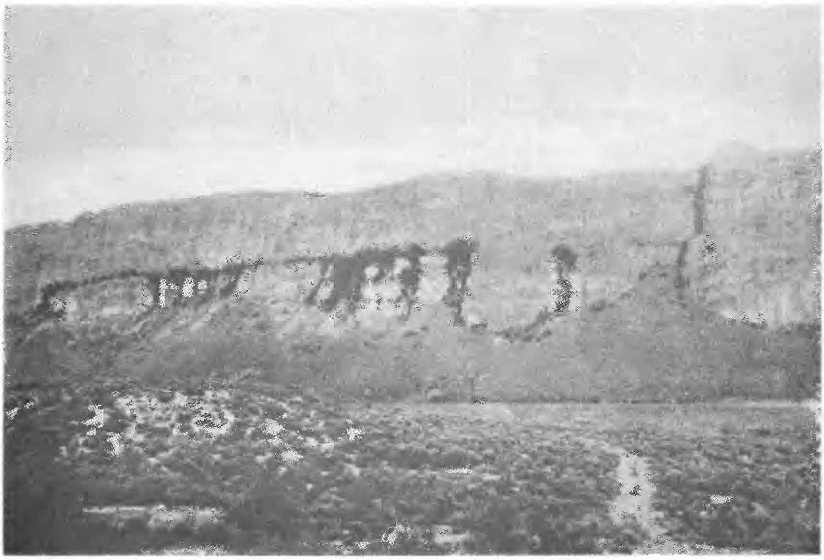
B. VIEW SHOWING ROUGHNESS OF SURFACE OF THE LAVA.

BEDS OF EXTRUSIVE BASALT, SHOWING IRREGULAR SURFACES AND LARGE IRREGULAR OPENINGS.

Photographs by O. E. Meinzer.

A. BASALT IN COLUMBIA PLATEAU, SHOWING STRATIFICATION.

Abandoned falls of Columbia River in the Grand Coulee, 400 feet high. Photograph by A. T. Schwennesen.



B. BASALT IN COLUMBIA PLATEAU, SHOWING SPRING HORIZON AT CONTACT BETWEEN SUCCESSIVE LAVA BEDS.

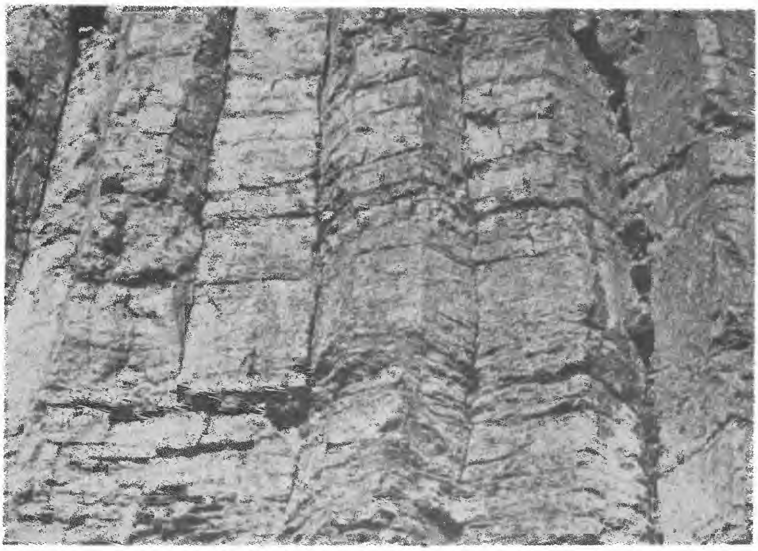
Photograph by O. E. Meinzer.

THOUSAND SPRINGS, SNAKE RIVER CANYON, IDAHO.

The water issues from the open-textured part of a lava sheet. The height of the falls is 180 feet. The springs yield enough water to supply the city of New York. Photograph by I. C. Russell.

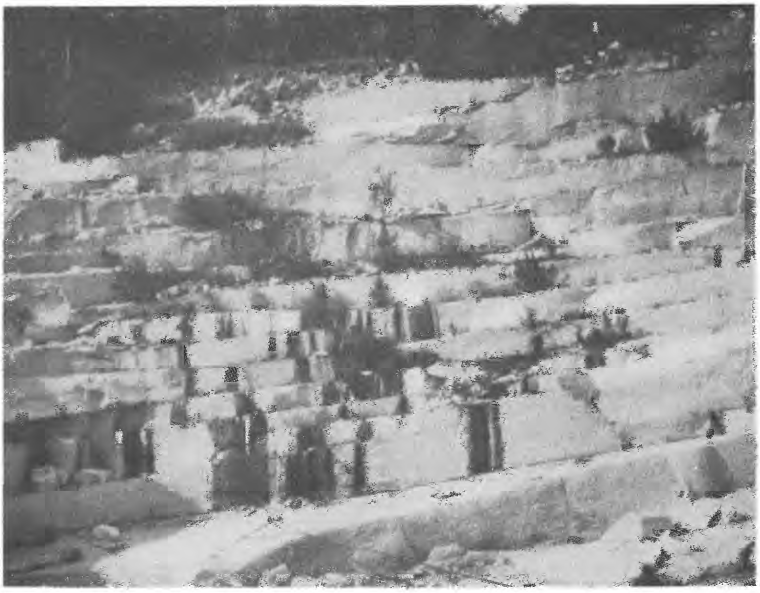
A. OBSIDIAN CLIFF, YELLOWSTONE NATIONAL PARK, SHOWING WATER-BEARING JOINTS.

Photograph by J. E. Haynes.

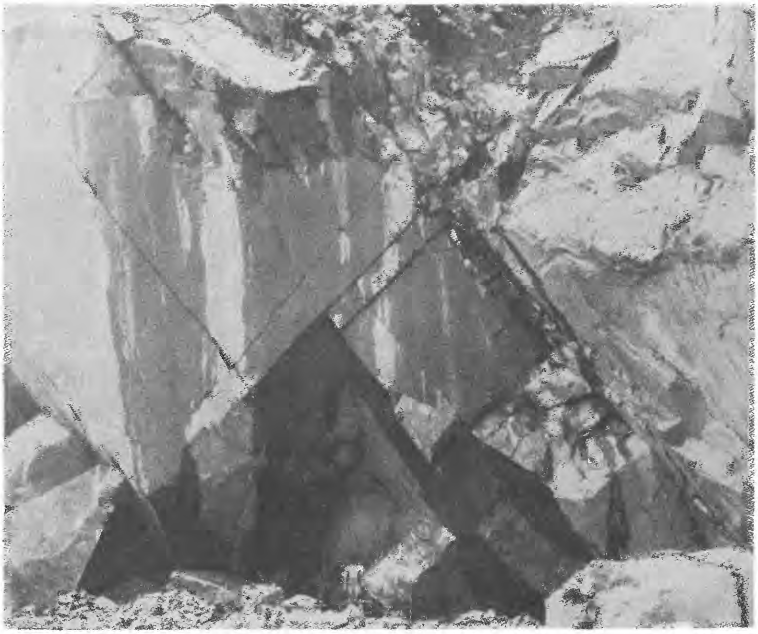


B. NEAR VIEW OF JOINTS IN THE ROCK OF OBSIDIAN CLIFF.

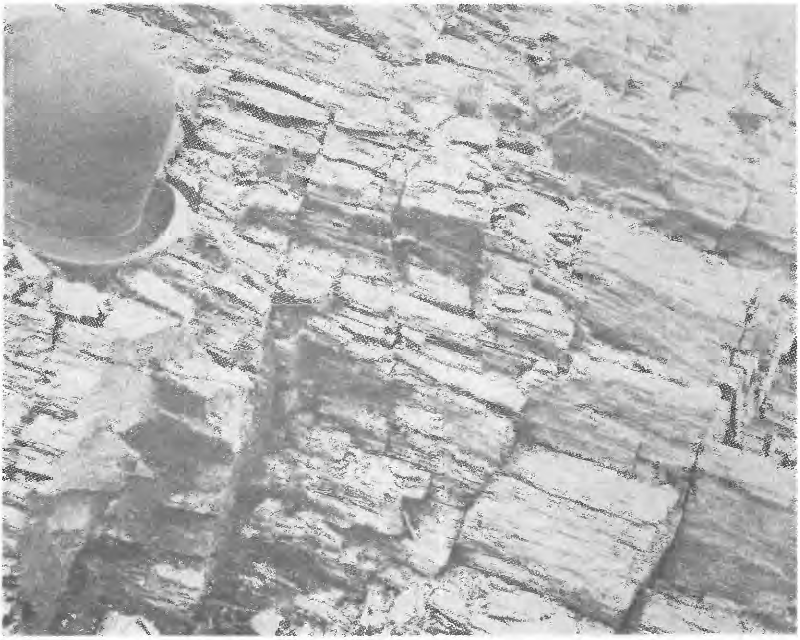
Photograph by J. P. Iddings.



A. GRANITE WITH HORIZONTAL JOINTS THAT ARE YIELDING GROUND WATER
Photograph by F. G. Clapp.

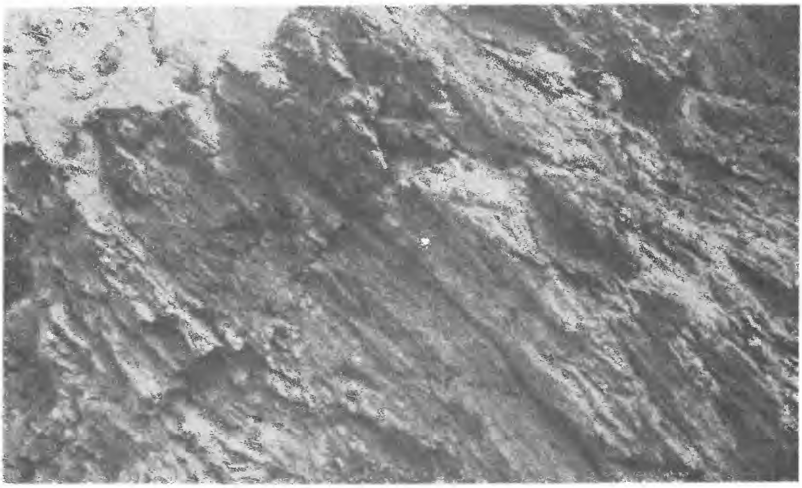


B. GNEISS, SHOWING JOINTS, SOME OF WHICH ARE YIELDING GROUND WATER.
Photograph by J. S. Diller.



A. JOINTED AND FISSILE SCHIST, SHOWING CHARACTER OF OPENINGS THAT MAY BE PENETRATED BY WATER.

Photograph by E. E. Ellis.



B. SCHIST, SHOWING FISSURES WHICH AT GREATER DEPTHS MAY AFFORD WATER SUPPLIES.

Photograph by A. J. Ellis.

A. THIN-BEDDED CALCAREOUS ROCKS OVERLAIN BY MORE MASSIVE SANDSTONE, SHOWING STRATIFICATION.

Photograph by Whitman Cross.

[illegible] SHOWING [illegible]

The occurrence of water in the basalt underlying Quincy Valley, Wash., is described by Schwennesen and the writer[41] as follows:

The basalt underlying Quincy Valley consists of a series of beds, each of which represents a separate flow. The upper crust of a lava sheet generally has a vesicular or "honeycombed" structure, caused by the escape of steam and other gases from the molten lava, and its upper surface is generally rough and broken, owing to sudden chilling of the lava. Consequently many openings, some of which are extensive, occur between the successive beds, and these are capable of holding much water. In some places the successive beds are separated by beds of tuff, but these interbedded deposits are of small volume and almost impervious and consequently furnish little storage space for water. The interior of a bed, formed of a lava that cooled gradually, is usually fine grained and compact, but in the process of cooling there was much contraction, so that joints and fissures, which provide for the storage and circulation of water, were formed throughout the mass. The total capacity of the basalt formation for water is therefore rather large.

In the western part of the basin almost all the wells obtain their water from the basalt. Near Quincy and Winchester large supplies are obtained for irrigation. A number of wells yield between 250 and 500 gallons per minute, and one well near Quincy produces between 900 and 1,000 gallons per minute under continuous pumping. Near the rim of the Columbia gorge some wells have failed to obtain adequate supplies, but throughout the rest of the region failures are rare. Most of the large yields of water are obtained from beds of the "honeycombed" texture found between layers of compact material. A few of them come from the massive basalt.

West of Quincy Valley the gorge of Columbia River extends far below the level of the water table of the deepest water-bearing bed that has been reached by wells in the basin. The loss of water from the basalt beds at the outcrops is, however, not so great as might be expected, as is shown by the form of the water table, by the large yields of wells situated within a a few miles of the gorge of Columbia River, and by the scarcity of large springs along the gorge. The retention of the water in the reservoir of basalt is probably due both to the eastward dip of the beds and to a general lack of lateral communication between the cavities in the basalt.

The following data in regard to the water supplies obtained from wells in basalt in the Hawaiian Islands are based on measurements made by tho United States Geological Survey. They give an idea of the very large supplies that may be obtained from rock of this type under favorable conditions. On December 31, 1916, there were a tctal of about 142 wells in the Honolulu city area, of which about 109 were active—that is, either flowing or capable of being pumped. When all the wells in this area are flowing or are being pumped at normal capacity about 57 million gallons a day is being drawn out of the artesian reservoir.[42] This is an average of nearly 400 gallons a minute for each well. It was estimated by Sedgwick that the entire supply delivered by wells in the city of Honolulu amounted in 1912 to about 55 cubic feet a second (nearly 25,000 gallons a minute).[43] The pumpage for the Honolulu waterworks and five large plantations on the

[41] Schwennesen, A. T., and Meinzer, O. E., Ground water in Quincy Valley, Wash.: U. S. Geol. Survey Water-Supply Paper 425, pp. 147-150, 1919.

[42] Larrison, G. K., Smith, A. G., and Sedgwick, T. F., Report of the Water Commission of the Territory of Hawaii to the Governor of Hawaii, pp. 8-9, Honolulu, 1917.

[43] Pierce, C. H., and Larrison, G. K., Water resources of Hawaii, 1912: U. S. Geol. Survey Water-Supply Paper 336, p. 128, 1914.

island of Oahu in the year July 1, 1915, to June 30, 1916, amounted to 63 billion gallons—an average of about 173 million gallons a day or 120,000 gallons a minute.[44] So far as is known all this water is pumped from wells that end in basalt.

The following data as to the yield of wells at the three principal pumping stations of the city of Honolulu, on March 9 or 11, 1920, were furnished by W. H. Bromley, the engineer in charge. These wells are supplied by basalt.

Yield of wells that supply the Honolulu city waterworks.

Pumping station.	Number of wells.	Depth of wells (feet).	Diameter of wells (inches).	Pumpage.		Drawdown (feet).	Specific capacity (gallons per minute for each foot of drawdown).
				Gallons per day.	Gallons per minute.		
Beretania	4	607	12	7,700,000	5,300	7	190
Kalihi	3	±400	12	5,200,000	3,600	3	400
Kaimuki	4	±400	12	5,500,000	3,800	1½	760
Do	1	±400	12	4,000,000	2,800		

The pumpage of ground water by a single sugar company on the island of Kauai in 1912 averaged 25,600,000 gallons a day, or about 17,800 gallons a minute.[45]

The following notes in regard to the yield of water from basalt on the island of Maui were made by the writer during a brief visit to the island in March, 1920:

On account of the saltiness of the deeper water the ground-water developments on Maui consist chiefly of tunnels run slightly below the water table and connected with shafts through which the water is pumped to the surface. The Puunene plantation has several plants for pumping ground water, with a combined capacity of fully 100 million gallons a day and a recorded pumpage in 1919 of about 18 billion gallons. One plant (Kihei No. 3), about 300 feet above sea level, delivers 20 million gallons a day (nearly 14,000 gallons a minute) with a drawdown of 12 to 14 feet, from a tunnel 260 feet long, 6 feet high, and 4 feet wide, the bottom of which is about 17 feet below the normal water level.

Basalt gives rise to numerous large springs. Many of these resemble springs from limestone in that they issue in copious volume from large, definite openings. Many also issue from the porous zones between successive lava beds, in some places making conspicuous spring horizons along cliffs formed by the lava (Pl. XV, *B*). Many examples could be given of large springs issuing from basaltic lavas

[44] Larrison, G. K., Smith, A. G., and Sedgwick, T. F., Report of the Water Commission of the Territory of Hawaii, Honolulu, 1917.

[45] U. S. Geol. Survey Water-Supply Paper 336, p. 99, 1914. See also Water-Supply Papers 318, 373, 430, and 445. The yield of basalt wells on the island of Molokai is given in Water-Supply Paper 77, by Waldemar Lindgren.

in the western part of the United States and in Hawaii. The most notable springs of this type are found in Idaho, especially those on the north side of the canyon of Snake River below Shoshone Falls, in a 40-mile stretch between Milner and King Hill (Pl. XVI). According to data collected by Crandall[46] the aggregate discharge of the springs between Milner and King Hill amounted to 3,885 cubic feet a second in 1902 and to fully 5,000 cubic feet a second in 1918, after irrigation developments had been made on the uplands.

Although the trap sheets in the Triassic rocks of the Eastern States are generally too dense to yield water, the extrusive sheets may in some places furnish moderate supplies. A group of five flowing wells in New Jersey supplied chiefly by extrusive trap has been described by Kümmel.[46a] These wells are near the base of the west or dip slope of the trap-rock ridge known as First Watchung and are 10 to 12 inches in diameter. Four of them end in trap at depths ranging from 289 to 355 feet, but the other well was drilled to a depth of 840 feet and ends in sandstone underlying the trap. A drill core showed that the trap consists of several sheets of extrusive basalt, each dense at the bottom but grading upward into porous vesicular rock, some parts being extremely porous and almost sponge-like. The weakest of these wells (331 feet deep) yielded 10 to 12 gallons a minute when pumped; the strongest (289 feet deep) yielded 40 to 50 gallons a minute by artesian flow and 220 gallons a minute in an eight-hour pumping test. When the 840-foot well was 300 feet deep and still in trap rock it was pumped at 108 gallons a minute, which lowered the water level in the well 75 feet. At first these wells together yielded 600,000 gallons a day when pumped, but after several years of service their combined yield has decreased to about 450,000 gallons.

RHYOLITE, OBSIDIAN, AND RELATED FINE-GRAINED ROCKS.

The more silicic varieties of volcanic rock differ considerably from basalt with respect to water, and as a rule they yield much smaller supplies. They contain fewer large openings and do not have such definite water horizons between successive deposits. They supply many shallow dug wells by slow seepage from their upper weathered parts and also deeper wells that penetrate fault or shear zones, where the rock may be broken and weathered to depths of a few hundred feet. In these rocks little is accomplished by deep drilling, but, where necessary, fairly large supplies can sometimes be developed by sinking numerous shallow holes or by extensive excavations below the water table. A good example of such a development in an arid

[46] Crandall, Lynn, The springs of Snake River canyon: Joint Conference of irrigation, engineering, and agricultural societies of Idaho Proc., 1918 and 1919, p. 147.

[46a] Kümmel, H. B., New Jersey Dept. Conservation and Development Ann. Rept. for 1922 (in press).

region where water is scarce is the Gemini pumping plant, in the Tintic mining district, Utah, described as follows:[47]

The water for the Gemini pumping station in the Homansville Basin is obtained from one or more shafts which are 60 feet deep and end in partly decomposed rock [rhyolite], and from two tunnels at the 60-foot level, which are about 5 by 7 feet in cross section and have a combined length of about 900 feet. At the time the plant was visited the water level was only 20 feet below the surface, but it is reported to descend nearly to the bottom in dry seasons. The pump is operated about 14 hours each day at the rate of 27 gallons per minute, and the engineer in charge estimated that the maximum yield for continuous pumping is only about 25 gallons per minute. The water is considered satisfactory for use in boilers.

The springs that issue from these more compact persilicic or intermediate types of volcanic rock are very different from the usual basalt springs. They yield smaller and less regular supplies, derived not from subterranean caverns but by slow seepage from the somewhat permeable material near the surface. In the Tintic mining district, not far from the Gemini pumping station, just described, numerous springs are found in those parts of the mountains where fine-grained persilicic or intermediate igneous rock constitutes the surface formation. The unweathered rock is nearly impervious, but the portion that has been disintegrated into loose, porous, gritty materials mantles the firm rock in localities that are sheltered from active erosion. The rain percolates into the mantle of disintegrated material but is prevented from descending far because of the underlying unweathered rock. Accordingly, the ground water either accumulates or seeps along the surface of the firm rock until it reaches a point where the rock crops out and the water is returned to the surface in the form of a spring or seep. Most of these springs are small, and as they are fed from shallow sources their flow varies greatly. The yield of a group of springs whose water is led through a pipe line to Silver City ranged from about 2 gallons to 30 gallons a minute in a period of three and one-half years, during which their flow was measured.

Rarely, however, large springs issue from fissures in rhyolite. On Warm River near Estes, Idaho, a spring yielding many cubic feet a second issues from a few definite openings at one spot in a cliff of rhyolite, forming a cascade about 50 feet high.

Obsidian, or volcanic glass, is relatively not abundant in the United States, and little attention has hitherto been given to its water-bearing properties. It occurs extensively, however, in Yellowstone Park and adjacent areas, where it grades into ordinary rhyolite. In this region it resembles basalt in being extensively jointed and in yielding abundant quantities of water from the large joint openings. The joints may also have been enlarged somewhat through the solution of the rock by the percolating water.

[47] Meinzer, O. E., Ground water in Juab, Millard, and Iron counties, Utah: U. S. Geol. Survey Water-Supply Paper 277, p. 84, 1911.

The well-known Obsidian Cliff, in Yellowstone Park, has a distinct columnar structure,[48] as is shown in Plate XVII, *A* and *B*. Water can be seen seeping from the rock at some height above the swampy tract that lies at the base of the cliff. Obsidian Creek is probably largely fed by springs from this rock. The rhyolite formation to which this obsidian belongs covers most of Yellowstone Park. Its glassy nature apparently renders it more liable to fracture and hence more permeable to water than ordinary rhyolite with stony texture that cooled more slowly and is consequently less fractured.

The Big Springs at Big Springs, Idaho, issue at the foot of a high cliff, which consists of rhyolite and spherulitic obsidian. This cliff marks the edge of an extensive timber-covered plateau with little run-off. Most of the water of these springs issues from several large vents within a distance of less than a quarter of a mile, between the pool shown in Plate XIII, *A*, and the cliff immediately to the right of the pool. Water can be seen flowing in large volume from holes in both obsidian and rhyolite. The combined flow of the springs was 190 cubic feet a second when measured on June 25, 1922, about 1 mile downstream from the springs, and 184 cubic feet a second when measured on August 29, 1922, about 400 feet below the highway bridge shown in the view.[49] These springs, therefore, rank among the largest in the United States. The temperature of the water on July 22, 1921, was 53° F.

GRANITIC ROCKS.

With respect to yielding water the coarsely crystalline igneous rocks of different mineral composition are much alike and resemble to a great extent the ordinary stony or felsitic varieties of rhyolite. They are poor water bearers and at considerable depths are almost devoid of available water. Where granitic rocks are buried beneath several hundred feet of other deposits drilling should be stopped when the granitic formation is struck, because the prospects of finishing a successful well in it are so poor as to be practically negligible.

Where granitic rocks lie at the surface, however, they yield small but reliable water supplies to many wells. In such situations they are generally the only source of ground water and may therefore be regarded as valuable aquifers. Water occurs in granitic rocks in two very different ways—in the small interstices of the somewhat decayed parts near the surface and in the joints that extend to greater depths (Pl. XVIII, *A* and *B*). The water is also recovered by means of wells of two very different types—dug wells with large infiltration surfaces, supplied chiefly from the decayed parts, and drilled wells that extend deeper and are fed chiefly by joint openings.

[48] See Iddings, J. P., Obsidian Cliff, Yellowstone National Park: U. S. Geol. Survey Seventh Ann. Rept., pp. 249–295, 1888.

[49] The first measurement was made by L. L. Bryan and the second by Berkeley Johnson, both of the U. S. Geological Survey.

Granitic rocks consist for the most part of unstable minerals that decompose under the attack of weathering agencies near the surface. Where they are not much exposed to erosion they may become somewhat altered to depths of as much as 100 feet or even more. The change is, however, very gradual from thoroughly disintegrated and often somewhat transported material near the surface to the firm unaltered rock far below the surface.[50] The disintegrated material is rendered granular and somewhat porous by the quartz grains and in arid regions also by particles of feldspar or other minerals that have broken loose without being decayed. Shallow dug wells that obtain their water from granitic residuum or decayed granitic rock are extensively used in many parts of the United States for small domestic and live-stock supplies and are satisfactory for these purposes. In a few places granitic residuum furnishes supplies for public waterworks and for irrigation. In several granite basins in San Diego County, Calif., many small irrigation pumping plants are supplied from such material. Where large supplies are required it is necessary to develop extensive infiltration surfaces by sinking a series of wells or by running tunnels out from the wells below the water level. Mountains composed of granite generally contain more springs and are more favorable for developing ground-water supplies than mountains composed of limestone, quartzite, or slate.

The following information in regard to the occurrence of water in the decomposed granite or granitic residuum of San Diego County, Calif., is given by Ellis and Lee:[51]

The most important source of ground water in the highland area is the residuum or, as it is commonly called, the "decomposed granite," which covers the bedrocks in all the highland basins and which occurs more or less generally throughout the area. This material consists of small lumps or grains of the original crystalline rocks that have been disintegrated by the removal or alteration of some of their mineral constituents. The disintegration is most complete at the surface, where in many places the rock has been completely reduced to soil, and it decreases gradually from the surface downward until, at depths ranging from 3 feet to more than 100 feet, it merges with thoroughly indurated rock. Granite is one of the most easily altered crystalline rocks and is the most prevalent rock in the area, so that by far the largest part of the residuum is derived from granite.

The porosity of residuum varies greatly, as it depends on the degree of disintegration, which is subject to wide variations, both vertically and horizontally. In one place, for example, a well may be easily dug with a pick and shovel to a depth of 50 feet or more, whereas in another place only a few rods distant blasting may be necessary at a depth of 15 to 20 feet. But as a rule the residuum is sufficiently porous and disintegrated to afford storage for water. There are many rock basins which are nearly water-tight and contain considerable disintegrated material in which water is stored. Ground water may be drained from a large area by sinking wells through the decomposed rock and digging tunnels or boring holes at right angles to the slope of the surface.

---

[50] Hall, C. W., Meinzer, O. E., and Fuller, M. L., Geology and underground waters of southern Minnesota: U. S. Geol. Survey Water-Supply Paper 256, pp. 34, 35, 49, 308-313, 316-323, 1911.

[51] Ellis, A. J., and Lee, C. H., Geology and ground waters of the western part of San Diego County, Calif.: U. S. Geol. Survey Water-Supply Paper 446, pp. 191-221, 1919.

The yield of wells has been found to range under different conditions from very small quantities to as much as 150 gallons per minute. The smallest yields are obtained from wells without laterals, in shallow decomposed rock or in unaltered rock, on upper slopes or in small ravines, or in other places where conditions are not favorable for large absorption; the largest yields are obtained from wells that penetrate residuum of considerable depth, that are provided with lateral tunnels and auger holes, and that are situated in valleys irrigated with water from an outside source. In general, it may be said that the specific capacity of the best wells in residuum is about 8 gallons a minute per foot of drawdown, that for many wells it is as low as 1 gallon a minute per foot of drawdown, and that for the poorest wells it is much less than 1 gallon.

The wells drilled into granitic rock depend chiefly on joints for their supplies. In many granitic formations there is a horizontal system of joints intersected by other less regular systems. As the joints are on the whole irregular in size and distribution the wells in the same locality differ greatly in yield. In this respect granite wells resemble limestone wells and basalt wells, but as the joints are much tighter the average yield is smaller. As in limestone and

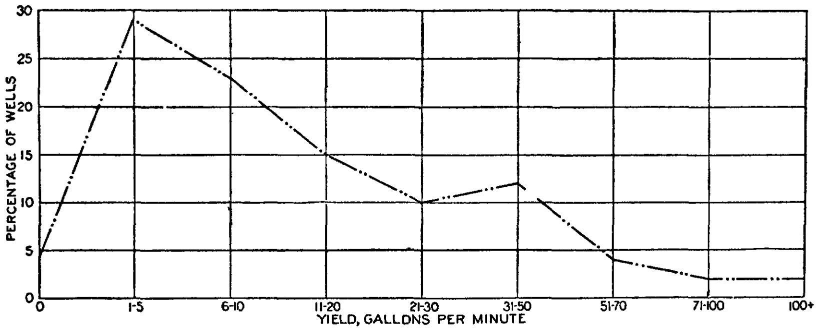


FIGURE 41.—Diagram showing yields of drilled wells ending in crystalline rocks or trap in Connecticut. (After A. J. Ellis.)

basalt the joints generally become fewer and tighter with depth. There is seldom much gained by drilling in granitic rock to depths of more than 300 feet although occasionally a large opening is struck many hundreds of feet below the surface. A well in granitic rock near Jicarilla, N. Mex., is reported to have struck a cavity at a depth of 402 feet, from which water was pumped for 48 hours at the rate of 150 gallons a minute.[52] Although success in finding water in crystalline rocks is largely a matter of chance, yet the chances of success can often be increased by selecting the well site with reference to the occurrence and dip of outcropping joints.

The experience in drilling in crystalline rocks in Connecticut is summarized by E. E. Ellis,[53] an abstract of whose statement is as follows (see also fig. 41):

[52] Meinzer, O. E., and Hare, R. F., Geology and water resources of Tularosa Basin, N. Mex.: U. S. Geol. Survey Water-Supply Paper 343, p. 175, 1915.

[53] Gregory, H. E., and Ellis, E. E., Underground water resources of Connecticut, with a study of the occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 232, pp. 91-94, 1909.

The average depth in rock in 163 wells is 89 feet, and the average total depth, including the surface material overlying the rock, is 108 feet. About 90 per cent of the wells are less than 300 feet deep, and 82 per cent are less than 200 feet. In many of the wells that have gone below 250 feet the main supply and in several the entire supply comes from seams less than 250 feet deep. From a study of the recorded wells it would appear, therefore, that if a well has penetrated 250 feet of rock without success the best policy is to abandon it and to sink in another location. The average yield of 123 wells in crystalline rocks is 12.7 gallons a minute and their average depth 108 feet. Dry wells are not common, but 12½ per cent of the wells examined yield less than 2 gallons a minute. Some water has been found at all depths at least as far down as 800 feet.

Information obtained in regard to granite wells in Maine is summarized by Clapp[54] as follows:

As most of the joints in granite are mere seams, the amount of water contained in them is necessarily small. Occasionally as much as 30 gallons a minute has been obtained with a steam pump, but in most wells the amount yielded is not over 10 gallons a minute. On account of the great irregularity of the spacing of joints in granite, the success of any well in this kind of rock is wholly a matter of chance, dependent on whether the location is a fortunate one with respect to the arrangement of the joints. * * * Of two wells drilled within 50 feet of each other one may be a failure and the other a marked success, the result depending on whether or not a water-bearing fissure is struck. * * * For ordinary domestic purposes in the Eastern States 1 or 2 gallons a minute will usually suffice for a single family, but if less water than this is obtained the well is generally ranked as a failure. A few experienced drillers report one or two wells out of a hundred that do not yield sufficient water. * * *

[Of 82 wells in Maine that are at least 50 feet deep and that end in granite] 87 per cent were successful enough for ordinary domestic use. The other 13 per cent were wells in which water was absent or insufficient in quantity, or in which it was not usable because the wells were drilled near the ocean and salt water entered them along the open joint cracks. Of 72 successful wells only 3 were reported to produce over 50 gallons of water a minute. * * *

To summarize, it is safe to say that under the conditions which prevail in the New England States about 90 per cent of the wells drilled in granite will find enough water to supply the domestic needs of a family. In about 85 per cent enough water will be found within 100 feet of the surface. A well should not be abandoned without sinking at least 200 feet, but drilling deeper than 200 feet is not advisable, although a few wells have procured water at greater depths. If a well owner does not obtain sufficient water at 200 feet, he is advised to sink a second well 100 feet or more distant, and the chances are good that the second attempt will be successful.

GNEISS AND SCHIST.

The various kinds of gneiss and schist resemble the crystalline igneous rocks with respect to their yield of water. In Plate XVIII, *B*, is shown an outcrop of jointed, water-bearing gneiss that illus-

[54] Clapp, F. G., Occurrence and composition of well waters in the granites of New England: U. S. Geol. Survey Water-Supply Paper 258, pp. 40-47, 1911.

trates well the character of rock of this kind although some of the water shown in the view may come from a surface source. The schists doubtless carry some water in small openings parallel to their schistosity, but most of them are softer than the granitic and gneissic rocks, and hence their water-bearing joints are closed at shallower depths. They do not have well-developed horizontal joints such as are common in granite. The character of openings in some jointed and fissile schists is shown in Plate XIX, *A* and *B*.

In his work in Connecticut E. E. Ellis examined 23 schist wells and 73 gneiss wells and found that the schist wells have an average depth of 110 feet and an average yield of 14 gallons a minute and the gneiss wells have an average depth of 131 feet and an average yield of 12 gallons a minute.[55] The following statements are made by Ellis [56] regarding the occurrence of water in schist and gneiss.

Little difference can be distinguished between the occurrence of joints in schist and that in gneiss, and in fact the two rocks grade into each other so completely that it is in some places difficult to say whether a rock is a schist or a gneiss.

The marked development of horizontal joints characteristic of granite is lacking in these rocks, and the more regular character of the vertical joints tends to produce a different manner of circulation through the rock. A single well, instead of drawing water from an area surrounding it on all sides, will draw from long distances through the feeding fractures and the vertical fractures connecting with them.

The wells in schist and gneiss have nearly the same average yield, but those in gneiss average 15 per cent deeper than those in schist. It is possible that the supply for the wells in schist comes not only through the joints but also through fissility openings or small fractures parallel to the schistosity. Such fractures are common near the surface and owing to their inclination might well absorb considerable volumes of water. Because of the small size and lack of continuity of these openings they would yield water very slowly to the well but might give an important amount in the aggregate. The derivation of a supply through such openings, which would have their greatest development near the surface, would account for the relative shallowness of wells in schist.

That fractures parallel to the schistosity may be important carriers of water is well shown on the east bank of Connecticut River above Hadlyme Landing, where there is a long exposure of fissile schist and a number of small springs issue from partings parallel to the schistosity.

VOLCANIC SEDIMENTS.

Deposits of fragmental volcanic material, such as agglomerates, volcanic breccias, and tuffs, are in many places porous enough to yield considerable water. In some places they form good aquifers between successive lava sheets. In Sacramento Valley, Calif., according to Bryan,[57] several wells drilled into the Tuscan tuff, which, however, includes some waterworn gravel, have yields of more than 600

[55] Ellis, E. E., Occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 160, p. 27, 1906.

[56] Gregory, H. E., and Ellis, E. E., Underground water resources of Connecticut, with a study of the occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 232, pp. 98-99, 1909.

[57] Bryan, Kirk, Ground water for irrigation in the Sacramento Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 375, pp. 9-10, 1916.

gallons a minute. In the vicinity of Honolulu there is much coarse porous volcanic ash which is very permeable and gives rise to a number of rather large springs. On the island of Hawaii much dense yellow ash mantles the lava or is interbedded with it. This ash yields small supplies in a few places but is more important in preventing downward percolation and thus producing perched water bodies in the overlying lava.

SUMMARY.

The unconsolidated deposits yield their water from the spaces between the fragments, which have generally been somewhat rounded by wear. The best unconsolidated water-bearing material is coarse, clean gravel. Next to gravel comes coarse sand. Unconsolidated water-bearing materials that yield smaller amounts but still supply many successful wells are the sediments of finer grain, such as loess and fine sand, and the mixtures of large and small grains, such as till, many alluvial deposits, and the products of rock decay that are still in place.

The consolidated rocks are of two kinds—those produced by solidification of molten magmas and those developed from unconsolidated sedimentary deposits through pressure, cementation, and recrystallization. Both kinds are generally broken into blocks and yield most of their water from the cracks or joints between the blocks or from porous zones and open passages developed by the decay and solution of the rocks where the water penetrates these cracks. The less thoroughly cemented sandstones yield most of their water from the original spaces between the grains, and they are on the whole the most important water bearers among the consolidated rocks. Next to sandstones rank limestones, which yield most of their water from large open passages produced by the solution of the rock, and basaltic lavas, which yield water from large openings produced when the lavas solidified and from open joints resulting from the rapid cooling of the solidified masses. Most of the other hard rocks, such as granite, quartzite, shale, slate, and schist, yield small amounts from joints or zones of decayed rock.

Among all kinds of rocks the best water bearers are deposits of gravel. Next to gravel come sand, sandstone, limestone, and basalt. Among the many kinds of rock material that do not yield water freely but are nevertheless drawn upon where first-class aquifers are lacking are the fine-grained and poorly assorted unconsolidated deposits and the hard rocks with only tight joints. The most completely unproductive of all materials are the true clays and fine silts, whose original interstices are too minute to yield water and which are too soft to have joints or other secondary openings.

CHAPTER III. STRUCTURE OF ROCKS AND ITS INFLUENCE ON GROUND WATER.

ROCK FORMATIONS.

The earth's crust consists of layers, or strata, of rocks of various kinds, lying one upon another, and massive or foliated bodies of rock that underlie or intersect these stratified series. Most of the sedimentary rocks and some of the igneous and metamorphic rocks are more or less stratified (Pls. V, *A*; VI, *A* and *B*; VIII, *B*; IX, *A* and *B*; XI, *A*; XV, *A* and *B*; and XX, *A* and *B*). Most of the igneous rocks, however, form massive bodies which solidified from fluid lavas that were intruded into or extruded through the stratified rocks.

A rock formation is a more or less distinct unit of the earth's crust consisting of stratified or of massive or foliated rocks of one or more kinds. Formations of stratified rocks range from a few feet to hundreds of feet in thickness, and they may extend over thousands of square miles, either at the surface or buried beneath other formations. In most places there are several formations lying one upon another, and these may be successively penetrated when a well is sunk. Formations differ from one another in their water-bearing character, and there are also likely to be important differences in the same formation at different horizons and in different localities. Therefore, a study of the ground water of a region involves, among other things, a study of the surface distribution of each formation and of its character, thickness, and depth below the surface in each locality.

GEOLOGIC SECTIONS.

The sedimentary formations and the extrusive igneous formations have been laid down in succession, one upon another. Thus, a given region may for long ages have been under water, or in some other position in which it received successive deposits of sediments or of lava. These deposits may still underlie the region—the oldest at the bottom, and the youngest at the top. They constitute a record of the history of the region during the periods of their deposition. The character of each formation shows the physical conditions under which it was deposited, and the fossils included in it show what kinds of animals and plants lived at the time of its deposition.

If a deep well is sunk in any region it may penetrate various formations laid down in that region during the geologic ages of the past. As a rule it will penetrate the youngest formation first and thence pass through successively older formations. Exceptions to the rule are found (1) where intrusive rock underlies a formation that existed before the intrusion occurred, (2) where the earth's crust has been closely folded and the folds have been overturned so that the older formations rest upside down upon the younger, and (3) where the earth's crust has been broken and the rocks on one side of the break have been thrust over those on the other side.

A correct log of a well gives a geologic section of the earth at the place in which it is sunk to the depth reached by the well. A geologic section may also be given by other excavations, either artificial or natural, such as mine shafts, railroad cuts, or gorges cut by streams. A dug well or other excavation that is large enough for a man to enter has the great advantage that the successive deposits can be carefully examined as they exist in place; a drilled well gives much less detailed and less accurate information but has the advantage that it can readily be sunk much deeper than the larger excavations. A geologist will utilize all kinds of opportunities to collect data from which to construct a geologic section of the region he is studying. He will examine natural outcrops and the exposures in artificial excavations and will also obtain the available logs of wells, especially of deep wells that extend to formations not reached by other excavations.

The principal clue to the ground-water conditions of a locality is its geologic section. The character, thickness, and succession of the underlying formations give the most important data as to the existing aquifers and the depths at which they can be tapped. For studies of ground-water conditions well records are especially valuable, because they give direct information as to the quantity, quality, and head of water obtainable from the successive formations, whereas all these properties can be forecast only with considerable uncertainty from examinations of exposures alone. Much can be foretold about the water-bearing properties of a formation by examining its exposures and applying the principles outlined in the two previous chapters; but there is generally considerable difficulty in making hydrologic forecasts based entirely on lithologic characteristics. Perhaps the chief difficulty lies in the fact that in most available exposures, especially in natural exposures, the rocks are not seen in their unmodified condition but are greatly altered by weathering.

Innumerable examples could be given of geologic sections and their use in developing ground-water supplies, but the essential principles involved are simple and can be adequately illustrated with a single example. The city well at Manchester, Iowa, is 1,870 feet deep and is situated on land 926 feet above sea level. It revealed the following section, briefly stated:[1]

[1] Norton, W. H., Hendrixson, W. S., Simpson, H. E., Meinzer, O. E., and others, Underground water resources of Iowa: U. S. Geol. Survey Water Supply Paper 293, pp. 306-309, 1912.

Condensed record of city well at Manchester, Iowa.

	Thickness.	Depth to bottom of formation.	Altitude of bottom of formation with respect to sea level.
	Feet.	*Feet.*	*Feet.*
Niagara dolomite	225	225	+701
Maquoketa shale	205	430	+496
Galena limestone to Platteville limestone, inclusive	354	784	+142
St. Peter sandstone	33	817	+109
Shakopee dolomite	65	882	+ 44
New Richmond dolomite	49	931	− 5
Oneota dolomite	275	1,206	−280
Jordan sandstone	90	1,296	−370
St. Lawrence formation (dolomite, sandstone, etc.)	242	1,538	−612
Dresbach sandstone	177	1,715	−789
Shale	155	1,870	−944

In this section the most productive aquifer is reported to be the Jordan sandstone, and other good water bearers are the Niagara dolomite and the St. Peter sandstone. Maquoketa shale will not yield much water, and the formations below the Jordan sandstone are also nearly barren of available water, the sandstones being fine grained, clayey, and cemented.

The information contained in the section as printed in full in the paper cited will obviously be of great practical value when other deep drilling is contemplated in the vicinity of Manchester. The loss of such information would be serious, yet this frequently happens if the well log is not placed in a permanent record, as by publication. The section shows with considerable accuracy that in future deep drilling in that vicinity the St. Peter sandstone will be struck about 142 feet above sea level, and that the Jordan sandstone, which is the best aquifer underlying the vicinity, will be struck about 280 feet below sea level; also that it will probably not be profitable to drill below the Jordan sandstone. The records of additional deep wells in the same vicinity will also have value because they will supplement and check the information given by the record of the first well. The records of all deep wells, or at least several of the most accurate and detailed records, should be preserved for each locality. These records should give the section in greater detail than appears in the above condensed record, and they should include all available information as to the yield, head, and quality of water from each important aquifer.

The practical use that can be made of available well records in forecasting ground-water conditions is shown by the experience at Waterloo, Iowa, 45 miles west of Manchester. After an epidemic of typhoid fever in this city caused by the use of surface water, attention was turned to possible supplies from wells, and W. H. Norton,[2]

[2] Op. cit., pp. 259-260, 1912.

representing the Federal and State geological surveys, was detailed to make an investigation. On the basis of the record of the Manchester well and a few other deep wells in that part of the State, he made a forecast which is shown in the following table, together with the results afterward obtained by drilling.

Condensed forecast of strata at Waterloo, Iowa, and section of deep well subsequently drilled.

	Depth to bottom of formation (feet).	
	Forecast.	Actual.
Devonian limestone	125	158
Niagara dolomite	260	265
Maquoketa shale	425	480
Galena limestone to Platteville limestone, inclusive	835	815
St. Peter sandstone	915	862
Shakopee dolomite, New Richmond sandstone, and Oneota dolomite	1,315	1,205
Jordan sandstone	1,415?	1,362

It will be noted that the Jordan sandstone was struck 110 feet nearer the surface than was predicted. Norton also predicted that the well would have an artesian flow not exceeding 300 gallons a minute from a 6-inch hole; the 8-inch hole that was drilled produced an artesian flow of 290 gallons a minute.

STRATIFICATION.

Most sedimentary formations consist of sheets or layers of rock that are very thin in comparison with the areas over which they are spread. Thus, the St. Peter sandstone, one of the most prominent aquifers in the north-central United States, is known to underlie large parts of Michigan, Ohio, Kentucky, Indiana, Illinois, Wisconsin, Minnesota, Iowa, Missouri, Arkansas, Nebraska, Kansas, and Oklahoma, forming a practically continuous layer of sandstone not less than 300,000 square miles in extent, and yet it has an average thickness of only about 100 feet. Over at least a large part of this vast area it consists of clean quartz sand. So distinctive is it that in many localities it is easily identified as the St. Peter by experienced drillers.[3]

The formations above and below the St. Peter sandstone shown in the Manchester section are likewise distinctive and persistent. They were laid down one after another and hence occur in the same succession wherever they are found, although the upper formations of the Manchester section may be absent, or younger formations than are found at Manchester may be present. These facts are well shown

[3] Fuller, M. L., Underground waters of eastern United States: U. S. Geol. Survey Water-Supply Paper 114, p. 223, 1905.

in figure 42. The succession of formations is the same at each of the four cities shown, where the St. Peter sandstone lies beneath the Galena and Platteville and rests upon the Shakopee dolomite. At Waterloo and Ackley the Maquoketa shale overlies the Galena dolomite, and the Niagara dolomite (Silurian) overlies the Maquoketa shale, but at Dubuque the Niagara, the Maquoketa, and most of the Galena and Platteville are absent, doubtless having been eroded away by Mississippi River. Here the drill starts in the lower part of the Platteville and very soon reaches the St. Peter sandstone. On the other hand, at Waterloo there is Devonian limestone that is not present at Manchester, and at Ackley the drill passes first through rocks of the Kinderhook group, then through the Devonian limestone, and then hits the strata of dolomite which lie at the surface at Man-

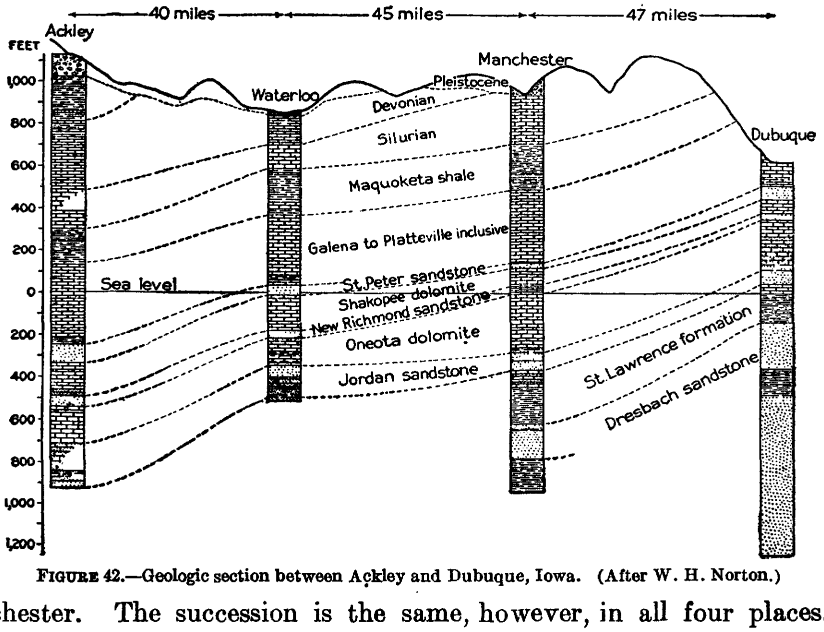


FIGURE 42.—Geologic section between Ackley and Dubuque, Iowa. (After W. H. Norton.)

chester. The succession is the same, however, in all four places. After leaving the St. Peter the drill penetrates in succession the Shakopee dolomite, the New Richmond sandstone, and the Oneota dolomite and then, in every place, enters that productive aquifer, the Jordan sandstone. The Dubuque and Manchester wells were carried far into the formations below the Jordan sandstone, and it is probable that these same formations would be struck at Waterloo and Ackley if the wells were drilled deeper.

The succession of formations shown in figure 42 is not exceptional but was chosen as a good example of the geologic and ground-water conditions in regions underlain by sedimentary rocks. Equally good examples of the persistence through wide areas of series of formations are afforded by the sedimentary beds underlying the Atlantic Coastal

Plain and by the Dakota sandstone and overlying deposits in the Great Plains and Rocky Mountains.

Not only do the sedimentary formations of a series lie on one another like a pile of books, but most of the formations are themselves stratified—that is, they consist of a succession of layers or beds, resting one upon another like the leaves of a book (Pls. VI, *A* and *B*; XX, *A* and *B*). Successive layers may differ in composition and compactness, or they may be very much alike but separated by films of different materials that cause partings between them. Many limestone formations consist of layers several inches thick, with clayey partings (Pl. XX, *B*). Some shale formations consist of exceedingly thin layers having somewhat the appearance of sheets of paper (Pl. VI, *A* and *B*).

All stratification is the result of changes in the physical conditions under which deposition occurred. The outstanding differences between successive formations are due to large and permanent changes; the minor differences in successive layers are due to local or tempo-

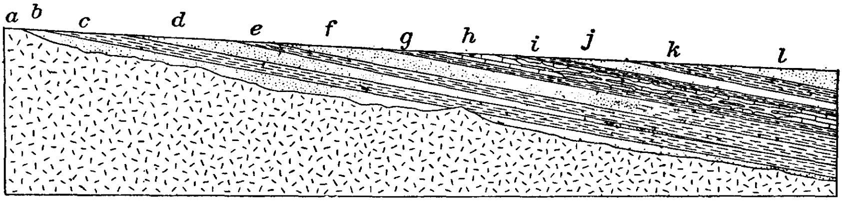


FIGURE 43.—Diagrammatic section of Atlantic Coastal Plain, showing changes in formations from place to place. (After L. W. Stephenson and J. O. Veatch.) *a*, Basal complex of crystalline rocks; *b*, *d*, *j*, *l*, sandy beds that yield water; *c*, *e*, *g*, *i*, *k*, clayey beds that do not yield much water; *f*, sandy water-bearing bed that changes to non water-bearing clay; *h*, limestone that is cavernous in upper part and becomes compact and noncavernous as it passes to greater depths. The water-bearing bed *b* is interrupted by an irregularity in the basal complex; the water-bearing bed *d* pinches out between the underlying and overlying clayey beds.

rary changes. The clayey partings between similar layers of limestone may be due to storms of exceptional violence that caused turbidity in waters which were usually clear, but the innumerable partings of some shales may be the result of ordinary changes in the weather or of annual weather cycles.

Stratification is of vast importance in the occurrence of ground water. The significance of the interbedding of aquifers with non water-bearing formations has been illustrated by means of the Manchester section. The more minute stratification within a formation also very largely controls the occurrence of water. Thus, the available water of an aquifer may be localized in certain porous beds or in the partings between beds of the same kind (Pl. IX, *B*).

LATERAL GRADATION OF STRATA.

A stratified formation generally changes gradually from place to place, both in thickness and in character of rock (fig. 43). Obviously this may be due to local differences in the conditions under which deposition occurred. Thus, a stream flowing from high mountains out upon a plain generally deposits its boulders and pebbles near the mountains and carries the silt and clay far out upon the plain. Thus, also, at some places along a shore there is a beach consisting of clean gravel, the movement of the waves and currents being adequate to agitate and ultimately carry away any finer materials that are washed into the body of water; at other places along the shore the waves and currents are not so strong, and hence sand or mud is deposited. Outward from shore there is generally a gradual change from thick accumulations of coarse débris to progressively thinner deposits of finer and finer sediments, and where the water is clear limestone may be forming.

Such lateral gradations are obviously of great significance with respect to the occurrence of ground water and must be studied in any adequate ground-water survey. The aquifers beneath the Atlantic Coastal Plain are relatively coarse at their outcrops and, as a rule, are found to become thinner and of finer grain seaward, away from the source of the sediments. Consequently, some formations of the Coastal Plain that are excellent water bearers near their outcrops become less and less satisfactory toward the coast—for example, the beds marked *d*, *f*, and *h* in figure 43. A similar lateral gradation, with a pronounced change in ground-water conditions, is found in the northern part of the Great Plains. A thick series of alternating beds of shale and water-bearing sandstone in Montana (the Montana group of the Upper Cretaceous) changes very gradually toward the east, away from the old land mass that furnished the sediments, until in South Dakota it is represented by a deposit of nearly pure shale, of less aggregate thickness, which is worthless as a source of water (Pierre shale). In figure 42 only slight lateral gradations are shown, and such as are shown are due partly to errors in the well logs. As a matter of fact, however, the recognized aquifers yield less water in the Ackley well than in the wells farther east.

In both glacial drift and alluvium the structure is very chaotic. Lenses and stringers of water-bearing sand and gravel occur irregularly and give way abruptly to impervious clays. This rapid lateral gradation is illustrated in figures 44 and 45. Figure 44 gives sections of the glacial drift in two counties in southwestern Minnesota, where the drift is exceptionally thick. It illustrates the radical changes that are to be expected from place to place. Figure 45 gives sections of the alluvial fill of a desert basin and is especially impressive because the four wells whose sections are given are in the same locality.

Although the general water-bearing conditions of both glacial drift and alluvium are well known, in sinking a well into these formations there is always uncertainty as to the depth at which water will be

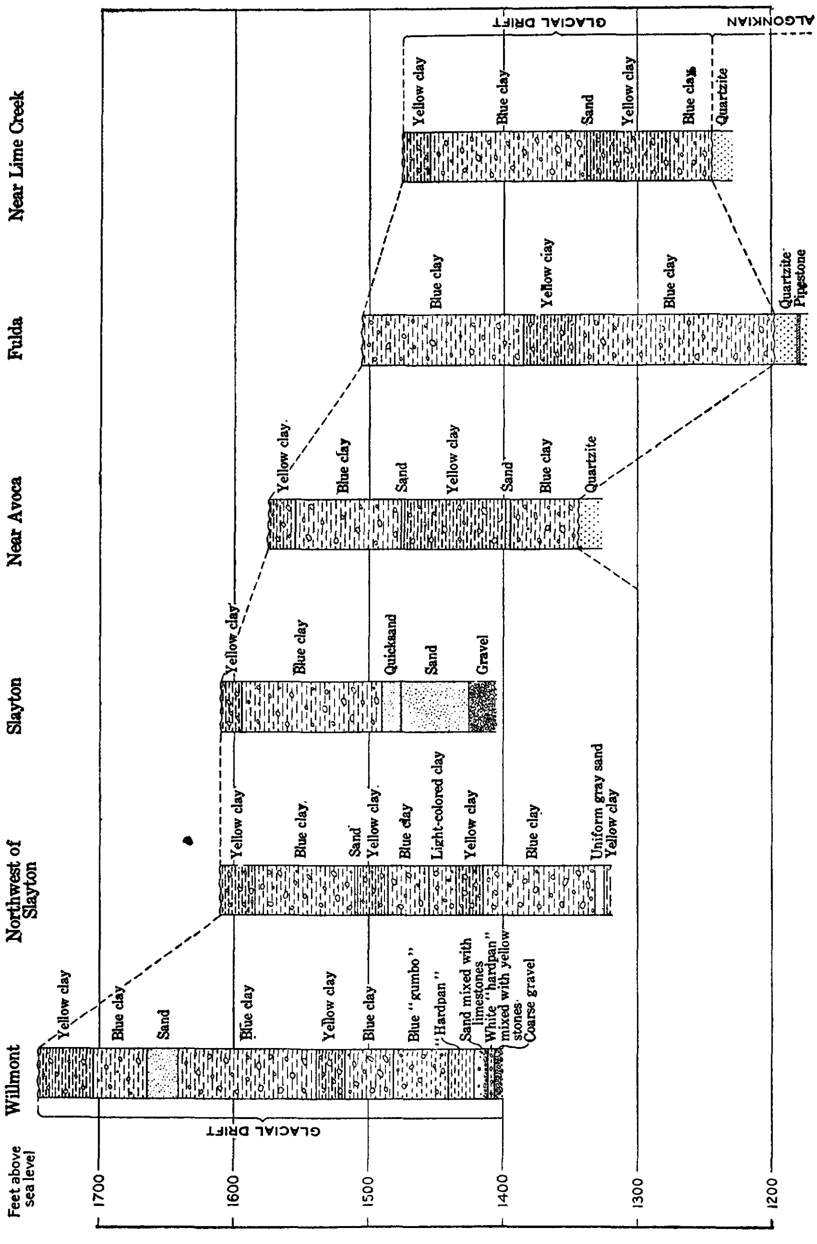


FIGURE 44.—Geologic sections of glacial drift in southern Murray County and northern Nobles County, Minn., showing changes from place to place.

struck and the quantity that will be found, even though a number of wells have already been put down in the vicinity. The extreme local variations in drift and alluvium, as shown in figures 44 and 45, are in striking contrast to the uniform conditions shown in figure 42,

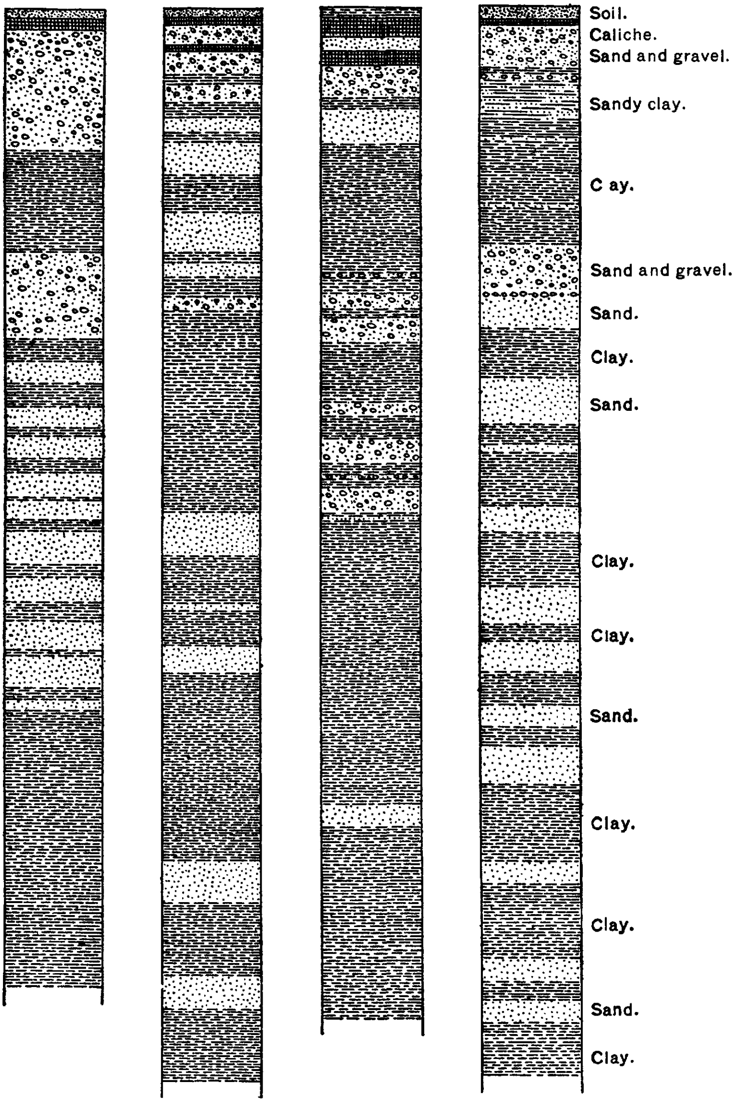


FIGURE 45.—Sections of alluvium in the desert basin near El Paso, Tex., showing abrupt changes from place to place. The wells that furnished the sections are all on the same tract of a few acres. (After G. B. Richardson).

where for 132 miles and indeed over a much wider area not shown in the figure there is so little lateral variation that the approximate depth and character of the principal water bearers at any place can be predicted with much confidence.

RELATION OF ORIGIN OF FORMATIONS TO THEIR STRUCTURE AND WATER-BEARING CHARACTER.

To evaluate rightly a formation as a water bearer and to understand its variations from place to place, it is helpful to know the origin of the formation. Glacial drift, for example, has a very chaotic structure and consists of nearly impervious stony clay with interbedded lenses of water-bearing sand and gravel. In the valleys in the drift-covered area and beyond the limits of the drift sheets there are great deposits of porous gravel made by the streams that flowed from the melting glacial ice. Such deposits are perhaps the strongest water bearers in the northeastern and central parts of the United States.

Alluvium differs from glacial drift in important respects, but it is also irregular in structure and includes much water-bearing sand and gravel. It is commonly confined to stream valleys, but in arid lowlands adjacent to mountains deposition by streams may be so rapid and extensive that the entire lowlands may become deeply underlain by alluvium, as in the intermontane basins of the western part of the United States and on much of the Great Plains. Deposits made in lakes or in the ocean are much better stratified than either glacial drift or alluvium, and they have fewer local irregularities. Their composition, like that of drift and alluvium, depends largely on the kind of rocks whose erosion supplied the material out of which they were formed.

CORRELATION OF FORMATIONS.

The correlation or determination of the relative age of formations in different localities is often difficult. It depends on either tracing one or more beds continuously from one locality to the other or identifying the same bed or beds in the two localities. Such identification depends on recognizing characteristic physical properties or characteristic fossils. If the two localities are not far apart their beds may often be easily correlated on the basis of their physical properties; but if they are considerable distances apart such correlation is impossible, or at least uncertain, because of the lateral changes in beds and because of the similarity of different beds. It may be obvious that a bed of sandstone that crops out on one side of a valley is the same as a similar bed of sandstone that crops out on the other side; but if it crops out some miles away it may belong to an entirely different formation, and the formation which consists of sandstone in the first locality may either not be present or may have changed in character between the two localities so as to be represented by a shale bed. If the two outcrops of sandstone are in different parts of the country it is probable that the beds do not belong to the same formation. Fossils afford much the best means for correlating widely separated sections; but certain distinctive physical characteristics may make it possible to identify a bed in widely separated outcrops or well sections. In nearly all parts of Iowa where the Prairie du Chien group has been reached in drilling the lithologic characteristics which these rocks show at their outcrops have been found quite unchanged.[4]

The fundamental bearing of geologic correlations on ground-water forecasts is illustrated by a very simple section represented in figure 46.

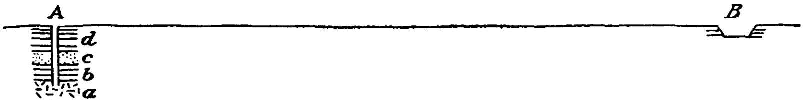


FIGURE 46.—Diagrammatic section showing relation of geologic correlation to location of ground water. *A* is a locality in which the geologic section and ground-water conditions are known; *a* is crystalline rock, *b* and *d* are shales containing different kinds of fossils, *c* is sandstone, which is assumed to be the only good aquifer in the locality. At *B* the geologic and ground-water conditions are not known. Obviously, the ground-water prospects are better if the shale that crops out at *B* is found, by its included fossils, to be the bed *d* than if it is found to be the bed *b*, for if the shale at *B* is the bed *b* then the aquifer *c* is absent.

METHODS OF CORRELATING WELL SECTIONS.

The methods of correlation based on examination of outcrops and the study of fossils yielded by the outcropping strata pertain to geology in general and need not be described in this paper. The methods of correlation based on study of well records and examination of samples of drillings are, however, of peculiar importance in connection with studies of ground water. Correlation from well records and drillings is peculiarly difficult except where a core drill is used. The following excellent discussion, which applies particularly to conditions in Iowa, is quoted from Norton,[5] whose wide experience and close application to the subject make his statements very valuable:

AVAILABLE DATA.

The data on which a geologic investigation of deep wells must rest consist of records made and samples of drillings collected when the wells were put down. Necessarily they are largely second-hand and are incapable of verification. A report such as this [Water-Supply Paper 293] deals with thousands of statements and observations made by many individuals, and the writer can do little except to determine the lithologic character of deep-well drillings, and in drawing inferences from these he must accept the reports of others as to the thicknesses and location of the strata which they represent. Fortunately, many owners of deep wells and many other citizens realize the scientific and practical value of the facts which can be obtained when a well is being drilled and at that time only, and these persons have placed on record many valuable

[4] Norton, W. H., Hendrixson, W. S., Simpson, H. E., Meinzer, O. E., and others, Underground water resources of Iowa: U. S. Geol. Survey Water-Supply Paper 293, pp. 68-69, 1912.

[5] Idem, pp. 34-40. An unusually interesting example of correlation by means of interpreting well sections is afforded by U. S. Geol. Survey Prof. Paper 90, pp. 69-94, 1914 (a deep well at Charleston, S. C., by L. W. Stephenson, with a report on the mineralogy of the water, by Chase Palmer).

data as to diameters of the bore and casings, fluctuations of water in the tube, depth, discharge, and head of water horizons and have obtained both the driller's log and samples of the drillings. In practically every place where such data have been gathered and preserved they have been placed at the service and disposal of the surveys. Unfortunately, of many wells little or nothing, except the existing head, discharge, and quality of the water, is known or can ever be known. In many parts of the State the writer is quite in the dark as to artesian conditions and is unable to make reliable forecasts for towns desiring to sink deep wells, not because no deep wells have ever been drilled within the area but because when they were put down no record was made of the essential facts.

COLLECTION AND STORAGE OF SAMPLES OF DRILLINGS.

Since the beginning of this investigation a special effort has been made to obtain full sets of samples of the drillings of the deep wells of the State, and it is on these samples that the geologic part of this report is largely based. Where such samples are taken directly from the slush bucket and labeled at once with the exact depth from which they were drawn, they form the most authentic record possible of the strata penetrated. When thus taken, at intervals not exceeding 10 feet and at every "change" in the strata, they afford a lithologic record and section inferior in value only to an exposure of the edges of the strata in an outcrop. Such reliable data have been obtained from an exceptionally large number of Iowa deep wells.

The value of sets of cuttings from some wells has been impaired by the neglect of precautions which should be obvious. Thus, if the samples are taken only at every "change" of the strata, it is left entirely to the judgment of the workman who empties the contents of the slush bucket to decide whether or not there has been any change. Several hundred feet of limestone, including two or more geologic formations, may be represented by a single sample. The depth is not always carefully taken, and remeasurements of the well on completion have shown that the driller's estimates of depth placed on samples or in the log were incorrect. If, however, the inaccuracy affects all depths alike little serious error is likely to result.

Some samples of drillings seem to have been labeled from memory after a considerable lapse of time. This fact affords an explanation of the reported occurrence of drift clays 1,000 feet and more below the surface, and perhaps also of the occurrence of several samples of nonmagnesian limestones of Platteville facies below the St. Peter sandstone. Some samples seem to have been scraped up from the ground instead of being taken in some clean receptacle immediately from the sand pump. The cinders which may be included are easily disregarded, but the admixture of chippings from higher levels is serious. In one or two extreme cases it seems probable that at the completion of the well the workmen went over the outwash from the slush bucket, dug up a sample here and there, and labeled it according to their recollection. But even such a record may be of value if nothing better is available.

The samples collected under the direction of the United States [Geological] Survey were sent to Washington in stout canvas bags provided with labels and were there transferred to wide-mouthed glass bottles with screw aluminum covers. In the collection made earlier for the Iowa State [Geological] Survey most of the samples were taken directly from the slush bucket, put into empty cigar boxes, labeled, and shipped to the writer at Mount Vernon, where they were transferred to wide-mouthed glass bottles for permanent preservation, each sample being thus kept separate and accessible. Some of the samples presented to the Iowa Survey had been mounted in long glass tubes, in which the chippings of any terrane are supposed to occupy a space proportional to the actual thickness of the terrane. Such a method of mounting has a certain advantage for purposes of exhibition, but its disadvantages are so great that it must be unqualifiedly condemned. The drillings from different strata settle and tend to mix. They can not be taken from the tube for study, and no adequate inspection can be made through the glass. Sooner or later the long tube is sure to be broken and the record of the geologic section is irretrievably lost.

Drillings should not be washed. When the drill is working in a pure limestone washing does little harm, for it removes only the fine flour of the stone, whose quality is fully represented in the larger chippings. But with some marls and shales and with clayey sandstones the removal of the finer material in washing leaves a residue far from representative of the rock. In some sets certain samples had been washed and others not, thus making error possible in the determinations, except where the treatment to which the cuttings had been subjected was indicated on the labels or could be told by inspection.

For all scientific purposes samples should be taken directly from the sand pump at every 5 or 10 feet, at the end of a cleaning out, and at every change of stratum. They should be placed, unwashed, in wide-mouthed bottles or glass jars (1 to 4 ounce bottles are large enough) and plainly and accurately labeled in india ink with the names of the town or other location and of the owner, the date, and the depth from which each was taken.

PETROGRAPHIC EXAMINATION.

The drillings were studied petrographically as an aid in identifying, from well to well, the strata from which they came. With some samples a simple inspection was sufficient, but as a rule this inspection was supplemented by other tests. Under polarized light in the field of the petrographic microscope the minerals making up the meal or flour of the drillings were generally readily determined, and their relative proportion in the rock was roughly indicated by their proportion in the microscopic field. Crystalline silica, flint and chalcedony, gypsum and anhydrite, glauconite, pyrite, and calcite—to mention only common minerals of the sedimentary rocks—were thus distinguished. The microscope was used also in determining the texture of such rocks as oolites, fine-grained sandstones composed of angular quartzose particles, sandstones of grains of crystalline quartz of various degrees of rounding and assortment, and sandstones whose grains have been enlarged by secondarily deposited silica. Limestones were tested with weak cold hydrochloric acid, free effervescence indicating a small percentage or total absence of magnesium carbonate and a slow and feeble effervescence a high percentage of the same carbonate, unless attributable to siliceous or other impurities. Residues after digestion in strong acid determined the argillaceous and siliceous contents of impure limestones. The relative amount of magnesium carbonate in some limestones was roughly estimated after a solution in hydrochloric acid had been neutralized with ammonium carbonate and treated successively with ammonium oxalate and hydric disodic phosphate. A number of quantitative analyses of samples of terranes of special interest were made in the chemical laboratory of Cornell College.

POSSIBILITIES OF ERROR.

Mention should be made of certain possibilities of error in any determination of the nature and thickness of the rock by means of drillings.

The most serious of these errors is due to fewness of samples. Where, as in some deep wells, samples are taken at irregular or considerable intervals, it may be naturally assumed that each sample represented to the driller a stratum of homogeneous rock and that each sample was taken at the change and thus designates the summit of its own terrane and the base of the terrane above it. This assumption may or may not be correct. Any such sample may possibly be taken midway or at any other point within a terrane instead of at its top, and the assumed thickness of one terrane may be as much too little as that of the next terrane is too great. This source of error is avoided when a sample is labeled not only with its own depth but with the upper and lower limits of the stratum which it is supposed to represent.

Another source of possible error lies in the fact that the contents of the slush bucket may not correctly represent the rock in which the drill is working. Along with cuttings from the contiguous rock are fragments of other and higher strata. The vibration of ropes and rods and the lifting and lowering of the drill and other implements may detach pieces of rock from any higher stratum. Caving shales and incoherent sandstones furnish a large admixture of shale and sand to the cuttings at the bottom of the drill hole. Thus black coaly shale from the coal measures (Pennsylvanian) may be recognized in otherwise clean limestone chips of the Mississippian or inferior [lower] terranes; the fossiliferous green shale of the Platteville is seen mingled with cuttings in the dolomites of the Prairie du Chien group [Shakopee and Oneota]; and the St. Peter and Jordan sandstones contribute a large arenaceous content to the cuttings of the dolomites below.

Where strata of different character alternate at short intervals the mingling of cuttings makes the determination of the rocks peculiarly difficult. Drillings from Ordovician and Cambrian strata below the St. Peter in many places contain a mixture of rolled quartz grains and chips of dolomite, and it may be a delicate question to decide whether the sand is wholly foreign, having fallen in from water-washed, loose overlying sandstones, or whether it is more or less native—that is, whether the sample represents either a pure dolomite on the one hand or an arenaceous dolomite or a calciferous sandstone on the other. If it is decided that some of the sand is native to the stratum, it still remains to be discovered whether the sand is disseminated through the dolomite or exists in thin interbedded layers. In some samples an interbedded sand grain or mold of sand in some larger chips of dolomite may decide in favor of dissemination.

In some drillings material fallen from above may be distinguished by its lithologic nature or by the size or shape of its fragments. The dislodged pieces from the sides of the drill hole should as a rule be larger than drill cuttings and of different shape. Fragments of easily worn shales fallen from overlying beds soon assume a rounded form. But in many wells, as, for example, where fragments from above have themselves been cut into chips by the drill, these tests are not decisive and the real nature of the bottom rock must be left in some doubt. To keep distinct the facts observed in the study of well drillings from the inferences drawn by the observer, a complete statement of the composition of the drillings should be given as well as an opinion as to the character of rock which they represent. * * *

FOSSILS.

The occurrence of a series of fossils in a given terrane—the sure means employed by the geologist whenever possible in his correlations—is lacking in well records and samples. The drill cuts and crushes the harder rocks to fine meal or powder and the softer to small chips. It is the rarest of good fortune that the drill leaves any fossil unbroken into unidentifiable fragments. The smaller the fossil the greater its chances of escape. The minute tests of the foraminifer *Fusulina* are sometimes obtained intact in considerable numbers from certain strata in the coal measures. Rocks fallen from higher strata in the drill hole give fragments of considerable size, and when these are fossiliferous and their own horizon can be determined by lithologic identity, they are of the greatest value. Thus the caving green shale of the Platteville is in places highly fossiliferous, and its fragments, along with bits of Ordovician brachiopods characteristic of the horizon, are often brought up when the drill is working in the subjacent strata. But such fossils will be a source of the gravest error if it is assumed that they belong to the same formation as that of the cuttings brought up with them from the bottom of the well.

LITHOLOGIC SIMILARITY.

The lithologic method employed by geologists in the field in tracing a terrane from point to point is by no means infallible when applied in studies of deep wells, but it is used when other methods are lacking. Certain terranes exhibit the same well-defined lithologic characteristics over a large part of Iowa and adjacent States. The coaly shale of the Pennsylvanian can hardly be mistaken for the calcareous (mud rock) shale of the Maquoketa, nor can either be confounded with the glauconiferous shales of the Cambrian. The white crystalline encrinital limestone and the cherts and oolites and geodiferous beds of the Mississippian are diagnostic, and the same is true of the arenaceous cherty dolomites [Shakopee and Oneota]. The presence of anhydrite or gypsum in certain beds has been used to correlate rocks in widely separated wells.

The magnesium carbonate content of limestones can be used [in Iowa] as a means of correlation but must be used with care. Thus, so far as known, from the Shakopee dolomite down all limestones throughout the State are thoroughly dolomitized. But above the Shakopee the changes in the magnesian content in the same terrane may be rapid and complete. Thus at Dubuque the Galena is a dolomite, but at Manchester, 40 miles west, a deep-well section finds it wholly of ordinary limestone. Similarly, some of the Devonian limestones of east-central Iowa pass into dolomites in the northern counties.

The lithologic nature of a terrane may be expected to change over so broadly extended an area as the State of Iowa. One formation may thin and disappear and give place to other formations of the same series. Thus the Niagara dolomite of northeastern Iowa apparently gives place to Silurian sandstones or sandy limestone in southeastern Iowa; and gypsiferous beds, perhaps of Salina age, appear in deep wells at stations as far separated as Mount Pleasant, Des Moines, Bedford, and Glenwood. An entire system may disappear—for example, the Silurian in the extreme northeastern parts of the area occupied by the Devonian in Iowa.

Lithologic similarity may only exceptionally be used as the sole means of correlation. It is a belief as mistaken as it is prevalent that a geologist can identify a formation simply by means of the physical characteristics of its rocks. In the study of deep wells this means should be used only with the greatest care and in combination with other and better methods.

KEY FOR EXAMINATION OF WELL SAMPLES.

The following systematic outline of procedure is given by Udden,[6] who has also given much careful study to this subject:

The sample should first be examined by direct inspection and with a hand lens.

I. If sample consists of sand, sandstone, gravel, or conglomerate, note adherence, size, form, polish or etching of surfaces, and mineral characters of grains or pebbles.

(1) Adherence is slight in soft sandstone, greater in hard. It may be due to the presence of a matrix or cementing material. Note nature of cementing material, whether abundant or scarce, whether calcareous, siliceous, ferruginous, etc. For this purpose it may be convenient to place a small fragment of the rock in a drop of dilute hydrochloric acid on a glass slide and examine without cover glass.

(2) Size of grains is best determined by making a mechanical analysis, using the method of the United States Bureau of Soils down to grains one-eighth of a millimeter in diameter and giving numerical expressions to quantities of the different grades.

(3) Form of grains discloses whether the sand is much or little worn and whether the grains have grown by secondary crystallization. The finer grains are invariably

[6] Udden, J. A., Some deep borings in Illinois: Illinois Geol. Survey Bull. 24, pp. 18-22, 1914.

more angular than the coarser grains in the same sand, owing to the lesser force of impact of the smaller grains and their more effective cushioning by water.

(4) The polish or etching of the surfaces of most sand grains is not conspicuous, and may be neglected, but it is sometimes an important characteristic.

(5) The mineral composition of sand grains is important. Numerical estimates of the different ingredients are always desirable. Most of the descriptions of the mineral composition of sands found in geological literature are inexact.

II. If sample is not as above, test for calcareous material by the application of a cold 10 per cent solution of hydrochloric acid.

(1) If there is no response to acid the sample is probably either argillite or gypsum. Determine mineral character and note texture, structure, color, and mineral and fossil contents. If necessary, first wash and then dry the sample. It must be remembered, however, that coarse dolomite will not respond to dilute acid, unless heated or unless the material to be tested is pulverized.

(*a*) Mechanical analyses of silts, shales, and clays are desirable but often impracticable to make. Instead of such, describe in general terms, such as "coarse," "medium," "fine," or "finest texture," supplying microscopic measurements of the bulk of the material when possible.

(*b*) Note whether the fragments show stratification, lamination, or lack of such structures. Describe any variations of these structures when present.

(*c*) Avoid exaggerations in describing colors.

(*d*) For determining the mineral contents of shales, examine sample under microscope and make blowpipe tests. Note the nature of escaping fumes before and during ignition, and changes in color. Also note the behavior of the material with magnet after ignition.

(*e*) Fossils should be sought in the larger fragments with a hand lens. Such fragments may be split edgewise with a knife when no fossils appear on the surface. The finer fragments should be sorted by sieves and each grade examined under a microscope for minute fossils, such as Foraminifera, Bryozoa, denticles of annelids, spores, spicules of sponges, small parts of brachiopods and gastropods, and many others. Look also for microscopic concretions.

(2) If there is effervescence with acid, the sample may be pure argillite mixed in the well with calcareous slime, clay ironstone, calcareous argillite, or marl, argillaceous limestone, dolomite, calcareous limestone, or a mixture of these. If the sample is not clean, it should be washed and again dried, then separated by sieves into many different sizes, and again tested for calcareous material.

(*a*) If the sample is a mixture, the ingredients will usually appear in unequal quantities in the different lots. Each ingredient should be separately examined.

(*b*) Clay ironstone effervesces extremely slowly and becomes magnetic after ignition.

(*c*) Marl treated in acid leaves a considerable insoluble residue.

(*d*) Argillaceous limestone treated in acid leaves a small insoluble residue.

(*e*) Dolomite effervesces slowly.

(*f*) Calcareous limestone effervesces rapidly. In distinguishing between dolomite limestone and calcareous limestone care should be taken to apply the acid on a surface of a fresh fracture of the rock fragment. Dolomite, when powdered, effervesces rapidly, like calcite. A good way for making this test is to place a drop of the acid on a glass slide, and then to place a small fragment of the rock in this drop and examine under a hand lens. Marls and argillaceous limestones should be examined in the same manner as argillites. Dolomites seldom have fossils, except as molds or casts in the larger fragments. Coarseness of the crystals should be noted in dolomites, either by examining the finer-grained lots under the microscope or by making a thin section from some large fragment. Calcareous limestones should be examined and described as to texture, sedimentary structure, color, and fossil and mineral contents. The procedure is the same as with argillites.

(f^1) Organic limestones: If organic fragments are present the limestone may be called organic. If organic fragments are invested by a thin surrounding coating of calcareous material, the rock may be described as an organic and incipiently oolitic rock. Organic fragments should be described as to size, form, abundance, arrangement, etc. When the organic fragments constitute the greater part of the rock and consist mostly of one class of organisms, this organism determines the name of the rock, as "encrinital limestone," "*Fusulina* limestone," "shell breccia," "coral limestone," etc.

(f^2) Characteristic minerals in limestones: Limestones containing grains of green glauconite are said to be glauconitic. Limestones or dolomites impregnated with bituminous material are said to be bituminous. Similar descriptive names may be used for any other mineral ingredients, as for example, "pyritiferous," "gypsiferous" limestones.

(f^3) Texture and structure of limestones: A limestone consisting of the finest calcareous material exhibiting no texture may be called compact. In some calcareous limestone the porous space has been filled with crystalline calcite. A limestone of somewhat open texture is porous. If the open spaces are large the rock is cavernous. If the rock consists of distinct thin layers it may be described as laminated.

(f^4) Color in limestones: As most colors in limestone are faint, care should be taken to avoid exaggerations in color descriptions. Some limestones exhibit uneven distribution of color throughout the mass, resulting in blotches or stains which merit notice and separate description.

(f^5) Fossils in calcareous limestones and marls: These rocks should always be examined for fossils. For the most careful work it will always be found necessary to separate the cuttings into lots of different sizes after washing and drying. These lots are then separately examined by the aid of a good hand lens. The cuttings should be spread on a black surface, barely covered with water, and separated into rows narrow enough to be seen in the field of the hand lens. Sufficiently strong light is always desirable for this work.

Recently the careful study of cuttings from deep wells drilled for oil or gas has been undertaken. A systematic outline for laboratory work has been published by Trager[7] comparable to the foregoing outline by Udden. Detailed study of well cuttings comprising some methods not used by Norton and Udden was recently undertaken by Goldman[8] for the United States Geological Survey. This study is briefly described by him as follows:

The paper is the result of the study of a nearly complete series of samples (representing mostly intervals of 10 feet) from 2,400 to 4,510 feet in the Seaman No. 1 well, Roxana Petroleum Corporation, Palo Pinto County, Tex. In each sample as many types of ingredients as could be recognized were differentiated under the hand lens, and their proportions estimated. Peculiar types and at intervals the common types were made into thin sections, studied under the compound microscope, and the proportion of sand, clay, and lime in each type estimated. Three graphic logs were presented—one showing the estimated proportion of sand, clay, lime, and flint in each sample, another the usual type of graphic log showing the succession of beds as indicated by the above examinations, the third the usual graphic presentation of the

---

[7] Trager, E. A., A laboratory method for the examination of well cuttings: Econ. Geology, vol. 15, pp. 170-176, 1920.

[8] Goldman, M. I., Lithology of the "Bend series" and contiguous formations of north-central Texas (abstract): Washington Acad. Sci. Jour., vol. 11, pp. 425-430, 1921. See also U. S. Geol. Survey Prof. Paper 129, pp. 1-22, 1921.

driller's log. From the first-named log (called the "percentage log") it appeared that there are in this well distinct lithologic units characterized by the proportion of the four ingredients differentiated, and that the boundaries between these are usually well defined. From the second log it appeared that these boundaries are usually marked by some distinct bed, sometimes by a conglomerate or sandstone, but in most cases by a coarsely glauconitic sandy bed. In this way it was possible to place the boundary between the Marble Falls (Pennsylvanian) and the Lower Bend (Mississippian) with absolute precision and in conformity with the paleontologic evidence. Boundaries between the Marble Falls, Smithwick, and Millsap were also suggested, though in the absence of paleontologic evidence these are uncertain. Other lithologic units not hitherto distinguished by names were indicated. It was shown that the driller's log gives little or no evidence for the most significant criteria.

In further support of a hypothesis previously offered that unconformities are marked by glauconitic beds, it was shown that a glauconitic layer occurring at the base of the Lower Bend just above the Ellenburger limestone in outcrops in San Saba County had been traced north through all three wells examined in which this contact appeared, including the Seaman well, more than 100 miles north of the outcrop. It was also indicated that pyrite or other sulphides are associated with glauconite and phosphate at unconformities, and it was suggested that the presence of all three minerals is due to the abundance of organic matter encountered by a transgressing sea.

In further explanation of his work Goldman[9] makes the following statements:

It is important to realize that this paper presents mainly a stratigraphic subdivision and only secondarily a correlation. There was no new principle in the method of study. There are two factors of this method deserving emphasis. One is that the examination, especially of the total sample, must be careful, as the most significant ingredients are often very scarce. The other is that the observer should avoid limiting his observations by some predetermined routine. The factors significant for each well should be determined by close observation of the material from that well.

INCLINATION OF STRATA.

The strata of rock formations are rarely horizontal. Slight dips may be due to deposition in a sloping position or to deformation after deposition; steep dips are almost invariably due to deformation. An alluvial deposit generally has a slight original dip downstream, and deposits in lakes or in the ocean are laid down with a gentle dip away from the shore, although some distance from shore they generally become virtually horizontal. Lava beds have original dips away from vents from which the lava was extruded. The movements of the earth's crust may be very gentle, tilting the strata so that they have an inclination of only a few feet to the mile, or they may be so pronounced as to turn the strata into a vertical position, or even to overturn them. Figure 42 gives an example of gentle dips. It shows that the St. Peter sandstone descends about 750 feet in the 132 miles from Dubuque to Ackley, or less than 6 feet to the mile.

[9] Written communication.

Excellent examples of widespread aquifers with gentle and relatively uniform dips are also afforded by the successive water-bearing sands and gravels beneath the Atlantic Coastal Plain (fig. 47) and by the Dakota sandstone beneath the Great Plains (fig. 48). In the section shown in figure 47 the base of the Pamunkey formation descends about 700 feet in 85 miles, or a little more than 8 feet to the mile. In all three regions the dips are believed to be partly original and partly caused by deformation.

Knowledge of the dip of the strata underlying a region is necessary in order to determine the distribution of the aquifers and to forecast the depths to them at particular points in the region. These facts are also well illustrated by figure 42. In the vicinity of Manchester the Niagara dolomite supplies many successful wells. Nearer Dubuque, however, on account of the rise of the rock strata and the descent of the land surface, this aquifer is absent. Where the edges of the strata are well exposed the boundary of the Niagara dolomite can be mapped from field observations; where they are concealed by a mantle of surficial deposits this is impossible, but the boundary can

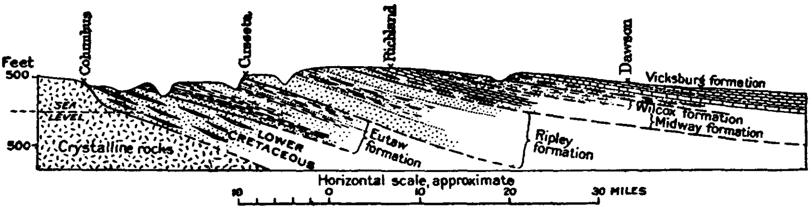


FIGURE 47.—Section across upper part of Atlantic Coastal Plain in Georgia. (After L. W. Stephenson.)

be inferred, approximately, if the dip and the altitude of the land are known. Obviously, unless the dip changes or the land rises greatly, the St. Peter sandstone and ultimately also the Jordan sandstone will disappear on the other side of Dubuque. When the forecast for Waterloo was made (p. 153) deep wells were already in existence at the other three cities shown in figure 42, and the dip of the formations was pretty well known. Any forecast made without taking account of the dip would have been sadly in error, even with the best of information as to the character, thickness, and succession of the various formations. Even though the dip is less than 6 feet to the mile—an exceedingly gentle slope—it produces a difference of 750 feet between Dubuque and Ackley in the depths to the successive aquifers, and this difference is a matter of immense practical importance in well drilling.

It is evident that a ground-water survey of a region underlain by stratified rocks involves a survey of the dips of the rocks. Such a survey is made by observing the dips where the rocks crop out and by correlating the formations in outcrops and well sections, as was so successfully done by Norton in Water-Supply Paper 293, already cited.

A hard, resistant member of a series of tilted beds that is crossed by a streamway may act as a dam to impound ground water on the upstream side. The aquifer under such conditions may be a porous formation belonging to the same series as the resistant bed, or it may be rock waste resulting from the decomposition and disintegration of less resistant rock on the upstream side, or it may consist of alluvium that has been deposited on the upstream side. Where the stream crosses the hard stratum its valley is likely to contract into a narrow gorge, whereas farther upstream the valley may be wider and more open. If the locality of the hard stratum has been elevated with reference to the upstream area there may be considerable water-bearing alluvium. Two examples of ground water impounded by hard tilted beds in the basin of Sulphur Spring Valley, Ariz., are described in the following paragraphs.[10] The structure of the rocks was not studied in sufficient detail to determine just how these barriers came into existence, but their effectiveness and economic importance are very evident.

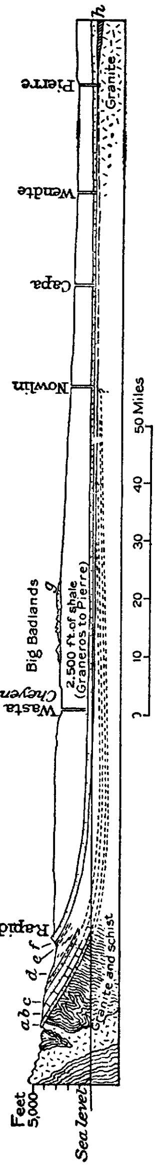


FIGURE 48.—Section across South Dakota from the Black Hills to Missouri River. (After N. H. Darton.) *a*, Deadwood formation; *b*, Englewood and Pahasapa limestones; *c*, Minnelusa sandstone; *d*, red beds (Opeche, Minnekahta, and Spearfish formations); *e*, Sundance formation, Unkpapa sandstone, and Morrison shale; *f*, Lakota, Minnewaste, Fuson, and Dakota formations; *g*, White River group in Big Badlands; *h*, pre-Cambrian quartzite. The Dakota sandstone is the leading aquifer. It gives rise to many strong artesian flows.

The Dos Cabezas Range is flanked on the southwest by hard Paleozoic quartzites and limestones that dip toward the southwest at a steep angle and, because of their resistant character, form a sharp, conspicuous ridge. Back of the ridge is a broad, relatively low basin which is underlain by granitic rocks covered with coarse rock waste and which drains into a canyon cut through the ridge. The upturned quartzite bed forms a dam which impounds the water in the sediments of the basin, thereby providing an abundant shallow-water supply for the village of Dos Cabezas, which is situated in the basin (fig. 49). The depth to water in the basin decreases downstream, and near the canyon and in its upper part ground water is virtually at the surface. Where the water is at shallow depth, trees of different kinds, including cottonwood, ash, walnut, hackberry, and willow, grow luxuriantly. Below the

[10] Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, pp. 112–113, 1913.

quartzite ledge there is no evidence of ground water, and the canyon has a barren aspect which is in striking contrast to the verdure of the upper tree-covered portion. This contrast is to some extent shown by two views in Plate XXI, *B* and *C*.

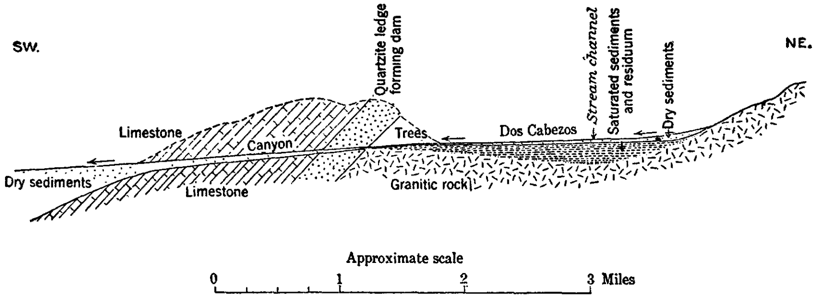


FIGURE 49.—Section showing shallow-water conditions at Dos Cabezas, Ariz., caused by resistant quartzite strata that have been tilted.

In the vicinity of Leslie Canyon the Swisshelm Mountains consist of eastward-dipping limestones covered with acidic lavas back of which is a basin comparable to that in the Dos Cabezas Range. Leslie Canyon cuts through the lava and limestone series and leads from the basin to Sulphur Spring Valley (fig. 50).

The lava is relatively resistant and impervious and therefore constitutes a dam behind which the water that has seeped into the sediments of the basin is impounded and can be recovered by means of shallow wells. At the entrance into the canyon the underground reservoir overflows, forming a good spring. The water from the

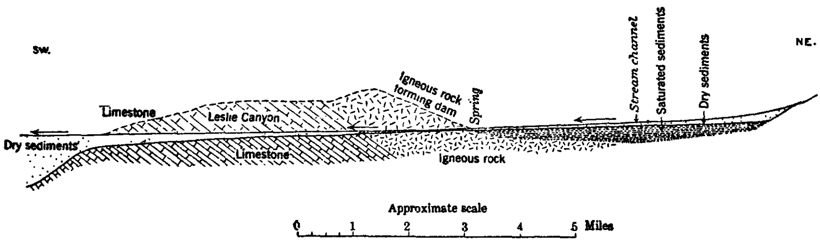


FIGURE 50.—Section showing shallow-water conditions at the head of Leslie Canyon in Swisshelm Mountains, Ariz., caused by tilted beds.

spring flows down the canyon, either at the surface or through the gravels near the surface, until it reaches the limestone, where it disappears, apparently through the crevices of this rock. Trees are growing near the spring and in the part of the canyon that passes through igneous rock; but in the lower part of the canyon, which is cut through limestone, only a few willows are found.

FOLDS.

If a series of strata everywhere had the same angle and direction of dip the problem of determining the distribution and depth of aquifers would be relatively simple. In most regions, however, the strata have been more or less warped, forming folds or irregular flexures. Folds include upfolds or anticlines, downfolds, or synclines, and simple tilts or monoclines. (See Pl. XXII.) An upfold may be ridgelike or may form a structural dome in which the strata dip in all directions away from a common center as in the Black Hills uplift (Pl. XXIII). Likewise, a downfold may be troughlike or may form a structural basin in which the strata dip from all directions toward a common center, as in the Paris Basin in France, or in the basin of the southern peninsula of Michigan (fig. 53).

The warping of the rock strata introduces much uncertainty into well forecasts and makes it necessary to get data at many points in a region in order to construct a reasonably accurate section or map showing the position of an aquifer in the region. The use of vertical sections to show the warps in the rock strata, and hence the positions of aquifers, is illustrated by Plate XXIII and figures 42, 47, 48, 51, and 53. The warps in the rock strata are also shown by areal geologic maps, on which are represented the areas in which the several formations occur at the surface (Pl. XXIII; figs. 51 and 53), and by structure-contour maps—that is, maps on which are shown successive contours of the upper or lower surface of a stratum or formation.

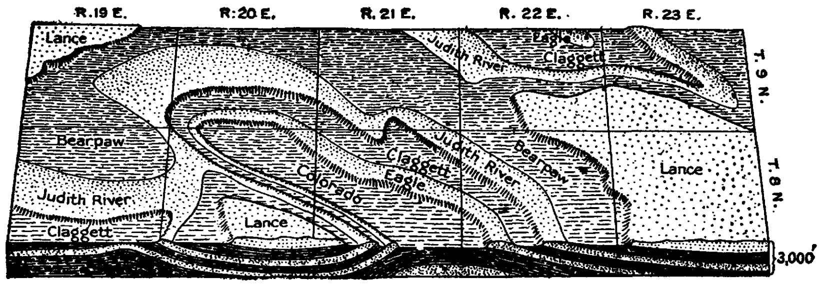


FIGURE 51.—Stereogram of an area in central Montana showing relation of ground-water conditions to stratigraphy and structure. The Bearpaw shale, Claggett formation, and Colorado shale yield little or no water to wells; the Lance formation, Judith River formation, and Eagle sandstone are relatively good water-bearing formations. (See pp. 260-262.) A good exercise is to forecast the results that will be obtained in drilling on each section in these townships.

The structure-contour map of Iowa in figure 52 shows numerous irregularities of dip with one prominent plunging syncline, the axis of which extends diagonally almost toward the southwest corner of the State. A map shows the conditions at all points in the region it covers, whereas a section shows only the conditions along a certain line. A section, however, shows the subterranean structure more directly and is therefore more easily understood and more readily interpreted. Frequently several sections are given, so that the conditions in the intervening areas can be interpolated, or the purposes of completeness and ease of interpretation are both accomplished by presenting a map and also a series of sections. Thus, the water-supply paper on Iowa contains not only an areal geologic map, with the structure contours that are shown in figure 52, but also a series of 14 sections similar to that in figure 42.

The relations of rock structure to the occurrence of ground water can be more fully appreciated by a study of Plate XXIII and figures

A. MUD SPRING, IN COCHISE COUNTY, ARIZ., SHOWING RELATION OF SHALLOW GROUND WATER TO PORPHYRY LEDGE.

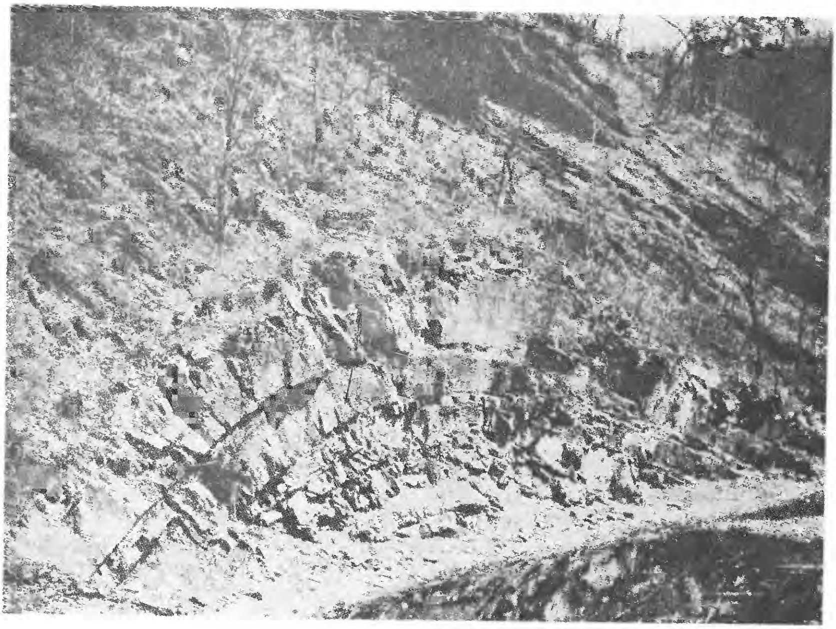
Photograph by O. E. Meinzer.

B. VALLEY DOWNSTREAM FROM DOS CABEZAS, ARIZ., SHOWING BARREN ASPECT BELOW QUARTZITE LEDGE.

Photograph by O. E. Meinzer.

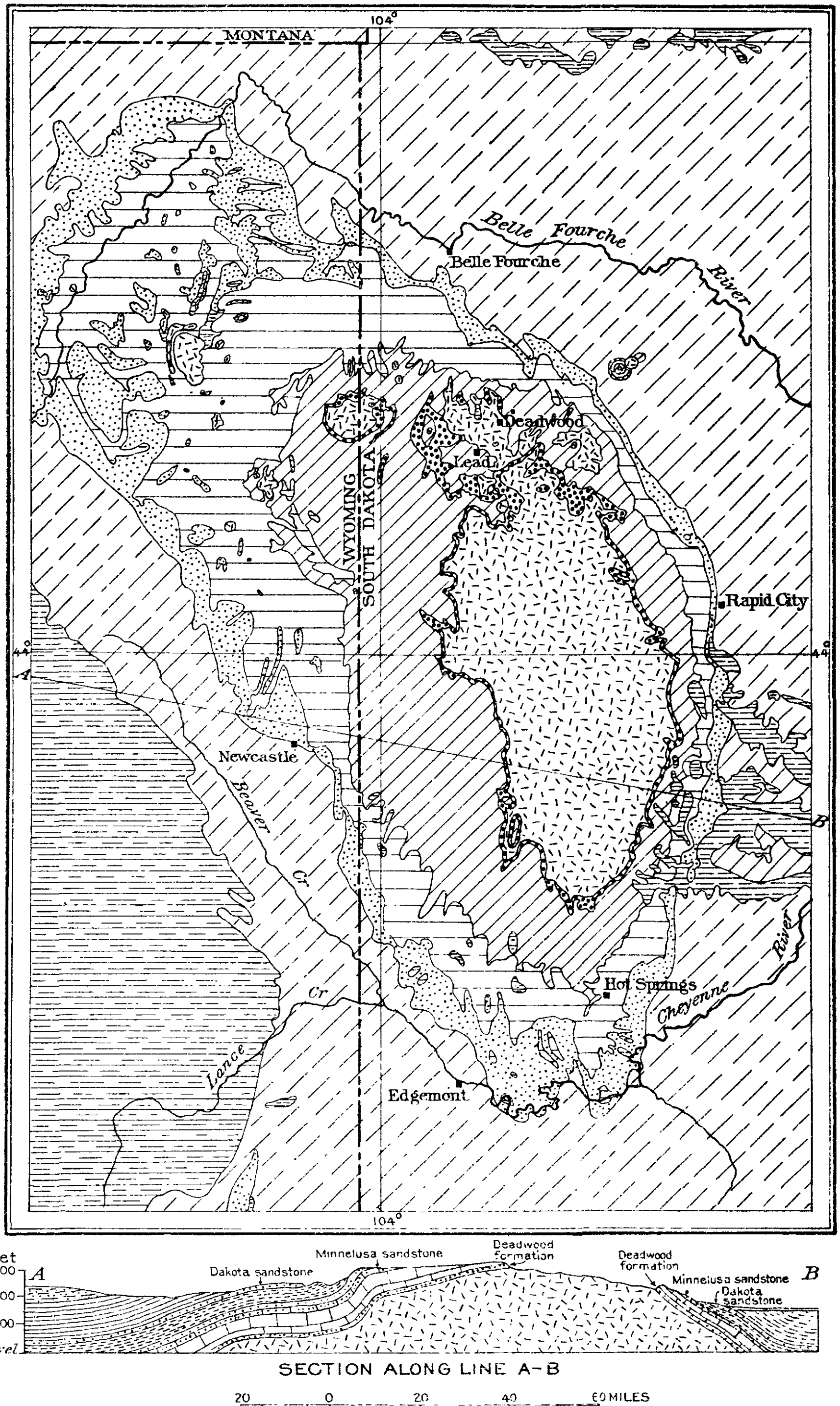
C. VICINITY OF DOS CABEZAS, ARIZ., SHOWING EVIDENCES OF SHALLOW GROUND WATER ABOVE QUARTZITE LEDGE.

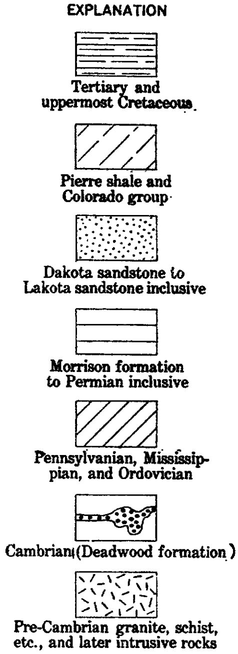
Photograph by O. E. Meinzer.



A. ANTICLINE.
Photograph by G. W. Stose.

B. SYNCLINE.
Photograph by C. D. Walcott.



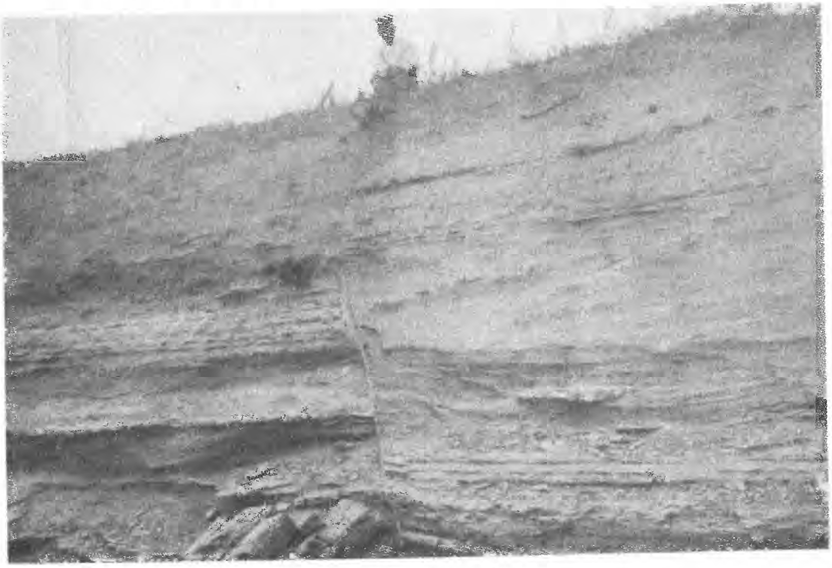


The principal water-bearing formation is the Dakota sandstone, which is a very important source of artesian water. Other recognized water-bearing formations are the Lakota sandstone (Lower Cretaceous), which lies not far below the Dakota and is mapped with it; the Minnelusa sandstone (Pennsylvanian); and the Deadwood formation. The section shows how the distribution and depth of these water bearers are affected by the Black Hills uplift

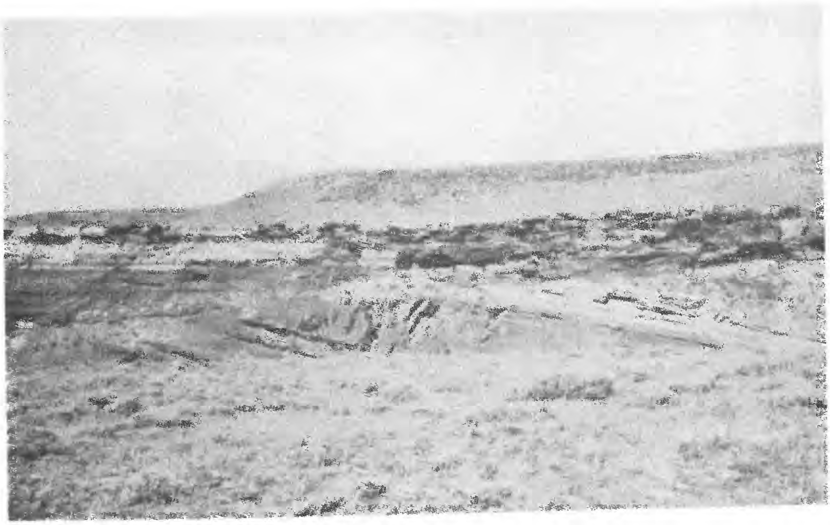
GEOLOGIC MAP AND SECTION OF BLACK HILLS, IN SOUTH DAKOTA AND WYOMING, ILLUSTRATING A STRUCTURAL DOME.

After N. H. Darton.

497781 O-59 (Face Plate XXII)



A. FAULT.
Photograph by N. H. Darton.



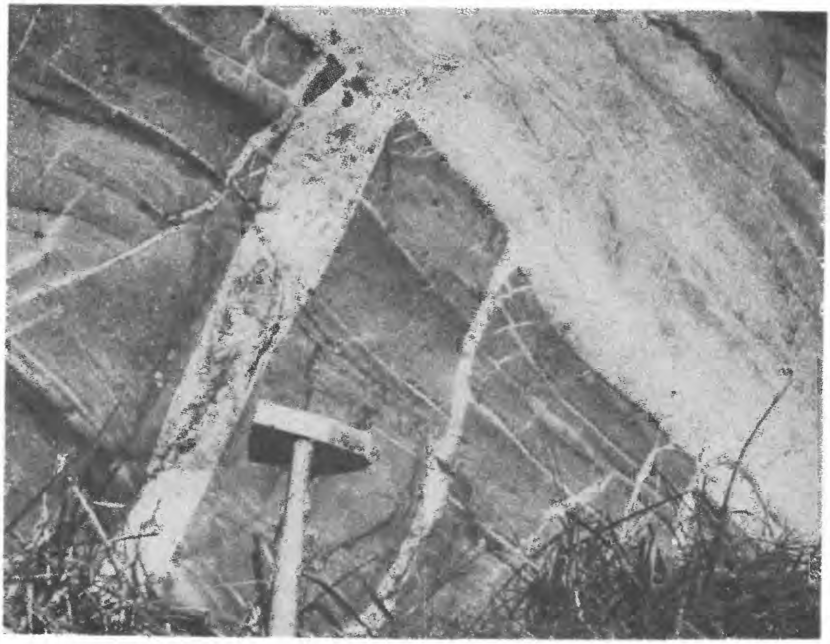
B. UNCONFORMITY OF HORIZONTAL BEDS RESTING ON IRREGULAR SURFACE OF TILTED BEDS.
Photograph by E. G. Woodruff.

A. SCARP OF NILES-IRVINGTON FAULT, IN SANTA CLARA VALLEY, CALIF.

Lagoon in foreground. View looking southwestward in the direction in which the water table drops, as shown in the profiles (fig. 65). Photograph by W. O. Clark.

B LAVA BED RESTING ON ALLUVIUM IN SULPHUR SPRING VALLEY, ARIZ.

Photograph by O. E. Meinzer.



A. SMALL DIKES AND SILL IN SCHIST.
Photograph by E. Howe.

B. LARGE DIKE.
Photograph by R. C. Hills.

497781 O–59–14

42, 47, 48, 51, and 53—for example, by drawing a north-south section through the Black Hills and an east-west section through the southern peninsula of Michigan, predicting the depth to the Dakota sandstone at various points in Plate XXIII, drawing a section of the St. Peter sandstone from the northeast corner to the southwest corner of Iowa, and drawing a section from the southeast corner northwestward to Sioux City.

The water table may cut across a series of folded beds in such a manner that a given permeable bed may in some places lie in the zone of saturation and hence be water bearing and in other places lie above the zone of saturation and hence be devoid of available water. This

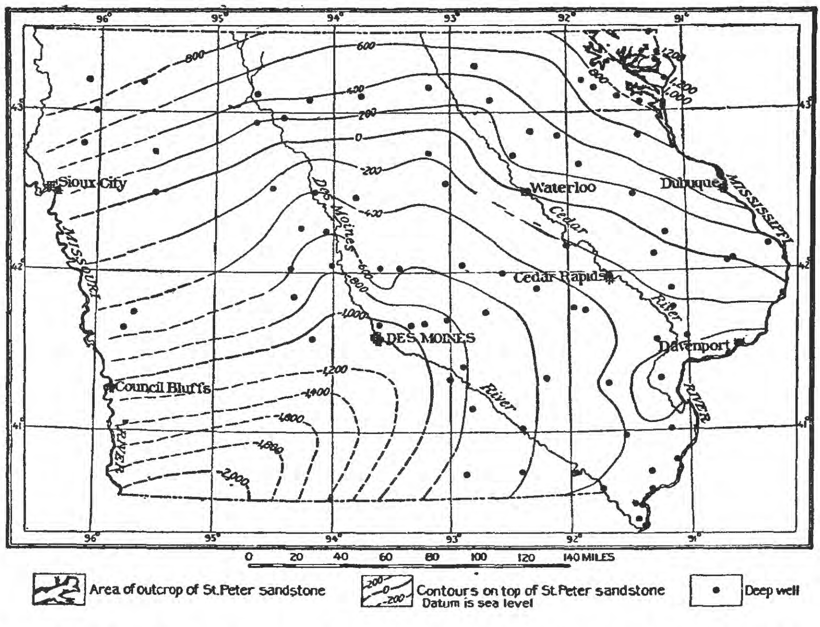


FIGURE 52.—Map of Iowa showing areas of outcrop of St. Peter sandstone and contours of its upper surface where it is buried. (After W. H. Norton.)

condition exists in an area of northern France that was occupied by the British Army during the war, as has been shown by Capt. King,[11] who was the geologist of the British forces chiefly concerned with water supplies and who drilled many wells in the area. The area is underlain by a porous flint-bearing chalk, which rests on a gray-blue clayey marl that is practically impervious to water. Both formations are gently folded to form a series of somewhat irregular anticlines and synclines. It was found that there was little use in drilling for water where the marl crops out or where the top of the marl is

[11] King, W. B. R., The surface of the marls of the Middle Chalk in the Somme Valley and the neighboring districts of northern France, and the effects on the hydrology: London Geol. Soc. Quart. Jour., vol. 77, pt. 2, pp. 135–143, 1921.

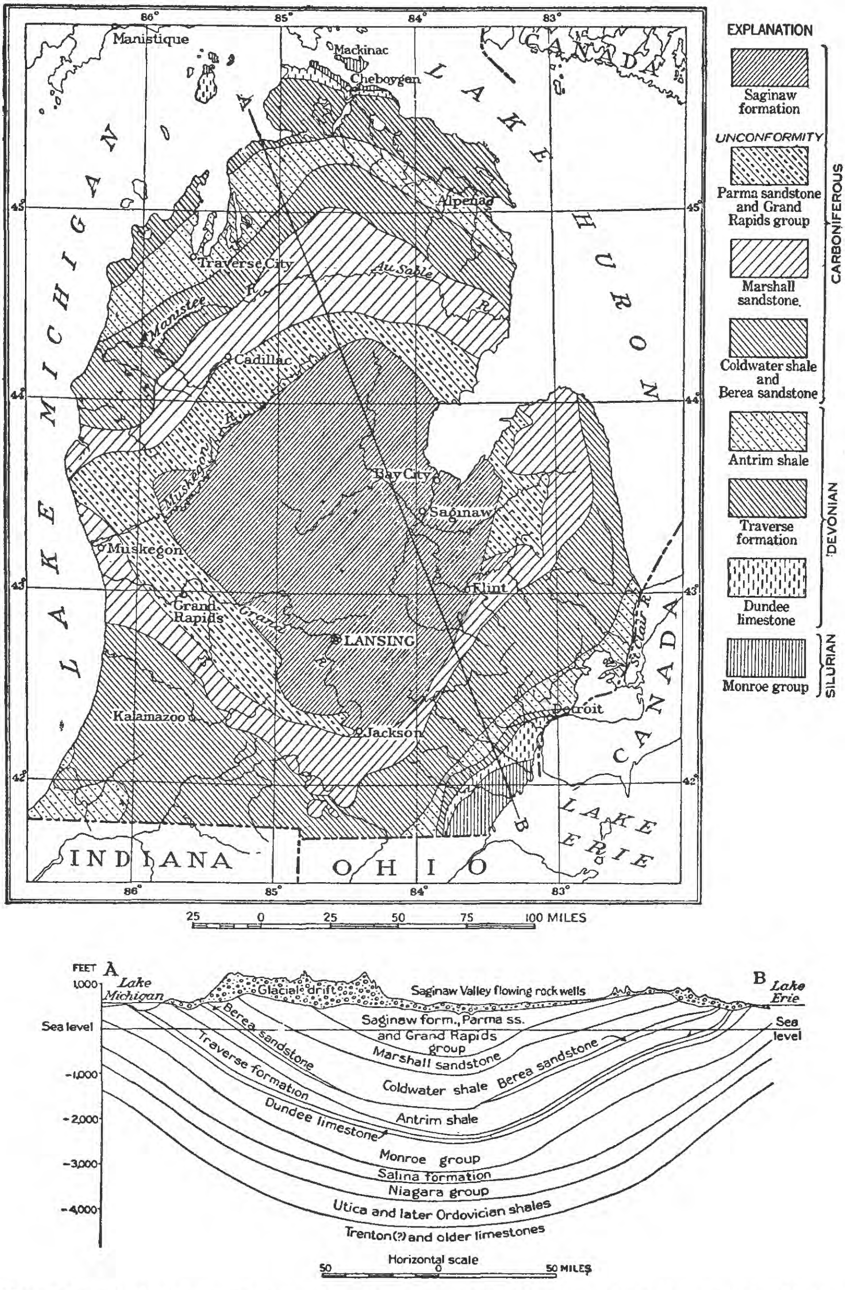


Figure 53.—Geologic map and section of southern peninsula of Michigan, illustrating a structural basin. (After A. C. Lane, with modifications.)

above the water table. At several points where the top of the marl is above the water table wells were obtained that yielded less than 1,000 gallons an hour. On the other hand, most of the wells drilled in synclines, where the water table is far up in the chalk, were successful and yielded from 6,000 to 12,000 gallons an hour.

The dip of the strata is also important in its bearing on artesian conditions. Flowing wells are more likely to be obtained in synclines than anticlines, or where the beds are tilted than where they are horizontal. This subject will be presented more fully in a forthcoming volume on the movement and head of ground water in the United States.

Rarely an anticline may form a ground-water dam, a good example of which in California is described by Mendenhall[12] as follows:

A crustal movement resulted in the lifting of a ridge—the formation of an irregular arched wrinkle—extending from the San Jacinto Mountains northwestward along the line of the Badlands, which separate San Timoteo Canyon from San Jacinto Valley. The rocks which were folded into this arch are soft shales and sandstones and gravelly alluvium, like that deposited by the rivers now in San Bernardino Valley. This clay and gravel ridge has been the most effectual of subsurface dams, against which the modern stream wash has accumulated, and behind which the waters percolating seaward through this wash have been stored, the excess rising in springs and flowing over the dam, to sink again in the sands and gravel below.

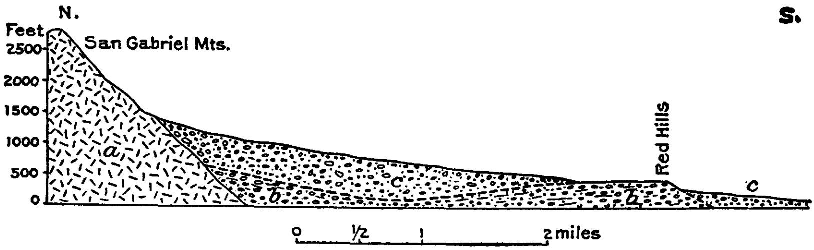


FIGURE 54.—Diagrammatic section through Red Hills, on Cucamonga Plains, Calif., showing effects of folding and unconformity in impounding ground water. (After W. C. Mendenhall.) *a*, Granitic rock; *b*, earlier alluvium; *c*, later alluvium. Dotted line represents hypothetical boundary between earlier and later alluvium. The older, relatively impervious alluvium produces a subterranean dam which in some places brings to the surface the water in the younger alluvium that is percolating from the mountains to lower levels. There is evidence that the protrusion of older alluvium is due to upfolding.

Another example of a ground-water dam produced partly by folding of the beds is shown in figure 54 and described by Mendenhall[13] as follows:

As a physical feature the Red Hills form a nearly flat-topped mesa, which interrupts the general slope of this part of the Cucamonga Plains. Approached from the north the mesa appears only as a lessening of the slope, but its southern edge is a scarp 50 to 150 feet high. The hills are made up of a deposit of the earlier red alluvium which has here escaped the destruction of the older topography of erosion during the deposi-

[12] Mendenhall, W. C., The hydrology of San Bernardino Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 142, p. 30, 1905.

[13] Mendenhall, W. C., Ground waters and irrigation enterprises in the foothill belt, southern California: U. S. Geol. Survey Water-Supply Paper 219, pp. 34–35, 1908.

tion of the later alluvium. The low mound therefore represents the top of a hill of red clay, sand, and gravel, whose slopes are deeply buried under modern wash [fig. 54]. Where the hills of the older, concealed topography lie athwart a line of underground circulation through the later alluvium, they serve as an underground dam, forcing the waters which are percolating through the overlying gravels to or near to the surface, where they flow out in springs or are easily developed by wells. As the older alluvium has been folded in some localities by crustal disturbances which have taken place since its deposition, it may be that where it projects above the general plains surface it has been brought to this position by folding. The section of the Eddy tunnel through the base of the Red Hills near their western margin seems to show a dip of the beds toward the north. It is probable, therefore, that this body of older alluvium stands above the general plain because it has been brought up along or near the axis of such an arch.

UNCONFORMITIES.

In many regions there are two or more series of rocks separated from one another by unconformities. An unconformity represents an interval of time that may amount to many thousands of years, during which practically no sediments were deposited in the region where it occurs but the existing rocks were eroded and perhaps also tilted, warped, or broken. The rocks above the unconformity represent a later period of deposition. An unconformity is a fossil land surface. It shows approximately the topography of the region just before the deposition of the overlying formations. (See Pl. XXIV, *B*.) To the extent that the overlying formations have been deformed this fossil land surface has also been deformed.

The six simple vertical sections in figure 55 show different types of unconformities. The region shown in section A has not been deformed, but after the lower series of rocks had been deposited it was eroded until it became a hilly country. The upper series was deposited on this irregular land surface. The region shown in section B is likewise free of deformation. The erosion surface on which the upper rock series rests is not nearly so irregular as that in section A, because the region prior to the second period of deposition either was not lifted high enough to become much dissected or was worn down by long-continued erosion. Section C represents only a slight unconformity. The lower series was gently warped but apparently not eroded before the second series was laid down. At the left of the section the two series may be conformable, or there may be an omission of formations that intervene elsewhere and that represent a long interval. Toward the right the successive beds of the upper series overlap one another, perhaps representing a gradual encroachment of the sea upon the old land surface. In section D the older rock series was tilted and eroded into a hilly country before the younger series was deposited. In section E the older rocks were tilted and then reduced by erosion until an almost level surface resulted. Unconformities such as those shown in sections D and E, in which the two series differ in dip, are often called angular unconformities. The unconformity shown in Plate XXIV, *B*, is an angular unconformity. Section F shows a region which has been tilted toward the left since the younger series was deposited. If the section is turned so as to restore the younger beds

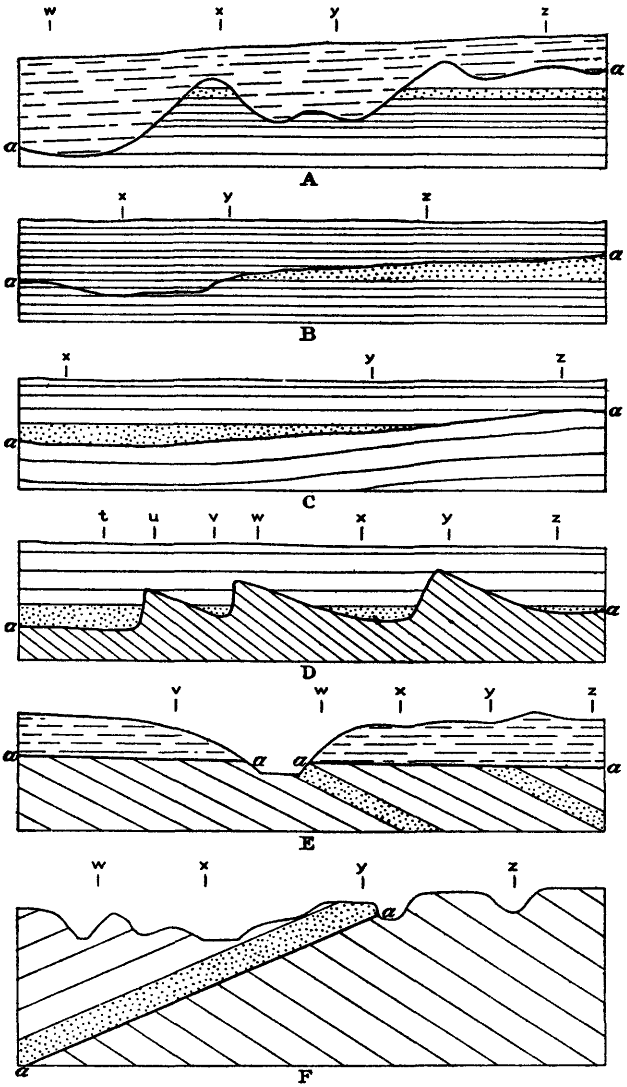


FIGURE 55.—Sections showing different types of unconformities (*a*–*a*) in relation to well prospects.

to their original horizontal position, it becomes obvious that before the younger beds were deposited the old rocks had been tilted to the right and then beveled by long-continued erosion, essentially like the older series in section E.

Unconformities are very common and far-reaching structural features, and they have very important effects on the occurrence of ground water. The distribution of an aquifer in either the upper or the lower series may be controlled largely by the intervening unconformity. This fact may be more fully appreciated after considering the conditions that would be encountered in drilling at each of the points t to z shown in the sections in figure 55, assuming that the strata shown with dots are the aquifers.

A study of unconformities is an important part of many ground-water surveys. An unconformity is detected by a difference in the dip of two superimposed series, by irregularities in the contact surface, by interruptions in the formations of either series, or by a weathered condition of the underlying series near the contact. Data as to un-

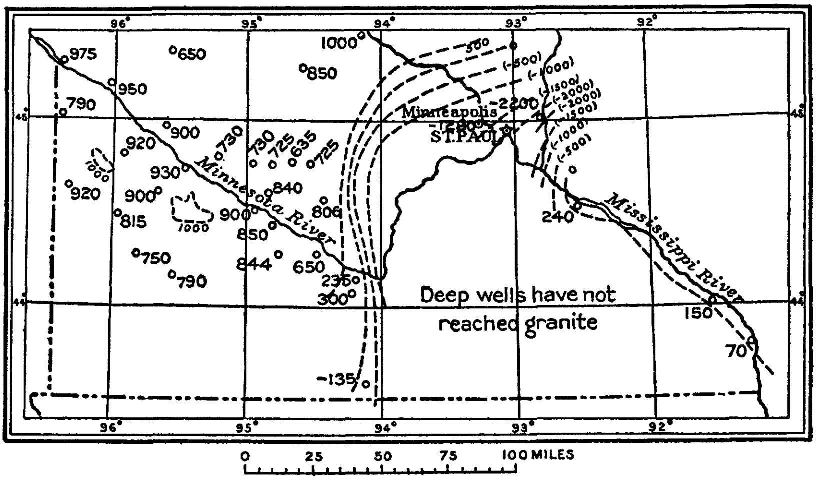


FIGURE 56.—Map of southern Minnesota, showing the position, in feet above sea level, of the granitic rocks, which are overlain unconformably by younger formations. (After map in U. S. Geol. Survey Water-Supply Paper 256.) The granitic rocks yield little or no water, and it is generally advisable to stop drilling when they are struck.

conformities are obtained from observation of natural and artificial exposures and from well logs. Unconformities are characterized by great irregularities and therefore introduce much uncertainty into ground-water forecasts. It is seldom possible to construct a contour map of a buried or fossil land surface that is more than a rough approximation. (See fig. 56.) However, an understanding of the geologic processes involved in the production of an unconformity helps greatly in the interpretation of available data.

In most regions the lowest known system of rocks consists of hard crystalline igneous or metamorphic rocks, or of a complex of such rocks. This basal complex extends to unknown depths. It commonly has an eroded upper surface, and in most places it is overlain by various younger formations, some of which may be water bearers.

If in drilling in a series of younger beds the drill reaches the hard basal complex, the prospects of finding water at greater depths are very poor, and it is generally advisable to abandon the hole (fig. 56).

There is great variety in the succession of materials in different series of conformable beds. Not uncommonly, however, the lowest member of a series, resting unconformably on older rocks, is a deposit of gravel or sand. If it is gravelly it may be called a basal conglomerate. Water is, therefore, often obtained in gravelly or sandy beds directly above an unconformity. In the Atlantic Coastal Plain such a gravelly aquifer is commonly found at or near the bottom of the sedimentary beds resting on the erosion surface of the ancient crystalline rocks that form the basal complex. It yields copious supplies of water to many wells. Another example is afforded by the Dakota sandstone—one of the best aquifers in the United States—which in some areas rests unconformably on older rocks. There is a general tendency for the beds of a sedimentary series to become increas-

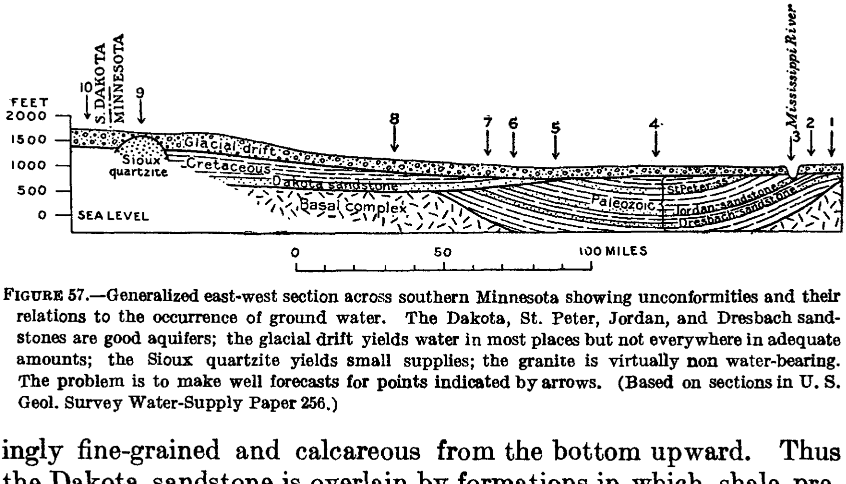


FIGURE 57.—Generalized east-west section across southern Minnesota showing unconformities and their relations to the occurrence of ground water. The Dakota, St. Peter, Jordan, and Dresbach sandstones are good aquifers; the glacial drift yields water in most places but not everywhere in adequate amounts; the Sioux quartzite yields small supplies; the granite is virtually non water-bearing. The problem is to make well forecasts for points indicated by arrows. (Based on sections in U. S. Geol. Survey Water-Supply Paper 256.)

ingly fine-grained and calcareous from the bottom upward. Thus the Dakota sandstone is overlain by formations in which shale predominates. Thus also the Paleozoic rocks of the interior of the United States are largely sandstone near the bottom and limestone higher up, as is shown in figure 42.

An instructive example of the relation of unconformities to ground-water conditions is afforded by a section in southern Minnesota (fig. 57). Five great rock systems must here be taken into account—(1) the basal complex of granite, gneiss, etc., which is very unpromising as a source of water, (2) the Sioux quartzite, which yields meager supplies, (3) the thick series of Paleozoic beds, which contain several good aquifers, including the St. Peter, Jordan, and Dresbach sandstones, (4) the Cretaceous beds, whose basal formation is the Dakota sandstone, a good aquifer, and (5) the glacial drift, which supplies many wells but in some places does not yield large amounts. The drift is spread as a mantle over the eroded surfaces of the other four systems, largely concealing their relations to one another. The Cretaceous beds, several hundred feet thick in places, extend eastward over the basal complex, in the north wedging out before they reach the Paleozoic beds (fig. 58), but in the south extending far over their beveled edges (fig. 57). The Cretaceous surrounds the highest masses of Sioux quartzite, as the sea surrounds a group of islands. In most of southwestern Minnesota the basal complex is not more than several hundred feet below the surface, and in some localities it crops out; in the southeastern part of the State it is at great depths, forming a basin in which lie the Paleozoic beds. By considering the ground-water conditions that would be encountered in each of the ten localities indicated by arrows in figure 57, it becomes evident that a knowledge of the unconformities is absolutely essential for making well forecasts.

The significance of unconformities is shown in a striking manner by figure 58. The entire region shown is covered by glacial drift and looks alike at the surface. As there are flowing wells at Marshall, on the west, and at Mankato, on the east, it was argued that flowing

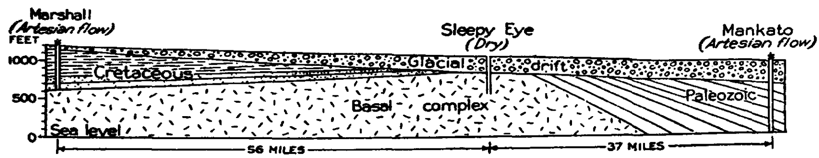


FIGURE 58.—Section through Marshall, Sleepy Eye, and Mankato, Minn., illustrating effect of unconformities on ground-water conditions.

wells could certainly also be obtained at Sleepy Eye, which is intermediate in position and altitude. Accordingly, a deep well was drilled, but without results. The difficulty, as determined by M. L. Fuller, is clearly shown in figure 58. The wells at Marshall are supplied by a formation entirely different from that which supplies the wells at Mankato, and although both formations are widespread aquifers neither extends quite to Sleepy Eye, where the drift is underlain by granite.

JOINTS, VEINS, AND MINOR STRUCTURAL FEATURES.

A joint is a natural rock fracture. If there has been slippage of the blocks of rock on opposite sides of the fracture so that the blocks are dislocated with reference to each other, the fracture is called a fault. Joints have already been discussed as among the most important of water-bearing openings. They are characteristic of hard, brittle rocks, not of plastic and unconsolidated materials, and they result chiefly from compression during earth movements and from rock shrinkage due to drying of sediments or cooling of igneous rocks.

In massive igneous rocks it is common to find three directions of jointing approximately perpendicular to one another. Two are approximately vertical and the third is commonly horizontal. Basalts and other extrusive rocks may have columnar jointing, whereby the rocks are broken so as to form vertical columns. Joints are variously spaced. They may be only a few inches apart or they may be several feet or even several yards apart (pp. 113–114). They differ greatly in their lateral persistence and in the depths to which they extend. They may form tight cracks or wide open fissures.

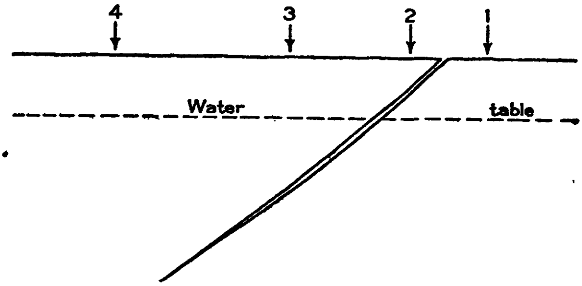


FIGURE 59.—Diagrammatic section illustrating relation of wells to a large water-bearing joint. A well drilled at site 1 will not strike the joint; one drilled at site 2 will penetrate it above the water table; one drilled at site 3 will encounter it where it is open and full of water; one drilled at site 4 will either fail to reach it or will reach it at considerable depth, where it has become tight and will therefore not yield much water. Site 3 is the most favorable.

If a formation is traversed by a limited number of large joints, or by fractured zones with intervening belts of more compact rock, it is sometimes practicable to select a site that is more favorable for sinking a well because of numerous joints than an average site selected at random. If there is a rather wide fractured zone it may be wisest to locate the well at the middle of such a zone. If there are relatively few large and definite joints it may be possible to ascertain approximately the direction and angle of their dip and to locate the well far enough on one side of such a joint to intersect the joint at some distance below the water table (fig. 59). In sinking wells along the seashore there is more danger of contamination by sea water if the prominent joints dip toward the land than if they dip toward the sea (fig. 60).

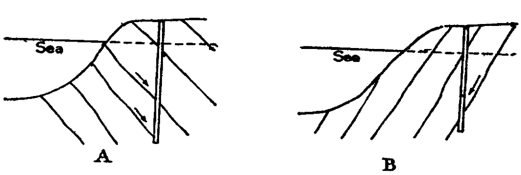


FIGURE 60.—Diagrammatic sections illustrating effects of the dip of joints on contamination of wells by sea water.

Veins are openings that have been partly or completely filled with mineral matter deposited by percolating waters. To the extent that they are filled they no longer function as water bearers, but they may have to be reckoned with in drilling. For example, a hard quartz vein traversing a relatively soft formation, such as a partly decomposed schist, is difficult to penetrate and is likely to deflect the drill, thus making the hole crooked. Under certain conditions a vein may also act as a dam that impounds ground water.

The smaller structural features, such as slaty cleavage and schistosity, have been discussed in connection with the water-bearing properties of rocks (pp. 126, 146, 147).

FAULTS.

EFFECT OF FAULTS ON POSITIONS OF AQUIFERS.

A fault is a structural feature consisting of a fracture and a dislocation of the rocks on one side of the fracture with reference to those on the other (Pl. XXIV, *A*). Faults are of two kinds—normal faults, illustrated in sections A and B of figure 61, and thrust faults, illustrated in section C of figure 61. Faults differ greatly in their lateral extent, in the depth to which they reach, and in the amount of displacement. Minute faults do not have much significance with respect to ground water except as they may, like other fractures, serve as containers of water. But the large faults that can be traced over the surface for many miles, that extend down to great depths below the surface, and that have displacements of hundreds or thousands of feet are very important in their influence on the occurrence and circulation of ground water. Not only do they affect the distribution and position of aquifers, but they may also act as subterranean dams, impounding the ground water, or as conduits that reach into the bowels of the earth and allow the escape to the surface of deep-seated waters, often in large quantities and at high temperatures.

In some places, instead of a single sharply defined fault, there is a fault zone in which there are numerous small parallel faults or masses of broken rock called fault breccia. Such fault zones may represent a large aggregate displacement and may afford good water passages.

The effect of faults on the distribution and depth of aquifers is illustrated simply in figure 61, in which the formation represented by dots is an aquifer and the arrows show the directions in which the broken layers of rock were displaced. In the region shown in section A a driller may sink wells at points t, u, and v, striking water at about the same level in each well. When he drills at point w he may be greatly bewildered and disappointed by finding very different conditions. If, however, he also drills at points x, y, and z, he may discover that he is drilling to the same water-bearing bed which he tapped in wells t, u, and v, but that beyond a certain line it lies at a lower level. In the region shown in section B tilted beds are faulted and the resulting structure is somewhat less simple. A driller may here be surprised to find that the conditions found at points s, t, and u are repeated at points x, y, and z. In the region shown in section C the basal non water-bearing rock has been thrust up over the younger water-bearing series, producing the unusual condition, in a well at w and perhaps in one at x, of finding the water-bearing stratum after passing through the basal rock. It should be said, however, that ground-water literature affords relatively few authentic examples of changes produced by faults in the depth to aquifers, as shown in sections A and B, or in the relative position of aquifers, as shown in section C. Drillers frequently assume faults to account for changes which they do not understand, but most of these assumed

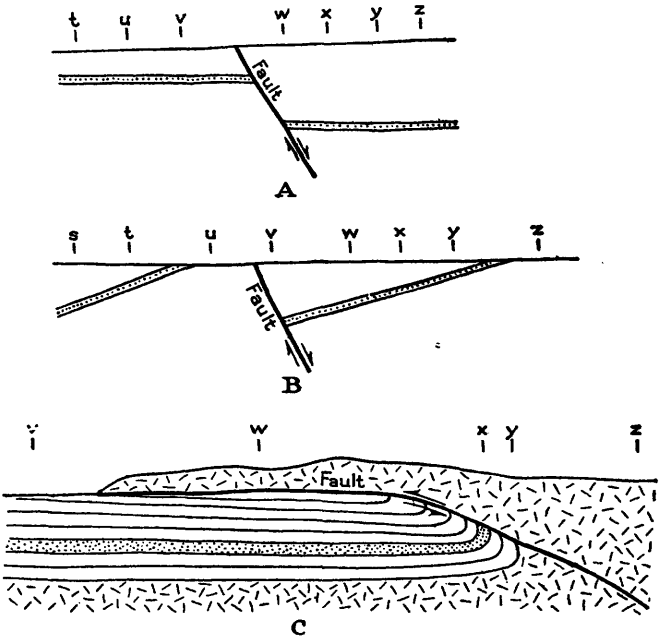


FIGURE 61.—Diagrammatic sections showing how faults may control the distribution of aquifers and their depths below the surface. Arrows show the directions in which the blocks have moved in relation to each other. The strata shown by dots are aquifers. The effects of the faults are illustrated by the results that will be obtained by drilling at points t to z in section A, at points s to z in section B, and at points v to z in section C.

faults do not exist, the changes generally being due to unconformities or to mere lateral gradation. It is chiefly in regions of flat-lying or only gently disturbed beds that water is recovered through wells, and in these regions large faults are rare. Good examples of faults that profoundly affect the depths to certain water-bearing formations in parts of Texas are given by Hill and Vaughan,[14] and an example

[14] Hill, R. T., and Vaughan, T. W., Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Tex., with special reference to the occurrence of underground waters: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 2, pp. 258–260, 308, 314–316, 1898. Hill, R. T., Geography and geology of the Black and Grand prairies, Tex., with detailed descriptions of the Cretaceous formations and special reference to artesian waters: U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pp. 382–385, pl. 52, 1901.

of a probable fault affecting ground-water conditions in the same State is given by Deussen.[15] Good examples of faults that affect the position of the water-bearing beds in Montana are given by Hall.[16]

AQUIFERS PRODUCED BY EROSION OF FAULT SCARPS.

The raised side of a fault may produce an escarpment, as shown in section A in figure 62. Faulting therefore affects the ground-water conditions not only by displacing the aquifers but also by producing radical differences in the altitude and topography of the surface on opposite sides of the fault, which may result in the deposition of water-bearing beds on the downthrown side from rock waste derived by rapid erosion of the exposed rocks on the raised side. An example of such a structure is afforded by the Toyabe Range and Big Smoky Valley, Nev.[17] (Pl. XXX, *A* and *B*, p. 298). With the lapse of geologic ages, however, so much erosion may occur that the escarpment is obliterated and no definite topographic evidence of faulting may remain. This is the condition shown in figure 61, sections A and B, and also in figure 62, section B, which shows the same region as section A after the rocks have been greatly eroded and worn down to a surface of low relief (*a–a* in section A). The fault may be further concealed by later deposition of sediments over the entire region, as in figure 62, section C.

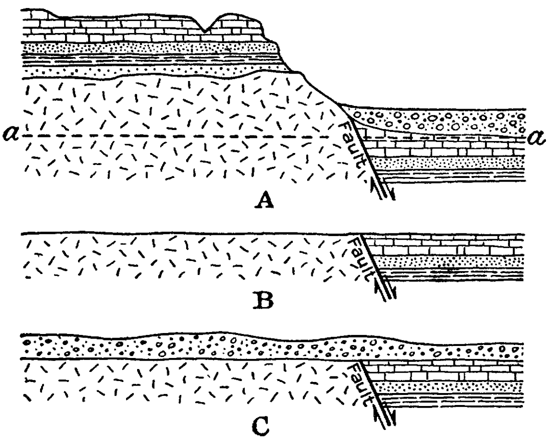


FIGURE 62.—Diagrammatic sections illustrating effects of faults on ground-water conditions. The conditions in section B are produced by the beveling of the region shown in section A down to the level *a–a*. The conditions in section C are produced by deposition of younger beds on the beveled surface.

Many striking examples of the effect on ground-water conditions produced by large faults with prominent escarpments are found in the western United States. The ground-water conditions in western Utah are radically different from those in eastern Utah, on account of a great fault zone that extends through the State. The region

[15] Deussen, Alexander, and Dole, R. B., Ground water in Lasalle and McMullen counties, Tex.: U. S. Geol. Survey Water-Supply Paper 375, p. 148, pl. 8, 1916.

[16] Hall, G. M., Ground water in Yellowstone County, Mont.: U. S. Geol. Survey Water-Supply Paper — (in preparation).

[17] Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring valleys, Nev.: U. S. Geol Survey Water-Supply Paper 423, pp. 18-22, 44-45, 1917.

east of the fault zone has been uplifted thousands of feet and forms a high plateau province, most of which is underlain by more or less flat-lying sedimentary beds, some of which yield water. The region west of the fault zone has been dropped and in most parts covered to depths of hundreds of feet with sediments, largely derived from the plateau province. These sediments include much sand and gravel, which supply numerous wells, in many places yielding water in very large quantities. Striking examples of the effect of faults on ground-water conditions are also afforded by large faults that have produced many of the Basin Ranges of the West and the intervening desert valleys. These valleys are underlain by thick deposits of rock waste, which are invaluable as sources of water supply.[18]

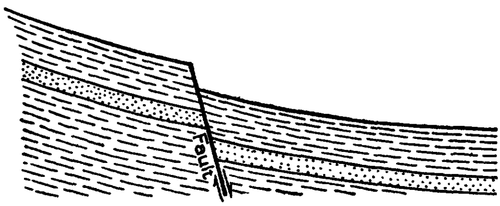


FIGURE 63.—Diagrammatic section showing the impounding of ground water by a fault. The permeable water-bearing bed is represented by dots. The ground water moving down the dip, toward the right, is impounded on the upthrown side of the fault.

IMPOUNDING EFFECT OF FAULTS.

A fault may act as a subterranean dam, impounding the water as it percolates through the earth, and thus bringing it to the surface along the fault or at least causing a notable difference in the water level on opposite sides of the fault. This impounding may be due

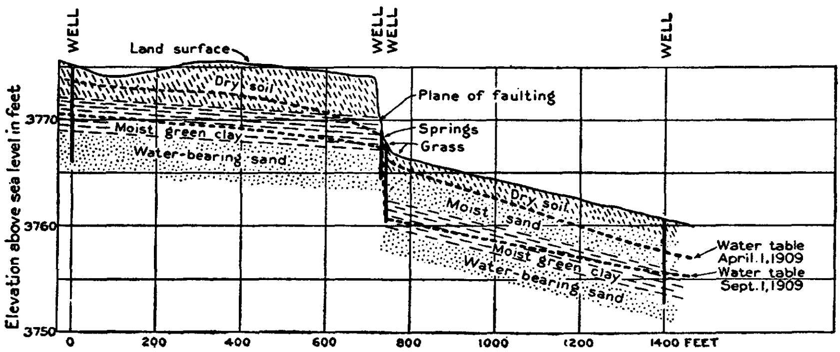


FIGURE 64.—Section in Owens Valley, Calif., showing a spring produced by the impounding effects of a fault. (After C. H. Lee.) The "moist sand" on the downthrown side is equivalent to some of the "dry soil" on the upthrown side and apparently has an impounding effect.

to the displacement of alternating permeable and impermeable beds in such manner that the impermeable beds are made to abut against the permeable beds, as shown in figures 63 and 64. It may also be due to clayey gouge along the fault plane produced by the rubbing and mashing during displacement of the rocks, this gouge being smeared over the edges of the permeable beds. The impounding

[18] See U. S. Geol. Survey Water-Supply Papers 157, 181, 199, 217, 277, 333, 365, and 423.

effect of faults is most common in unconsolidated formations that contain considerable clayey material. In hard rocks the material on opposite sides of the fault pack together less snugly, and there is less tendency to form impervious gouge to plaster shut the edges of the water-bearing beds. The side on which the water is impounded depends on the direction of movement of the ground water. It may

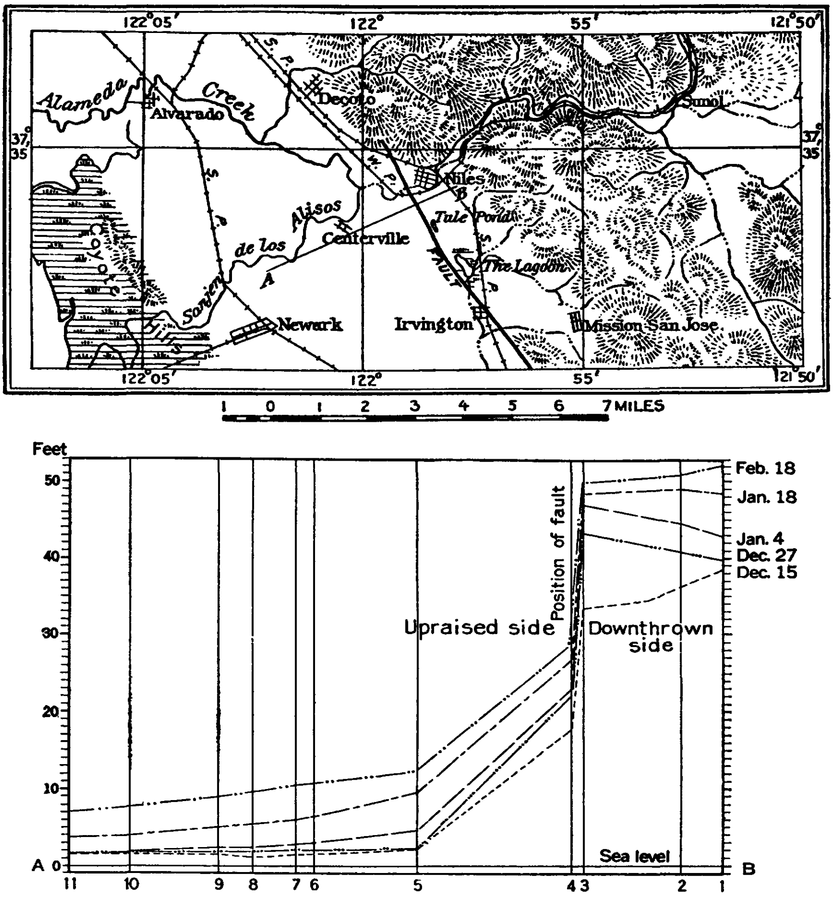


FIGURE 65.—Map showing Niles-Irvington fault in Santa Clara Valley, Calif., and profiles of water table across the fault. Numbers at bottom of section indicate observation wells. (After W. O. Clark.)

be impounded on the upraised side, as shown in figure 63, which represents essentially the conditions of a series of fault springs in the alluvial slopes of Big Smoky Valley, Nev.[19] It may also be impounded on the downthrown side, as at the Niles-Irvington fault, in Santa Clara Valley, Calif., described by Clark[20] and shown in Plate XXV, *A*, and in figure 65.

[19] Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring valleys, Nev.: U. S. Geol. Survey Water-Supply Paper 423, p. 90, 1917.

[20] Clark, W. O., Ground-water resources of the Niles cone and adjacent areas, Calif.: U. S. Geol. Survey Water-Supply Paper 345, pp. 127-168, 1915.

Faulting across a stream channel underlain by gravel that rests on impervious rock may produce a rock ledge in the stream channel that will impound water in the gravel upstream and may bring it to the surface at the ledge, as is illustrated in figure 66. Many examples of valleys underlain by water-bearing gravels that have resulted from faulting in the manner shown in figure 66 occur in California.[21] Such a condition is likely to result only where the faulting movement has been rapid or where the erosive power of the stream is feeble, as in arid regions, so that erosion has not kept pace with the uplift.

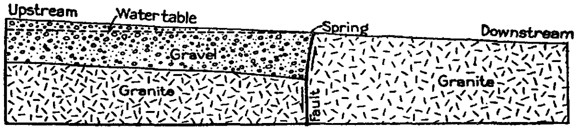


FIGURE 66.—Diagrammatic section showing how a fault crossing a stream channel may cause the deposition of water-bearing gravel on the upstream, downthrown side of the fault.

FAULTS AS WATER CONTAINERS.

Although some faults act as dams for ground water, others are important containers and conduits of ground water. The opposite sides of many faults, especially normal faults in hard rocks, are not everywhere pressed together but form fissures through which the water may flow. This is largely due to the fact that the fracture surfaces are irregular. After there has been displacement the two sides no longer fit each other, but projections on opposite walls may be brought opposite each other, leaving intervening openings, as shown in figure 67. To the extent that the projections have been rubbed off during displacement the intervening openings are reduced.

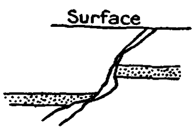


FIGURE 67.—Diagrammatic section showing openings produced by a fault with irregular fracture surfaces (After M. L. Fuller.)

Few faults are single, clear-cut breaks. The walls of some are crushed into small fragments called fault breccia and some consist of a number of nearly parallel breaks that result in shattering the rock throughout a zone of considerable width, forming an aggregation of larger angular blocks with intervening interstices called a "fault zone," as shown in figure 68. These breccias and fault zones may become important reservoirs of water.

FAULTS AS WATER CONDUITS.

Perhaps the most important function of faults in relation to ground water is that of conduits leading from deep sources of water up to the

[21] Mendenhall, W. C., The hydrology of San Bernardino Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 142, p. 30, 1905. Clark, W. O., Ground-water resources of the Niles cone and adjacent areas, California: U. S. Geol. Survey Water-Supply Paper 345, pp. 128, 139, pl. 9, 1915. Ellis, A. J., and Lee, C. H., Geology and ground waters of the western part of San Diego County, Calif.: U. S. Geol. Survey Water-Supply Paper 446, p. 37, 1919. Brown, J. S., The Salton Sea region, Calif.: U. S. Geol. Survey Water-Supply Paper 497 (in press).

497781 O-59-15

surface. Openings of no other kind probably extend so far below the surface, and no other structural features are so effective in allowing the ascent of deep-seated waters. Many springs owe their existence to the damming effects of faults, but many others are the outlets of waterways that follow faults. Many of the springs of the latter type have a large and relatively uniform discharge, and many yield water of high temperature, doubtless because it comes from great depths, where the earth is hot.

Excellent examples of springs produced by the rise of deep waters through fault openings are to be found along the edges of the mountain ranges of Nevada and western Utah (fig. 69). Many of these springs have large yields, some of them discharging several cubic feet a second. The abundance of these springs and the copious flow of some of them are the more impressive because of the aridity of the

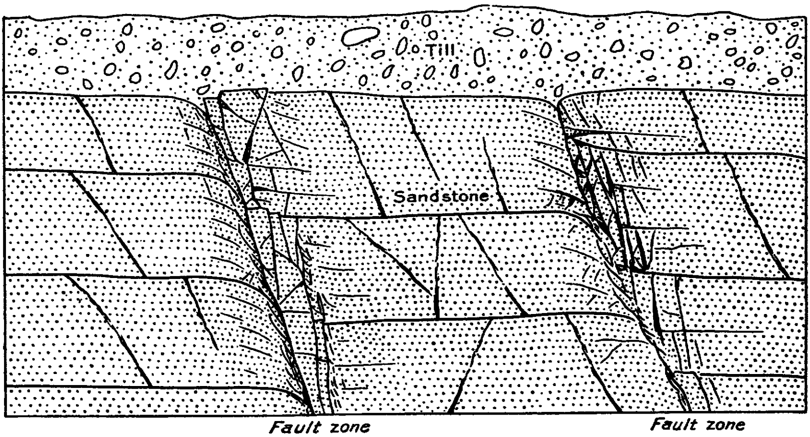


FIGURE 68.—Diagrammatic section showing fault zones in sandstone. (After H. E. Gregory.)

region in which they occur. The ranges of this region consist largely of tilted fault blocks, and in many places there are recent fault scarps in the alluvial slopes at the foot of the mountains (Pl. XXX, *A*, p. 298). That many of the springs along these fault lines are not merely returning to the surface water that percolates into the sediments of the adjacent alluvial slopes but yield water that ascends from deep sources along faults seems to be shown by the following facts: (1) The springs are situated along the general courses of the fault scarps, some of the groups having a more or less linear arrangement; (2) the yield of many of the springs is larger than would be expected if they were supplied from local sources, and some with the largest yields occur along narrow dry ranges that supply but little water; (3) they have relatively uniform flow throughout the year, whereas ordinary springs in the region fluctuate more with the season; (4) many of these springs yield water whose temperature is above the mean annual temperature of the region, and hot springs that are not associated

FIGURE 69.—Map of a part of the Basin and Range province, showing pre-Quaternary faults and associated springs, many of which are thermal. (After I. C. Russell, U. S. Geol. Survey Mon. 11, pls. 3 and 8, 1885.)

with volcanic rocks are abundant; (5) many of the springs issue from deep pools that are believed to be associated with fissures.[22]

[22] For descriptions of some of these springs see U. S. Geol. Survey Water-Supply Papers 277, 365, 423, and 467.

Another remarkable example of large springs produced by water rising along faults is described by Hill and Vaughan[23] as occurring along the Balcones scarp, in Texas. This great escarpment, extending through eight counties, is caused by a fault or series of faults with an aggregate displacement of 500 to 1,000 feet. For a distance of 200 miles along the fault zone there is a series of remarkable springs with large and nearly uniform discharge, which appear as extensive pools, many of them in the level prairie. The average discharge of several of these springs ranges between 39 and 350 cubic feet a second, and the discharge of the Comal Springs has varied from 267 to more than 400 cubic feet a second.

Many examples of important springs situated along fault lines in California are described by Waring.[24]

STRUCTURAL FEATURES FOUND ONLY IN IGNEOUS ROCKS.

With respect to ground water, extrusive rocks differ from plutonic and intrusive rocks; moreover, extrusive rocks formed from fluid lavas, such as basalt, differ from extrusive rocks formed from the viscous lavas of persilicic composition. The differences are not only in porosity and water-yielding capacity but also in the structural features that control the occurrence and behavior of ground water.

Formations of plutonic and intrusive rocks are generally massive bodies that extend downward indefinitely, but extrusive basalt generally forms sheets that range in thickness from less than 100 feet to not more than several hundred feet, and spread out over many square miles. Hence if the drill strikes granite or other plutonic or intrusive rock there is very little prospect of getting through it into any other formation, even though the hole is carried to a great depth; but if it strikes a sheet of extrusive basalt or other lava it may be entirely practicable to drill through it and to tap underlying aquifers. The persilicic lavas are as a rule more viscous than the subsilicic lavas and hence to a greater extent accumulate in massive cones about the volcanic vents instead of spreading out into sheets before they solidify. (See pp. 105–106.)

Large areas in the northwestern United States are underlain by very extensive sheets of basalt laid one upon another like the successive beds of a series of sedimentary rocks (Pl. XV, *A*, p. 138). In the gorge of Columbia River, adjacent to Quincy Valley, Wash., six or eight successive sheets of basalt can be identified.[25] The individ-

[23] Hill, R. T., and Vaughan, T. W., Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Tex., with special reference to the occurrence of underground waters: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 2, pp. 193-322, 1898.

[24] Waring, G. A., Springs of California: U. S. Geol. Survey Water-Supply Paper 338, p. 11, pl. 3, 1915.

[25] Schwennesen, A. T., and Meinzer, O. E., Ground water in Quincy Valley, Wash.: U. S. Geol. Survey Water-Supply Paper 425, pp. 131-161, 1919.

ual beds are usually not more than 50 to 150 feet thick, but their lateral extent is great, for their edges may be traced for miles along the canyon walls without any evidence of thinning out (fig. 70). Most of the water is found at or near the tops of the successive sheets, where the lava is more vesicular and probably more jointed because of rapid cooling, and where there may be some fragmental material. Thus, these lavas have water horizons that are revealed in springs and recognized by drillers, resembling the water horizons of sedimentary formations (Pl. XV, *B*.)

Excellent examples of thin sheets of extrusive basalt overlying beds of water-bearing gravel are found in Sulphur Spring Valley and San Bernardino Valley, in southeastern Arizona[26] (Pl. XXV, *B*). In each valley there are sheets of lava at the surface, overlying gravelly alluvial deposits, and also sheets of lava a few hundred feet below the surface, interbedded with alluvium. The interbedded sheets consist of lava that was poured out on the surface and later covered

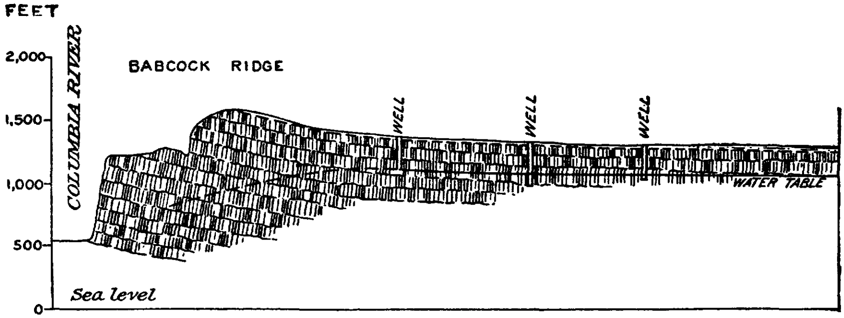


FIGURE 70.—Section extending from Columbia River eastward into Quincy Valley, Wash., showing successive sheets of extrusive basalt. (After A. T. Schwennesen.)

by alluvium, as is shown by the vesicular and weathered upper parts of these sheets. A buried sheet in Sulphur Spring Valley was struck at depths of 299 feet and 340 feet in two different wells and was found to be 53 feet thick in one well and about 100 feet thick in the other (fig. 71). In Sulphur Spring Valley not much water was found in the alluvium below the buried lava sheet, but in San Bernardino Valley there are nine flowing wells that pass through a buried lava sheet and are supplied from successive beds of gravel at lower levels.[27]

Coarsely crystalline igneous rocks almost invariably belong to large plutonic or intrusive masses that cooled slowly. It is therefore practically useless to drill into them, except to get the small supplies that may be found in the decomposed upper part or in joints of the

[26] Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U S. Geol. Survey Water-Supply Paper 320, pp. 68–70, 1913.

[27] Idem, p. 127.

rock. In some places, however, molten magma has been intruded between sedimentary beds, forming relatively thin sheets called sills (Pl. XXVI, *A*); in other places it has been intruded along fractures that cut across sedimentary beds, forming walls of igneous rock called dikes (Pl. XXVI, *A* and *B*); and in still other places it has been intruded into other rocks in irregular stringers. If these intrusive bodies are small or thin they may have cooled rather rapidly and may not be coarsely crystalline. It may in some places be practicable to drill through such intrusive bodies.

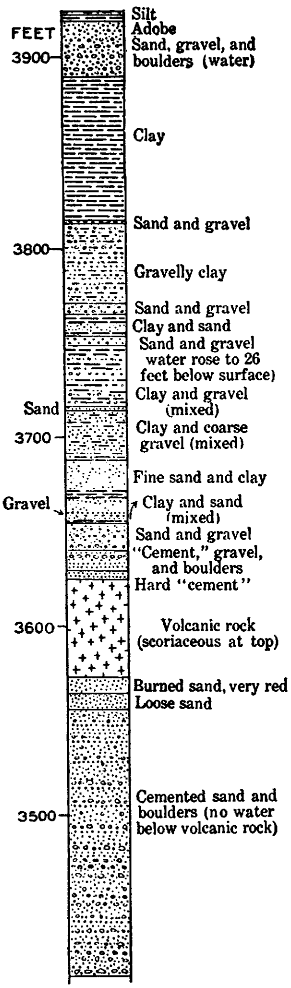


FIGURE 71.—Section of county hospital well near Douglas, Ariz., showing relation of extrusive lava bed to underlying and overlying alluvium. Based on driller's log.

Sills and dikes may act like veins in forming barriers to ground water. Good examples are afforded by the sills and other intrusive bodies in the Cretaceous strata in the vicinity of Oscuro, N. Mex., illustrated in figure 72 and described as follows:[28]

> The Cretaceous rocks consist of alternating pervious and impervious sedimentary strata that dip toward the mountains and are intruded by masses of impervious igneous rock. The impervious beds form a series of underground dams that follow the strike of the rocks and lie athwart the course in which the ground water is moving. The ground water has adjusted itself to these dams in much the same manner as the water of a stream adjusts itself to artificial dams or natural barriers in the course of the stream. Like a vast stream of exceedingly slow motion, it descends through the pervious strata from the mountains to the lowlands in reaches and rapids. Back of each dam the water is impounded in a reservoir composed of porous beds and the water table has only a slight gradient, but at the dam the reservoir overflows and the water cascades, as it were, to a lower level, where it is impounded in the same manner by the next dam in the series. Some of the barriers are visible at the surface, but most of them are concealed beneath a smooth plain [thin mantle of rock waste], and their presence can only be inferred from the irregularities in the water table that are discerned when wells are sunk [fig. 72].
>
> Milagro Hill forms an effective ground-water barrier. Near the south end of the hill flood waters have cut into the igneous rocks a notch through which some of the impounded ground water escapes, forming Milagro Spring. In this vicinity the water level drops abruptly, being much higher east of the igneous sill or dike than west of it. In

[28] Meinzer, O. E., and Hare, R. F., Geology and water resources of Tularosa Basin, N. Mex.: U. S. Geol. Survey Water-Supply Paper 343, pp. 141, 153, 1915. See also pp. 62–64, 138–140; for another example see pp. 160–162.

a shallow well * * * at the south end of Milagro Hill water was found so near the surface that it was possible to conduct it by means of a siphon to the house at the foot of the escarpment.

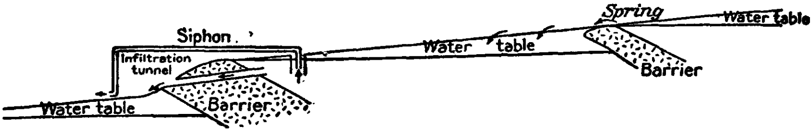


FIGURE 72.—Diagrammatic section showing relation of barriers formed by intrusive igneous rocks to the water table.

Another example of igneous rock acting as a barrier to ground water is illustrated in Plate XXI, *A* (p. 170). In the locality shown a spring, a shallow well, and a clump of trees are found on the upstream side of a ledge of resistant red porphyry, which apparently extends underground across the valley and obstructs the water that is seeping downstream through the valley gravels.[29]

The Hawaiian Islands afford good examples of dikes that impound ground water and apparently also of sills that support perched water bodies. The Waiahole tunnel was driven through the principal range on the island of Oahu a distance of 14,567 feet at altitudes of 752 to 724 feet above sea level. It penetrated a number of dikes behind which was impounded a great quantity of ground water. The following details regarding this remarkable tunnel are taken chiefly from a paper by Kluegel,[30] the inspecting engineer of the project:

The dikes range in thickness between 4 and 14 feet and consist of hard close-grained rock that is apparently waterproof. They are nearly vertical and trend at angles of approximately 45° to the tunnel. Between the dikes there is porous lava rock which was thoroughly saturated with water under considerable pressure, so that when a dike was penetrated the water would spout out from the drill holes and would gush forth from the openings blasted in the headings. A gage on some of the plugged drill holes showed a pressure of 65 pounds per square inch, corresponding to a static head of about 150 feet.

On breaking through the first dike, 200 feet from the north portal, water was encountered amounting to 2,000,000 gallons a day. As the work progressed the quantity of water increased, until at about 900 feet from the north portal the flow was 26,000,000 gallons a day, and at about 1,400 feet it was 35,000,000 gallons a day. The first dike on the south side was struck at 10,518 feet from the south portal, the first evidence of water being from the drill holes, from which water spouted under pressure. The flow from the south heading reached 17,000,000 gallons daily by the time the two headings met at 11,679 feet from the south portal.

The maximum quantity of water developed was on October 16, 1914, and was approximately 35,000,000 gallons daily from the north portal. The flow has varied considerably from time to time and has been decreasing, apparently indicating that the water stored in the mountain between the dikes is gradually being drained off. It is

[29] Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, p. 114, 1913.

[30] Kluegel, C. H., Engineering features of the Waiahole water project of the Waiahole Water Co., island of Oahu, Territory of Hawaii: Hawaiian Eng. Assoc. Press Bull. 55, Honolulu, 1916.

thought that the permanent or continual flow from the tunnel will be governed by the rainfall over this drainage area. The present flow of water percolating into the main tunnel [1916] is 14,000,000 gallons daily.

Measurements made February 3 to 8, 1920, showed that during this period approximately 9,000,000 gallons a day percolated into the tunnel and was discharged at the south portal.

RELATION OF THE RELIEF OF THE LAND TO GROUND WATER.

The relief of the land has a very important influence on ground-water conditions. In a flat, low-lying region that is not bordered by higher land the porous formations become filled with water nearly to the surface, but as a rule there is little movement of ground water and few springs of consequence, and if the formations contain much soluble matter the water is highly mineralized. In a hilly or mountainous region, on the other hand, the water that seeps into the earth percolates rapidly downward and is likely soon to be discharged at a lower level, where some formation through which it is percolating crops out. This active flow of ground water has resulted in effective

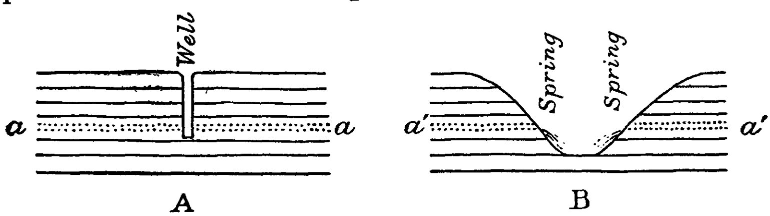


FIGURE 73.—Diagrammatic sections showing how a valley that extends into or through an aquifer performs a function with respect to recovery of ground water that is comparable to that of a well. In section A the aquifer *a–a* is tapped by a well; in section B the similar aquifer *a'–a'* is tapped by a valley.

leaching of the rocks and removal of the readily soluble material. Hence the ground water issuing from these rocks at the present time is generally of good quality.

In a flat region there may be good aquifers that will yield large supplies, but these supplies can as a rule be recovered only by sinking wells; in a region of great relief, on the other hand, the ground water is more largely returned to the surface through springs, and there is not so much need for wells. Thus, in a gully or valley that has been eroded down to an aquifer water will flow out of the aquifer, forming a spring. The gully or valley is not essentially different from a well dug to the aquifer, as is illustrated in figure 73.

In mountainous regions wells are usually not numerous, because ample supplies of good water are generally available from springs or from streams heading in springs. Ground water is not unimportant in mountainous regions, but its recovery involves relatively few problems, because it is so commonly returned to the surface through springs.

CHAPTER IV. WATER-BEARING FORMATIONS IN THE UNITED STATES.

OUTLINE OF ROCK SYSTEMS.

The rock formations of the earth have been grouped, according to age, into several rock systems, and these systems have been divided into several series. The successive systems and series are separated from one another by more or less pronounced unconformities. The time during which the formations of a system were deposited is called a geologic period, and the time during which the formations of a series were deposited is called a geologic epoch. The unconformities were produced by physical changes that occurred at the ends of the successive epochs and periods.

This grouping of the formations of the earth is unavoidably somewhat arbitrary and imperfect and is subject to revision as geologic information accumulates. It forms, however, a scheme that is indispensable for the orderly description of the geology of the earth or of any part of it. As the occurrence of the ground water of a region is governed by its geology this scheme is also essential for an orderly discussion of ground-water conditions.

Twelve rock systems have been recognized by the United States Geological Survey. In the order of their age these are as follows, the oldest being given first: Archean, Algonkian, Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary. The deposits of each system, with their included fossils, form the record of the physical events and the life of the corresponding period.

Great physical changes took place at the end of the Algonkian period, at the end of the Carboniferous period, and at the end of the Cretaceous period. These changes are represented in the rocks by three unconformities of great magnitude, which are of far-reaching influence on the occurrence of ground water in the United States. The Archean and Algonkian systems, which lie below the lowest of these three great unconformities, are commonly called pre-Cambrian rocks. The remaining systems are separated by the other two great unconformities into three major divisions—the Paleozoic, comprising the Cambrian, Ordovician, Silurian, Devonian, and Carboniferous systems; the Mesozoic, comprising the Triassic, Jurassic, and Cretaceous systems; and the Cenozoic, comprising the Tertiary and Quaternary systems.

Some of the subdivisions of the different systems are given on succeeding pages. The most important, at least so far as ground water is concerned, are those of the Carboniferous, Cretaceous, Tertiary, and Quaternary systems. The Carboniferous system comprises, in ascending order, the Mississippian series, the Pennsylvanian series, and the Permian series; the Cretaceous system comprises the Lower Cretaceous and Upper Cretaceous series; the Tertiary system comprises the Eocene, Oligocene, Miocene, and Pliocene series; and the Quaternary system comprises the Pleistocene and Recent series.

On the basis of the preceding statements the formations in the United States can, for the purposes of this paper, be grouped as shown in the following outline, in which the youngest is at the top and the oldest at the bottom:

- Cenozoic rocks:
  - Quaternary system:
    - Recent series.
    - Pleistocene series.
  - Tertiary svstem:
    - Pliocene series.
    - Miocene series.
    - Oligocene series.
    - Eocene series.
- Mesozoic rocks:
  - Cretaceous system:
    - Upper Cretaceous series.
    - Lower Cretaceous series.
  - Jurassic system.
  - Triassic system.
- Paleozoic rocks:
  - Carboniferous system:
    - Permian series.
    - Pennsylvanian series.
    - Mississippian series.
  - Devonian system.
  - Silurian system.
  - Ordovician system.
  - Cambrian system.
- Pre-Cambrian rocks:
  - Algonkian system.
  - Archean system.

RELATION OF AGE OF ROCKS TO THEIR WATER-BEARING PROPERTIES.

The age of rocks is not a key to their properties as water bearers. The geologic column of an area and the positions of the various aquifers in that column are studied not because the water-bearing properties of a formation depend on its age but because a knowledge of the succession of the formations is fundamental to a study of the distribution and depths of the aquifers and the circulation of water in them. On the whole, however, the younger formations are better water bearers than the older ones and are more extensively used for water supply. As a rule, they lie nearer to the surface and are less cemented and less compacted by pressure. Hence, as a rule, they are more porous, more easily reached in drilling, and more readily recharged with water from the surface. In any rock series, however, the best water-bearing formation is likely to be the basal conglomerate or sandstone.

PHYSIOGRAPHIC PROVINCES OF THE UNITED STATES.

Plate XXVIII is a map showing the major physiographic divisions and the physiographic provinces of the United States adopted by the Association of American Geographers[1] and the United States Geological Survey. In Plate XXVII is shown a relief map of the United States. In the following descriptions of the water-bearing formations it is necessary to refer repeatedly to different parts of the country, and in so far as convenient the names of physiographic divisions and provinces, as shown in Plate XXVIII, are used.

GEOLOGIC MAP OF THE UNITED STATES.

Figures 74–85, 87–94, 100, and 109, which show the distribution of the several rock systems and the most important rock series in the United States, were compiled chiefly from the geologic map of North America by Willis and Stose.[2] The departures from this map are in part based on more recent geologic maps and are in part due to the greater facilities afforded by the present series of maps for showing small outcrops in areas of complicated geology. The most radical change is in the geology of southwestern Arizona, for which the reconnaissance maps of Bryan[3] and Ross[4] were used, and in parts of the Atlantic Coastal Plain that have recently been studied by Cooke,[5] Stephenson,[6] Deussen,[7] and Trowbridge.[8] The maps of the Atlantic Coastal Plain from South Carolina to Alabama, inclusive, and in some other parts are based on unpublished field maps by C. W. Cooke. No attempt was made to examine all existing geologic maps, and the reader should understand that the maps herewith are incomplete and inaccurate in numerous details.

---

[1] Fenneman, N. M., Physiographic divisions of the United States: Assoc. Am. Geographers Annals, vol. 6, pp. 19–98, 1916.

[2] Willis, Bailey, and Stose, G. W., Index to the stratigraphy of North America: U. S. Geol. Survey Prof. Paper 71, pl. 1, 1912.

[3] Bryan, Kirk, Erosion and sedimentation in the Papago country, Ariz., with a sketch of the geology: U. S. Geol. Survey Bull. 730, pp. 19–90, 1923.

[4] Ross, C. P., Geology of the lower Gila region, Ariz.: U. S. Geol. Survey Prof. Paper 129, pp. 183–197, 1922.

[5] Cooke, C. W., and Shearer, H. K., Deposits of Claiborne and Jackson age in Georgia: U. S. Geol. Survey Prof. Paper 120, pl. 7, 1919. Also unpublished data.

[6] Stephenson, L. W., and others, unpublished geologic map of Mississippi.

[7] Deussen, Alexander, Geology of the Coastal Plain region of Texas: U. S. Geol. Survey Prof. Paper 126 (in press)

[8] Trowbridge, A. C., A geologic reconnaissance in the Gulf Coastal Plain of Texas near the Rio Grande: U. S. Geol. Survey Prof. Paper 131, pl. 38, 1923.

PRE-CAMBRIAN ROCKS AND YOUNGER CRYSTALLINE ROCKS.[9]

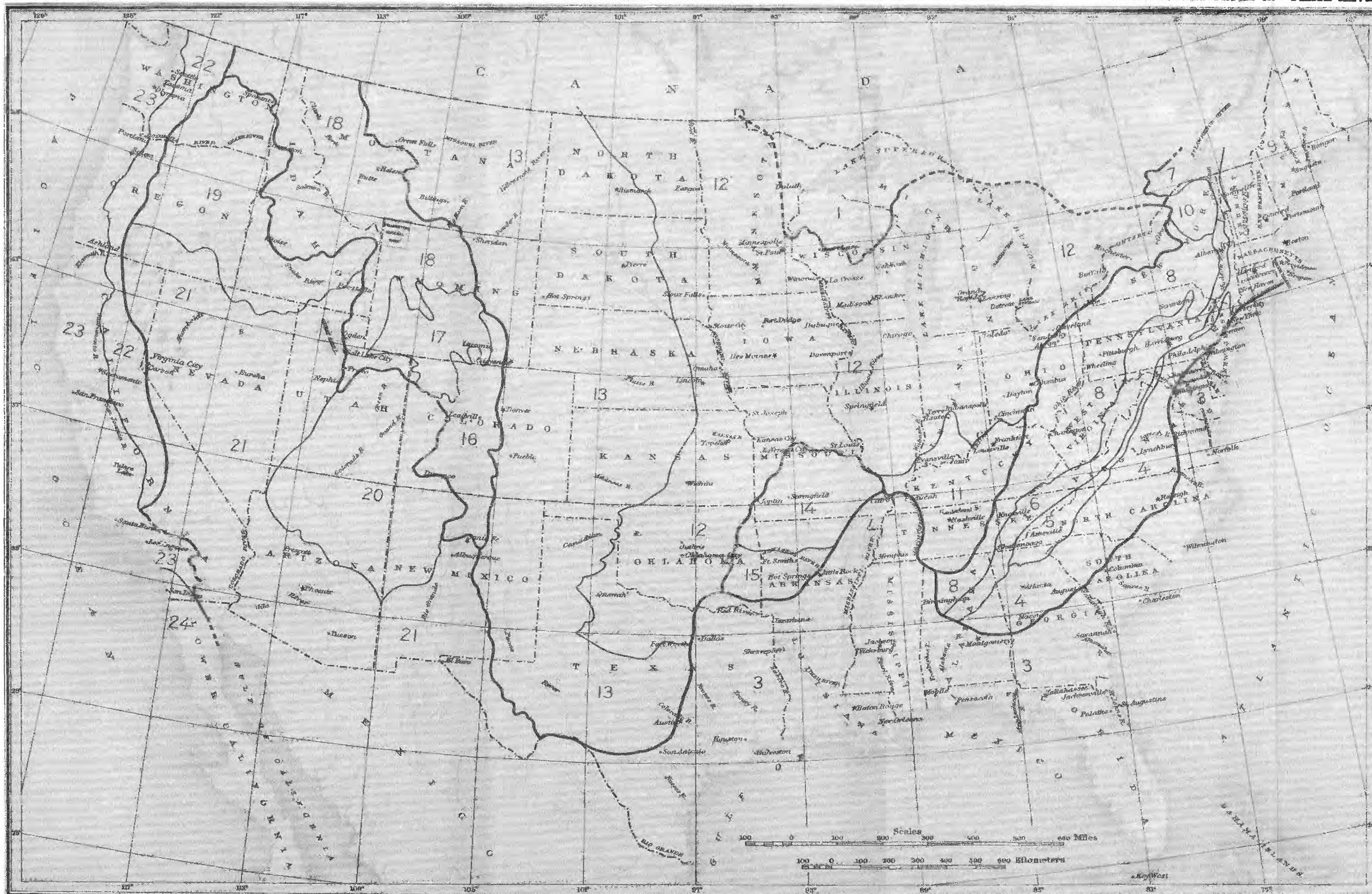
The pre-Cambrian rocks are those of the Archean and Algonkian systems. As a rule they are greatly deformed and metamorphosed and include large bodies of intrusive or plutonic igneous rocks. The Archean system consists largely of granite, gneiss, and schist; the Algonkian includes also much quartzite and slate and some unmetamorphosed sedimentary rock. In some places these rocks lie at or near the surface, but more commonly they are overlain by deposits of Cambrian or later origin. In most places where they have been observed or have been reached in drilling they form a basal complex that is strikingly different from the overlying beds and is separated from these beds by a pronounced unconformity. In exceptional localities, however, the Algonkian rocks are not greatly deformed or intruded. On the other hand, in some localities Paleozoic or even younger rocks have been so greatly deformed, intruded, and metamorphosed that they form a basal complex not essentially different from that commonly formed by pre-Cambrian rocks.

With respect to ground water the basal complex is of great importance, but whether it is composed of pre-Cambrian or less ancient rocks is not important. It is the hard, nearly impervious bottom on which rest the younger deposits with their various water-bearing

[9] The following publications (of the U. S. Geol. Survey, except as otherwise indicated) give information regarding water in pre-Cambrian rocks in the United States:

Alabama, Water-Supply Paper 114.
Arizona, Water-Supply Paper 320.
Connecticut, Water-Supply Papers 114, 232, 374, 397, 449, 466, 470.
Delaware, Geol. Folio 211; Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).
District of Columbia, Water-Supply Paper 114; Geol. Folio 152; Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).
Georgia, Water-Supply Papers 114, 160; Georgia Geol. Survey Bull. 15 (cooperative report).
Iowa, Water-Supply Papers 114, 293.
Maine, Water-Supply Papers 114, 145, 223, 258; Geol. Folio 149.
Maryland, Water-Supply Paper 114; Geol. Folios 152, 204, 211; Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).
Minnesota, Water-Supply Papers 114, 256; Geol. Folio 117.
Missouri, Water-Supply Papers 114, 195.
Montana, Water-Supply Papers 345, 400.
New Hampshire, Water-Supply Papers 114, 145.
New Jersey, Water-Supply Paper 114; Geol. Folios 157, 191.
New Mexico, Water-Supply Paper 343.
New York, Water-Supply Papers 110, 114; Geol. Folio 157.
North Carolina, Water-Supply Paper 114; Geol. Folios 124, 147, 151.
North Dakota, Geol. Folio 117.
Pennsylvania, Water-Supply Papers 106, 114; Geol. Folios 162, 157, 211
Rhode Island, Water-Supply Paper 114.
South Carolina, Water-Supply Paper 114; Geol. Folio 147.
Tennessee, Geol. Folios 124, 151.
Texas, Geol. Folios 183, 194.
Vermont, Water-Supply Paper 110.
Virginia, Water-Supply Paper 114.
West Virginia, Water-Supply Paper 114.
Wisconsin, Water-Supply Paper 114; Wisconsin Geol. and Nat. Hist. Survey Bull. 35 (cooperative report).

RELIEF MAP OF THE UNITED STATES.



PHYSIOGRAPHIC DIVISIONS

MAJOR DIVISION	PROVINCE
Laurentian Upland	1. Superior Upland
Atlantic Plain	2. Continental Shelf (submerged) 3. Atlantic Coastal Plain
Appalachian Highlands	4. Piedmont province 5. Blue Ridge province 6. Appalachian Valley province 7. St. Lawrence Valley 8. Appalachian Plateaus 9. New England province 10. Adirondack province
Interior Plains	11. Interior Low Plateaus 12. Central Lowland 13. Great Plains
Interior Highlands	14. Ozark Plateaus 15. Ouachita province
Rocky Mountain region	16. Southern Rocky Mountains 17. Wyoming Basin 18. Northern Rocky Mountains
Intermontane Plateaus	19. Columbia Plateaus 20. Colorado Plateaus 21. Basin and Range province
Pacific Mountain region	22. Sierra Nevada and Cascade Mountains 23. Pacific Border province 24. Lower Californian province

MAP OF THE UNITED STATES SHOWING MAJOR PHYSIOGRAPHIC DIVISIONS AND PHYSIOGRAPHIC PROVINCES

Based on map prepared by a committee of the Association of American Geographers, N. M. Fenneman, chairman

1923

497781 O-59 (Face back of Plate XXVII)

beds. Where it is buried under more than 100 feet of sedimentary beds it is generally of no value as a source of water, and every effort should be made to develop the necessary supplies from the overlying beds. In such places it is generally advisable to stop drilling when the basal complex is struck. It is important to understand that the basal complex commonly extends to indefinite depths, and that, with rare exceptions, no water-bearing formations occur beneath it.

Where the basal complex is at or near the surface, however, it may be the only available source of water. Fortunately, in these localities it generally yields supplies which, though small, are usually reliable and of good quality and are likely to be very valuable because of the lack of other supplies. It gives rise to numerous small springs, which are usually supplied from the surficial decayed parts of the complex. Such springs fluctuate with the season and may dry up in summer. The wells that get water from the basal complex are of two distinct types—shallow dug wells with large infiltration surfaces, receiving the seepage from the decayed upper parts of the complex, and drilled wells, commonly 6 inches in diameter, ranging from less than 100 feet to a few hundred feet in depth and supplied chiefly from water-bearing joints.

In the northern part of the United States the basal complex, even where it is near the surface, is generally mantled with glacial drift that supplies dug wells. Here as a rule only drilled wells extend into the basal complex. In the southern part of the country, where glacial drift is absent, both dug and drilled wells obtain supplies from the basal complex or from the residual waste formed by the decay of these rocks.

A vast area of pre-Cambrian rocks lies in the northeastern part of North America, chiefly in Canada but with projections into the United States. In figure 74 are shown the areas in the United States in which pre-Cambrian rocks or post-Cambrian intrusive or plutonic rocks lie at or near the surface.

The largest pre-Cambrian areas in the United States are in the East, in the Lake Superior region, and in the Rocky Mountains; smaller areas are found in the Ozark Mountains, in the Wichita Mountains, in the vicinity of Llano, Tex., in the Black Hills, and in many widely scattered western mountain ranges, especially in southern and western Arizona and in southeastern California. Many irregular areas of post-Cambrian intrusive rocks are found in the East, as is shown in figures 74 and 75; large areas occur in Idaho and California, and numerous small areas are found in other parts of the West.

The principal areas of water-bearing pre-Cambrian rocks in the eastern United States are shown approximately in figure 75. They

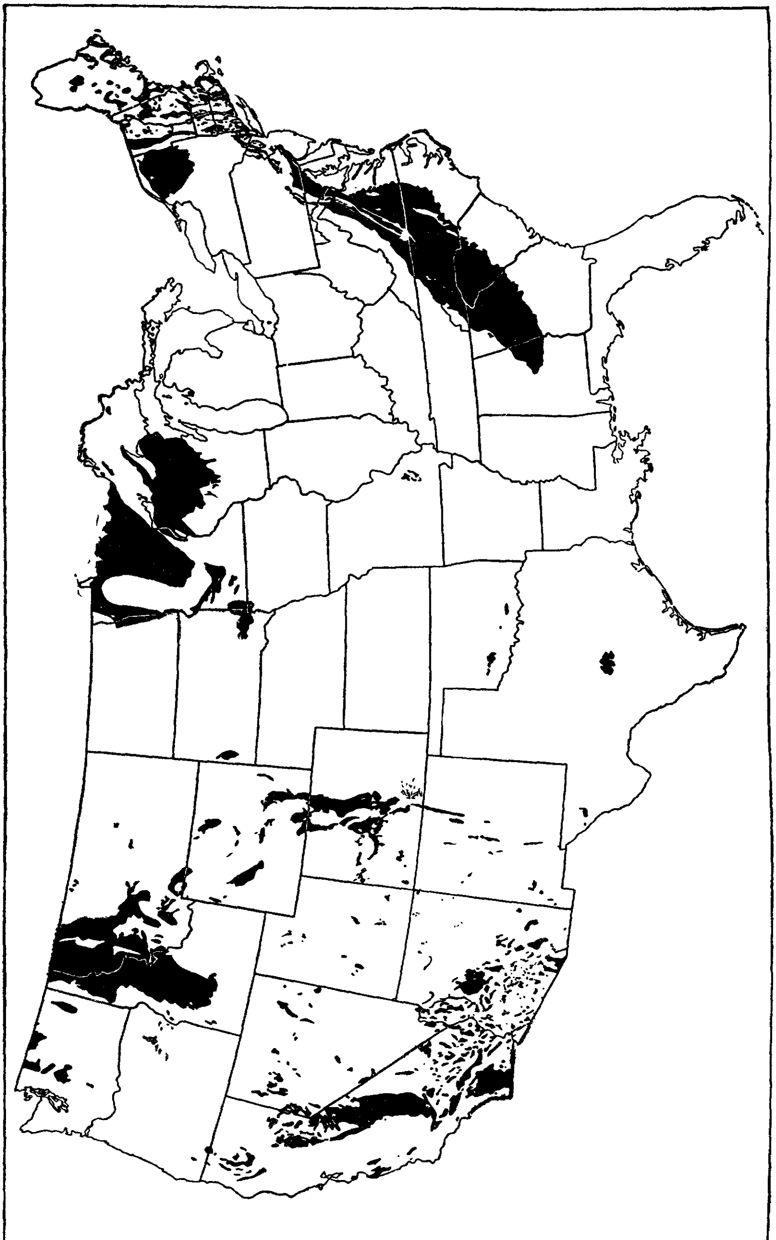


FIGURE 74.—Map of the United States showing areas in which pre-Cambrian rocks or post-Cambrian intrusive or plutonic rocks are at or near the surface. These rocks yield small supplies of water to springs, to dug wells that end in the disintegrated surficial parts of the rocks, and to drilled wells that encounter water-bearing joints within a few hundred feet of the surface.

occupy most of the Piedmont Plateau, a large part of the Appalachian Mountain region, the Adirondack Mountains, and parts of New Eng-

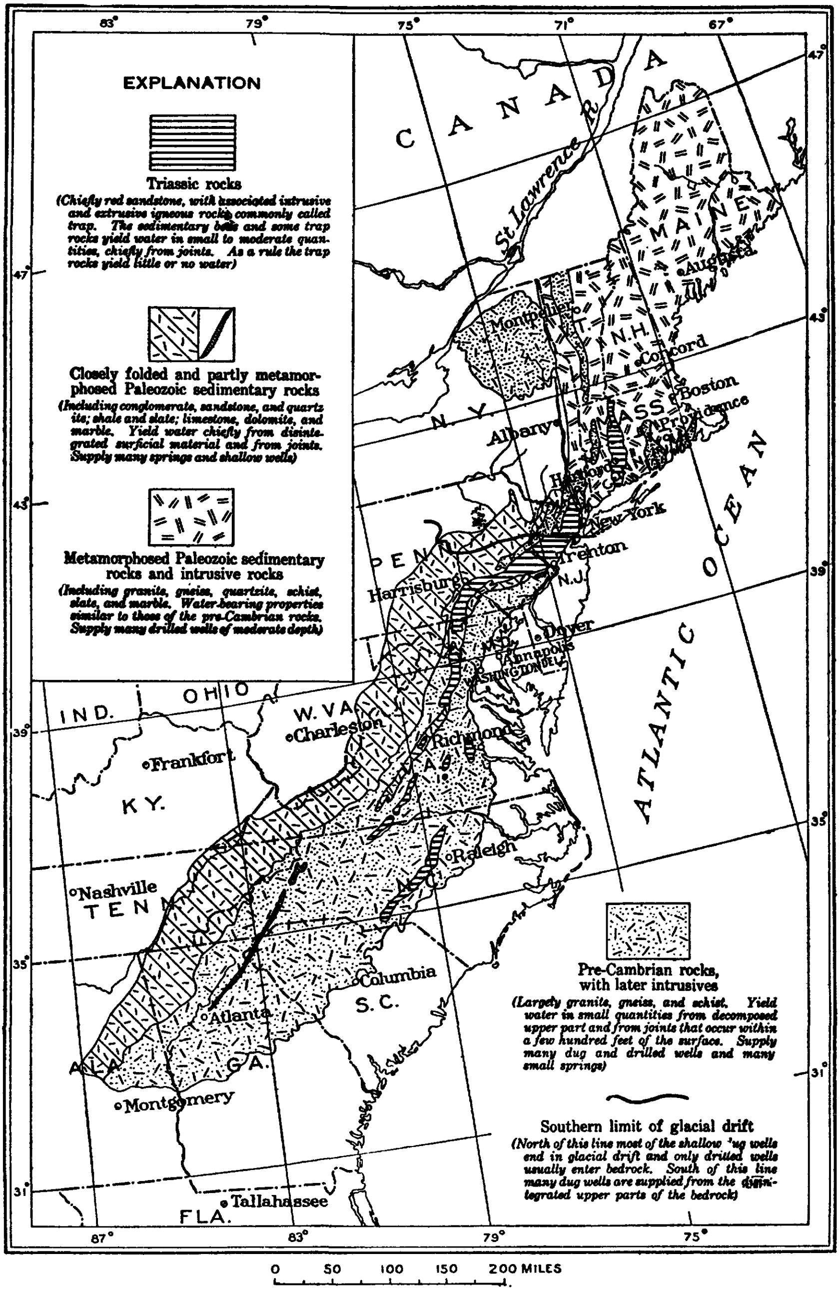


FIGURE 75.—Map of the eastern part of the United States showing areas in which pre-Cambrian rocks, metamorphosed and closely folded Paleozoic sedimentary rocks, Triassic sedimentary rocks, and post-Cambrian intrusive and extrusive rocks are at or near the surface.

land. On the Piedmont Plateau the pre-Cambrian rocks constitute a very important source of water. Here, over wide areas of well-populated country, they furnish water to innumerable wells and springs that provide practically all the domestic supplies and many of the small industrial and public supplies, the largest supplies being obtained from streams. In New England the water from these rocks is less needed because of the presence of the glacial drift, but it is nevertheless utilized by many drilled wells for domestic and small industrial supplies. Most of New England is underlain by crystalline Paleozoic rocks that are difficult to differentiate from the pre-Cambrian and are essentially like them in water-yielding properties (fig. 75). The closely folded Paleozoic rocks of the Appalachian region are also in part metamorphic and somewhat like the pre-Cambrian rocks with respect to water (fig. 75).

The areas of pre-Cambrian rock in the vicinity of Lake Superior (fig. 74) may be regarded as belonging to the vast pre-Cambrian region of eastern Canada. Pre-Cambrian rocks lie near the surface in about one-half of the northern peninsula of Michigan, most of the northern half of Wisconsin, most of the northern and western parts of Minnesota, and small adjacent parts of North Dakota, South Dakota, and Iowa. They are largely Archean granite and gneiss but also include quartzite, some sedimentary beds, and lava flows belonging to the Algonkian system. These rocks are commonly overlain by glacial drift, and in western Minnesota and adjacent parts of North Dakota, South Dakota, and Iowa they are overlain by thin Cretaceous deposits. They are therefore not the main source of ground water in this region and are drilled into only where overlying formations are absent or too thin to yield much water. Along Red River and along Minnesota River above the big bend many wells end in granite, but they do not generally yield enough for the public supplies of even small villages. In a number of small tracts in southwestern Minnesota and adjacent parts of South Dakota and Iowa the Sioux quartzite, a hard, compact rock of Algonkian age, lies at or near the surface and affords small but reliable supplies to many wells. (See p. 121.)

In the Rocky Mountains and farther west the pre-Cambrian rocks (fig. 74) are largely granitic. The granite has in many places been weathered and worn down to form pockets or undulating surfaces with porous residuum underlain by the firm impervious rock. In such places small supplies of good water can commonly be obtained from shallow wells even in arid regions, and in some places enough water is found for irrigation on a small scale. Large parts of the Sierra Nevada and the Peninsular Mountains, in California, are underlain by post-Cambrian granitic rocks (fig. 74) that supply water from their upper decomposed parts—in a few places in sufficient quantities for irrigation. Much of the northern part of Washington is also underlain by crystalline rocks that are younger than pre-Cambrian, but they are here largely covered with glacial drift. Another extensive area of younger crystalline rocks is in central Idaho (fig. 74), where these rocks give rise to numerous springs, many of them thermal.

In western Montana and northern Idaho large areas are underlain by Algonkian rocks known as the Belt series (fig. 74). They consist chiefly of quartzite, shale, and limestone several thousand feet in aggregate thickness, with some intrusive igneous rocks. These rocks have been deformed but still show their stratification. They furnish small supplies to a few wells, but, so far as known, they are unsatisfactory as a source of water.

PALEOZOIC SYSTEMS.

GENERAL CONDITIONS.

The Paleozoic rock systems of the United States comprise a succession of formations consisting chiefly of sandstone, shale, and limestone or dolomite and aggregating many thousand feet in thickness. The areas in which they are at or near the surface are shown in figure 76. They are important sources of water over much of the eastern and central parts of the country, including most of New York, Pennsylvania, West Virginia, Kentucky, Tennessee, northern Alabama, and parts of the States east of those mentioned, all or nearly all of Ohio, Indiana, Illinois, Iowa, Missouri, and Oklahoma, the southern peninsula and some of the northern peninsula of Michigan, southern and central Wisconsin, southeastern Minnesota, southeastern Nebraska, eastern Kansas, north-central Texas, and northwestern Arkansas. They are also sources of water supply in the Pecos Valley and adjacent regions in New Mexico and Texas. They are exposed in many areas in the western part of the United States, chiefly in mountain ranges (fig. 76), but are of little consequence in these areas as sources of water.

Except along the eastern margin and in a few other localities, the Paleozoic formations of the eastern and central United States lie nearly horizontal, but their dips are sufficient to produce differences from place to place in the geologic section and the depths to particular formations. There are several unconformities within the Paleozoic sequence, but none of them involve any radical differences in structure or in character of rock. In the West the Paleozoic rocks generally appear in faulted and tilted blocks in mountainous regions, and in these positions they are generally barren of water to great depths.

The great Paleozoic area of the eastern and central United States (fig. 76) extends northward to the Canadian border or to the areas of pre-Cambrian rocks; eastward into the Appalachian Mountains and New England, where the Paleozoic formations are deformed and metamorphosed and more or less interfolded and faulted with the

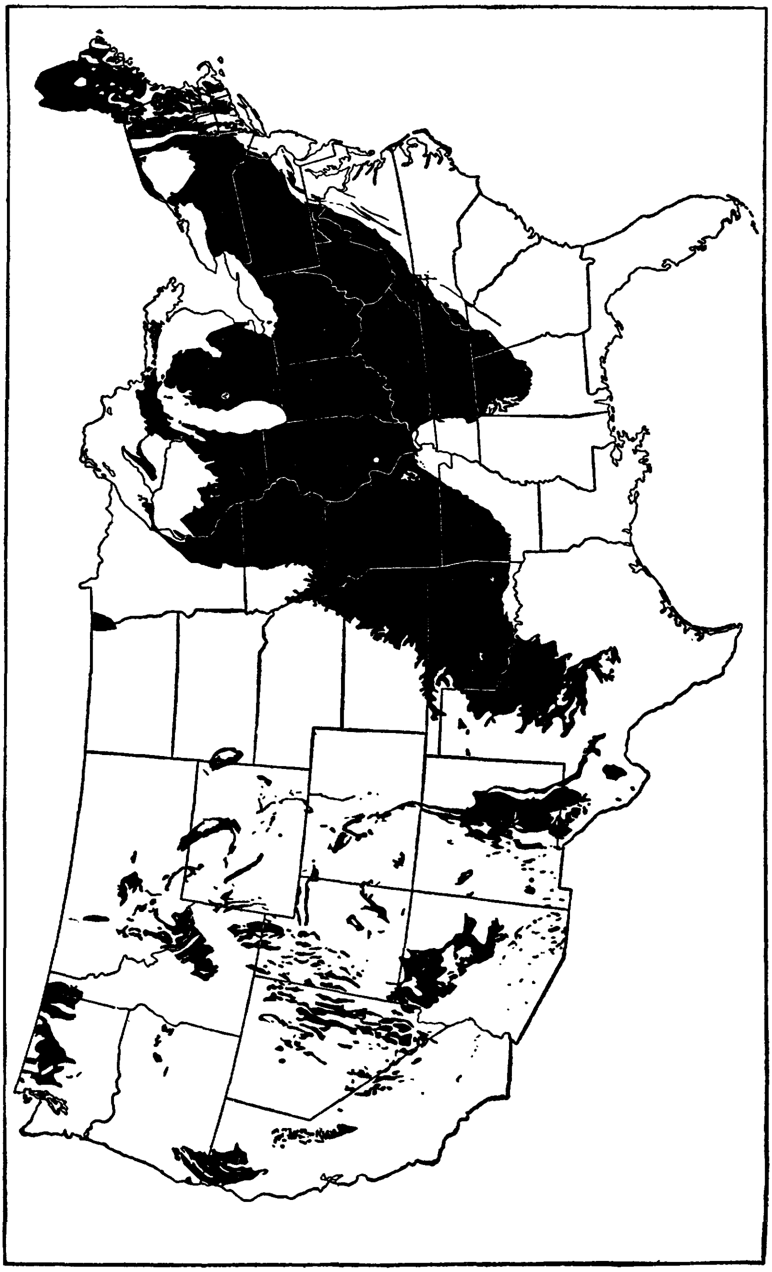


FIGURE 76.—Map of the United States showing areas in which Paleozoic rocks are at or near the surface. In the large areas the Paleozoic formations generally lie nearly horizontal and include a number of valuable sandstone and limestone aquifers. The deeper waters are in most places highly mineralized.

pre-Cambrian; southward to the Coastal Plain, where the Paleozoic formations pass to great depths beneath younger deposits; and westward to the Great Plains, where the Paleozoic formations likewise disappear under younger deposits. In the New Mexico-Texas region the succession of Paleozoic formations reappears, with modifications, and is water-bearing in the Pecos Valley and other areas where the formations lie at sufficiently low levels and their dips are not too great.

The Paleozoic succession of the eastern and central United States includes a number of prominent water-bearing sandstones and limestones. Among the most important water-bearing sandstones are the thick and widespread sandstones of the Cambrian system, the St. Peter sandstone in the Ordovician system, and the sandstone at the base of the Pennsylvanian series of the Carboniferous system. Among the important water-bearing limestones or dolomites are the Oneota dolomite and related beds in the lower part of the Ordovician system, the Galena dolomite and related beds in the Ordovician system above the St. Peter sandstone, the Niagara dolomite and related beds that constitute a large part of the Silurian system, and the several limestone formations that make up a large part of the Mississippian series of the Carboniferous system. Prominent non water-bearing shales are found in the Cambrian system, at the top of the Ordovician system, in the Devonian system, and in the Pennsylvanian and Permian series of the Carboniferous system. The Devonian system is not of leading importance as a source of water except in New York and some other parts of the East. The Pennsylvanian and Permian series contain many sandy beds that yield water, but these are interbedded with shaly beds, and, on the whole, these two series are not very satisfactory in respect to either the quantity or the quality of water which they yield.

In most parts of the large Paleozoic area numerous wells penetrate sandstone or limestone and furnish supplies for domestic, stock, and industrial uses and for the waterworks of villages and the smaller cities. Flowing wells are obtained in many localities, chiefly in the valleys of Mississippi River and its tributaries. Many of the wells are less than 100 feet deep, and only a small proportion are more than 200 feet deep. However, in Wisconsin, Illinois, Minnesota, Iowa, and Missouri there are many deeper wells, and a considerable number have been drilled by municipalities and industrial concerns to depths of more than 1,000 feet to reach well-known Paleozoic sandstones. Most of the deep wells in these States yield abundant supplies.

The most serious problem in connection with the Paleozoic formations relates to the quality of the water. Throughout most of the area the rocks lying more than a few hundred feet below the surface yield water that is too salty to be used. This condition appears to be due chiefly to the sluggish circulation of the ground water at some distance below the levels of the principal streams. The quality of the water in the Paleozoic rocks of this region depends on its position with respect to the drainage level rather than on the formation in which it exists. Fortunately, the water within 200 or 300 feet of the surface is generally of good quality except that it is rather hard. Only in Kansas, Oklahoma, and Texas are the shallow Paleozoic waters commonly too highly mineralized for use. In the central zone of the area, running through Wisconsin, Illinois, Minnesota, Iowa, and Missouri, the water of deep-lying Paleozoic rocks is generally rather highly mineralized but yet, as a rule, good enough for domestic uses. East of Illinois the deeper waters are all bad and no successful wells have been reported more than 500 feet deep.

COLUMNAR SECTIONS.

Generalized geologic sections of the Paleozoic rocks in different parts of the eastern and central United States, with brief statements as to the water-bearing properties of the formations, are given below.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies.

New York.[a]

System	Subdivision.	Lithologic character.	Water supply.
Carboniferous.	Pennsylvanian series.	Chiefly shale and sandstone.	The Carboniferous rocks extend into only a small part of New York. See next section — southwestern Pennsylvania, where the system is well developed.
	Mississippian series.		
Devonian.	Catskill formation.	Chiefly red sandstone and sandy shale.	Yield moderate supplies to many springs and wells, most of which are shallow.
	Chemung formation.	Chiefly gray and olive-colored sandstone and sandy shale.	
	Portage formation. Genesee shale.	Sandstone and shale.	
	Tully limestone.	Blue-black limestone.	
	Hamilton shale. Marcellus shale.	Shale and sandstone.	
	Onondaga limestone.	Limestone.	
	Schoharie grit. Esopus grit. Oriskany sandstone.	Grit and sandstone.	
	Helderberg group.	Limestone.	

[a] Geologic section compiled from various sources. Water-supply data chiefly from paper on New York by F. B. Weeks (U. S. Geol. Survey Water-Supply Paper 114, pp. 83-86, 1905).

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

New York—Continued.

System.	Subdivision.		Lithologic character.	Water supply.
Silurian.	Cayuga group, including Salina formation.		Shale, impure limestone, gypsum, salt.	Yields potable water to springs and wells, some of which is highly mineralized.
Silurian.	Niagara group.	Lockport dolomite.	Chiefly limestone.	Yields hard but potable water to wells and springs.
Silurian.	Niagara group.	Clinton formation.	Sandstone, shale, and some limestone.	Yields water.
Silurian.	Medina group.	Albion sandstone.	Conglomerate and sandstone.	Yield water freely.
Silurian or Ordovician.	Medina group.	Queenston shale.	Red and green shale and sandstone.	
Ordovician.	Oswego sandstone.		Gray sandstone.	
Ordovician.	Lorraine shale. Utica shale.		Shale, slate, etc.	Yield water to many wells. Much of the water is iron-bearing and sulphurous, and some of it is regarded as unfit for drinking.
Ordovician.	Trenton limestone.		Chiefly limestone.	Yields water. The mineral waters of Saratoga Springs come from fractured zones in this limestone.
Ordovician.	Black River limestone. Chazy limestone.		Chiefly limestone.	Yield some water.
Ordovician.	Beekmantown limestone.		Sandstone, sandy limestone, etc.	Yield some water.
Cambrian.	Upper Cambrian.	Little Falls dolomite.[b] Hoyt limestone.[b] Theresa sandstone.[b]	Dolomite, limestone, and sandstone.	
Cambrian.	Upper Cambrian.	Potsdam sandstone.[b]	Compact gray, buff, or reddish-brown sandstone, found chiefly north of the Adirondack Mountains.	Yields small supplies to springs and shallow wells. No records of deep wells in these sandstones have been obtained.
Cambrian.	Middle and Lower Cambrian.		Limestone and slate in eastern New York and adjacent parts of New England.	Yields water to many springs, some of which are large; also moderate supplies to wells, generally less than 100 feet deep.
Cambrian.	Cheshire quartzite.			

[b] E. O. Ulrich refers these formations to his Ozarkian system

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Southwestern Pennsylvania.[c]

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Permian series.	Dunkard group.	1,150	Prevailingly soft and shaly. Contain some sandstone and a number of coal beds, which are generally thin and unimportant.	Limestone near middle (Upper Washington limestone) and basal sandstone (Waynesburg sandstone) supply many wells and springs. Where they are not deeply buried their water is of good quality.
	Pennsylvanian series.	Monongahela formation.	400	The most important coal-bearing formation of southwestern Pennsylvania. The rocks are decidedly calcareous, but beds of sandstone are locally prominent members of the formation.	Some water from sandstone, limestone, and coal beds. Deep water is salty.
		Conemangh formation.	853	Chiefly shale of various colors, green and red the most pronounced, interstratified with beds of coarse sandstone which are fairly persistent but which occasionally lose their distinctive character.	Sandstones yield considerable potable water where not deeply buried. The Mahoning sandstone, at base of formation, is probably the best water-bearing member. Deep water is salty.
		Allegheny formation.	325	Less sandy than either of the contiguous formations. Largely shale, but in places sandstone is well developed. Three prominent coal beds occur.	Yields some water from sandstone and coal beds.
		Pottsville sandstone.	400	Generally coarse hard sandstone or conglomerate inclosing a thin irregular bed of shale.	Yields generous supplies of water to springs and wells in parts of Pennsylvania where it is well developed and lies near the surface.
	Mississippian series.	Mauch Chunk shale.	250	Red and green shales, with beds of greenish sandstone inclosing a lentil of blue fossiliferous limestone, which is the thin edge of the great Greenbrier limestone of Virginia.	In general not a good source of water.
		Pocono sandstone.	2,000	Sandstone varying from thin-bedded, flaggy rock to coarse, irregularly bedded conglomerate. Bed of siliceous limestone at the top.	Yields moderate supplies to many springs and wells. Where deeply buried its water is salty.
Devonian.	Catskill formation.		2,250	Red, black, and green shales and greenish sandstone. Nonmarine deposits.	
	Chemung formation.		3,400	Chiefly greenish-gray marine sandstone and shale.	
	Portage formation. Hamilton formation.				

[c] Section compiled from folios and reports on southwestern Pennsylvania. Water-supply data from folios and water-supply papers.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Ohio.[d]

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Permian series.	Dunkard group.	636	Sandstone, generally massive, shale, limestone, and thin coal seams; nonmarine at least in part.	
	Pennsylvanian series.	Monongahela formation.	275	Shale, limestone, and sandstone, with important beds of coal.	Yield small supplies of fair quality to shallow wells, especially where sandstone beds are near surface. Quantities of water generally too small for public supplies. Deep water is salty.
		Conemaugh formation.	500	Upper part mainly shale; lower part sandstone, with some shale and limestone.	
		Allegheny formation.	300	Shale, limestone, and sandstone, with important coal seams.	
		Pottsville formation.	435	Light-colored sandstone and conglomerate, with some shale and a few coal seams.	Yields considerable potable water to wells and springs where it crops out or lies relatively near the surface. Best supplies probably from basal beds. Where it lies deep its water is salty.
	Mississippian series.	Maxville limestone.	±100	Fossiliferous limestone, largely brecciated.	Entire series is poor in water. In large areas in which the shales are at the surface, water is scarce and reliance is largely placed on rain water stored in cisterns.
		Logan formation.	150	Sandstone, massive conglomerate, and shale.	
		Black Hand formation.	500	Sandstone, fine conglomerate, and shale.	
		Cuyahoga formation.	450	Light-colored argillaceous shale, with thin beds of sandstone. Shale characterized by ferruginous nodules.	
		Sunbury shale.	±40	Black bituminous shale.	
		Berea sandstone.	212	Sandstone, used for building stone and for grindstones; locally carries oil and gas.	
Devonian or Carboniferous.	Bedford shale.		150	Thin-bedded shale with some thin beds of sandstene.	

[d] Data compiled from various sources, including Fuller, M. L., and Clapp, F. G., U. S. Geol. Survey Water-Supply Paper 259, pp. 22, 23, 1912; Orton, Edward, U. S. Geol. Survey Nineteenth Ann. Rept., pt. 4, pp. 633–717, 1898; Prosser, C. S., Jour. Geology, vol. 11, pp. 520, 521; Ohio Geol. Survey, vols. 6, 7, Bull. 7, 4th ser., 1905; Mills, R. V. A., and Wells, R. C., U. S. Geol. Survey Bull. 693, 1919; and Fenneman, N. M., Ohio Geol. Survey, 4th ser., Bull. 19, pp. 59–70, 1916.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Ohio—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Devonian.	Ohio shale.	3,000	Mainly black or dark-brown shale.	Yields little water, most of which is highly mineralized.
	Olentangy shale.	80	Blue shale.	
	Delaware limestone.	70	Blue thin-bedded limestone.	Covered by thick, impervious shale, is of small importance as source of water but supplies a few flowing wells and some rather large springs.
	Columbus limestone.	110	Light-colored limestone containing masses of chert.	
Silurian.	Monroe formation.	600	Compact magnesian limestone, jointed and with numerous solution passages.	Most important source of ground water in the State except glacial drift. Where near the surface the rocks yield abundant supplies to many wells. Where they lie deep the water is salty.
	Salina formation.	600	Shale, dolomite, gypsum, and rock salt.	
	Niagara limestone.	600	Light-colored shale at base, dolomite and limestone above, and a thin sandstone bed at top.	Water found in joints and solution passages in the limestone. Most water is at contact of limestone with basal shales. Springs occur where this contact crops out. The limestone yields considerable water to shallow wells, but where it lies deep the water is salty.
	"Clinton" limestone.	250	Massive buff to pinkish horizontal or cross-bedded limestone, composed largely of minute shell fragments. Few joints or bedding partings. Locally replaced by iron ore.	Water found in moderate amounts in joints, bedding planes, and solution passages; springs numerous at top and bottom. Where formation lies deep water is salty.
	"Medina" shale.	400	Red or yellow nonfossiliferous shale, with local thin beds of sandstone.	Yields little water.
Ordovician.	Richmond and Maysville groups.	±650	Gray to blue limestone layers, 2 to 10 inches thick, alternating with shale. Prevailingly calcareous throughout most of thickness.	Yields moderate supplies to shallow wells. Most deep wells obtain very small supplies or none at all. Water in some wells brackish and in a few slightly sulphurous.
	Eden group. Latonia shale.	230	Blue and gray shales, weathering brownish or yellowish.	Rarely water-bearing. No successful deep wells known. Furnish small supplies to shallow wells.
	Eden group. Utica shale.	24	Black shale.	

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Ohio—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Ordovician.	Shale and limestone of Trenton age.	150	Dark hard, compact shale, in layers 2 to 10 inches or more thick, alternating with beds of impure gray limestone of similar thickness.	Carry water locally, but success of drilling is uncertain. Some of the water is salty or sulphurous.
	Limestone of Black River and Stones River age. (The so-called "Trenton" limestone of the drillers).	600	Massive, compact grayish limestone, breaking with conchoidal fracture.	More or less water generally present but commonly salty. Not to be depended on for supplies of fresh water.
	St. Peter sandstone.	400	Porous calcareous sandstone.	Yields large supplies of salty water under considerable pressure.
Ordovician and Cambrian.		3,000	Varicolored dolomitic limestone and marble, with possibly shale in some places.	Carry little or no water at depths at which they occur in Ohio.
Cambrian.			Probably prevailingly sandy.	Not penetrated in Ohio. Waters likely to be strongly mineralized and unfit for use.

North-central Kentucky.[a]

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.	
				To shallow wells.	To deep drilled wells.
Carboniferous.	Newman limestone.		Occurs in small areas on Waverly shale. Not important in this region.		
	Waverly shale.	300	100 feet or more of blue shale, covered by interbedded shales and hard, even-bedded greenish sandstones. Contains concretionary iron oxide at one or more horizons.	The sandstone furnishes very pure soft water at its junction with the underlying shale. The shale furnishes no water.	Not penetrated by deep wells in this region.
Devonian.	Ohio shale.	150	Thin-bedded carbonaceous black shale.	Yields an abundance of highly mineralized water. The most common mineral waters are sulphur, chalybeate, and alum.	Not penetrated by deep wells in this region.

[a] Matson, G. C., Water resources of the Blue Grass region, Ky.: U. S. Geol. Survey Water-Supply Paper 233, pp. 14–17, 1909.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

North-central Kentucky—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.	
				To shallow wells.	To deep drilled wells.
Devonian.		30	Usually a cherty magnesian limestone with some shale beds.	Furnishes considerable hard water where the limestone rests on shale.	Yields moderate quantities of hard water.
Silurian.	Panola.	60	Blue shale and yellow limestone, in places containing chert. Locally includes some sandstone. Varies greatly in thickness. Includes sediments of Niagaran and Onondaga age.	The limestone furnishes good supplies of hard water. The shale supplies some mineral water to springs and shallow wells.	The limestone furnishes considerable water in some localities.
Ordovician.	Richmond.	60	Heavy-bedded arenaceous limestone, gray or blue, weathering to buff; about 10 feet of dense calcareous shale in the lower part. Locally an impure sandstone.	Furnishes an abundance of hard water in the limestone areas and where the sandstone is not too shaly.	Penetrated by only a few wells. The sandy phase may furnish some water.
		125	Blue or dove-colored nodular limestone and blue shale, the shale beds predominating.	Furnishes moderate quantities of hard water.	Furnishes satisfactory supplies in but few places.
		80	Interbedded blue limestone and shale. Shale predominates in northern part of the region, but heavy beds of limestone occur farther south.	Where heavy beds of limestone are at the surface, good supplies of hard water are obtained from springs and shallow wells.	The limestone beds furnish considerable water where within 100 feet of the surface. Deep wells may encounter brackish water containing hydrogen sulphide. The best supplies are obtained where the limestone layers are near the surface.
	Maysville.	230	Interbedded blue limestone and shale, the alternate layers usually thin and nodular. In general the shale predominates, and the limestone layers are in places thin and shaly. Some moderately heavy beds of limestone occur at certain horizons, but the usual thickness of single beds is less than 1 foot.	Yields moderate quantities of hard water. Water conditions are most favorable where the formation contains most limestone at or near the surface. Contains many springs of moderate size, and shallow wells are commonly successful.	Seldom yields water at depths greater than 150 feet. The best supplies of hard water are commonly obtained within 50 feet of the surface, though in some localities good supplies are obtained at a depth of 100 feet or slightly more. Water encountered below the level of the surface streams is likely to be brackish and to contain hydrogen sulphide.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

North-central Kentucky—Continued.

System.	Subdivision.	Maximum thickness (feet.)	Lithologic character.	Water supply.	
				To shallow wells.	To deep drilled wells.
Ordovician.	Eden shale.	+200	In southern part of region upper beds are of shaly sandstone, in some places concretionary, called the Garrard sandstone member; lower part is same as the Eden farther north. In northern part of region the formation consists of blue shale, containing some sandy layers and local beds of limestone. Maximum thickness of the Garrard sandstone member is about 150 feet, and it gradually thins northward.	The sandstone supplies moderate quantities of water in some localities. The shale supplies small quantities of water.	Water bearing in but few places. Deep wells are unsuccessful.
	Winchester limestone.	+60	Blue and gray limestones with some blue shale. Limestone layers commonly rough and in some places having waved upper surface.	Moderate quantities of hard water.	Usually furnishes no fresh water, but may supply strong brines, which commonly contain hydrogen sulphide.
	Lexington limestone.	75	Gray crystalline limestone, usually lighter colored and more cherty than the underlying limestone.	Yields an abundance of hard water for springs and wells. Contains many large underground streams and supplies large springs.	Many good wells when penetrated below the level of surface drainage; the supplies are saline and saline-sulphur.
		194	Lower 10 to 35 feet consists of light-drab argillaceous limestone with shale beds; overlain by 100 feet of gray or blue thin-bedded nodular limestone, separated by thin partings of shale; at the top 20 to 60 feet of subcrystalline gray siliceous sand and locally phosphatic limestone.	Supplies an abundance of hard water for springs and wells.	Below the levels of surface drainage supplies mineral waters—usually salt or salt-sulphur.
		30	Heavy-bedded coarse-grained crystalline cherty limestone; usually gray.	Yields considerable hard water.	Will supply no fresh water when found below level of surface streams. May yield salt-sulphur water.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

North-central Kentucky—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.	
				To shallow wells.	To deep drilled wells.
Ordovician.	Highbridge limestone.		Dense fine-grained gray or light-drab limestone, 90 feet thick, near the base; covered by several feet of soft fine-grained limestone containing calcite crystals and some pyrite. The upper 20 to 40 feet dove-colored fine-grained limestone, containing many calcite crystals and separated by layers of shale a few inches to 4 feet thick. The top layer usually a light-gray crystalline limestone. Near the top a bed of soft unctuous green clay.	Considerable hard water for springs and shallow wells.	Yields considerable salt and salt-sulphur water.
		30	Dense fine-grained limestone, arranged in heavy even beds; light dove-colored to gray. Dolomitic at the top and bottom and containing many seams of dolomite through the entire series.	Some hard water for springs and shallow wells.	Not distinguished from the other Stones River formations. Will yield nothing but salt or salt-sulphur water.
		285	Dense fine-grained massive limestone in places partly crystallized. Usually dark drab or dove-colored. Heavy bedded, but with some shaly partings.	Yields considerable hard water for springs and shallow wells in Kentucky River gorge. Contains some caverns.	Yields salt or salt-sulphur waters only.
		100	Known only from well records. Limestone resembling the overlying beds; rarely shale.		Yields nothing but salt or salt-sulphur waters.
	St. Peter sandstone.		A siliceous limestone, not exposed and known only from well records. Occurs at horizon of St. Peter sandstone.		Yields strong salt-sulphur water. Furnishes flowing wells in the valleys of Ohio, Licking, and Kentucky rivers.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Michigan.[f]

System.	Series.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Pennsylvanian series.	Saginaw formation.	400	Sandy shale of various colors, with layers of fire clay and beds of coal; charged with iron pyrites; principal coal horizon of Michigan.	Yields much water that is highly mineralized but can be used. Supplies many shallow wells.
		Parma sandstone.	170	Porous.	Yields much brine but also some potable water.
	Mississippian series.	Grand Rapids group.	535	Limestone, largely underlain or replaced by shale and dolomite with gypsum.	Yields salty or bitter water.
		Marshall sandstone.	560		Yields large supplies of fresh water; also brine.
		Coldwater shale.	1,000	Blue sandy shales, with seams of fine-grained sandstone. Balls of kidney iron "ore" in some layers.	Does not yield much water
		Berea sandstone.	±65	Contains brine in large amounts; signs of oil and gas.	Yields brine.
Devonian.		Antrim shale.	480	Dark shale, in places black and bituminous. Contains iron pyrite, oil, and gas.	Does not yield much water.
		Traverse formation.	660	Bluish calcareous shale and thin-bedded limestone.	Yields water in northern part of State and to some extent in southern part.
		Dundee limestone.	255	Gray and yellowish bituminous limestone with sand and chert.	Yields considerable water charged with salt and other minerals. Some of the water is used as mineral water.
Silurian.		Monroe group.	1,200	Chiefly dolomite, in part shaly. Sandstone near top.	The sandstone yields much water. Fresh water has been found in one or two horizons near the outcrop.
		Salina formation.	960	Dolomite, in part shaly, with many beds of salt, the thickest being 100 feet thick.	Yields brine.

[f] Data compiled from the following sources: Lane, A. C., Water resources of the Lower Peninsula of Michigan: U. S. Geol. Survey Water-Supply Paper 30, 1899; Sherzer, W. H., U. S. Geol. Survey Geol. Atlas, Detroit folio (No. 205), 1917; Russell, I. C., and Leverett, Frank, idem, Ann Arbor folio (No 155), 1908; Lane, A. C., Michigan Geol. Survey, vol. 5, pl. 73, 1895, adjusted to nomenclature of geologic map in Michigan Geol. Survey, vol. 8, 1902. Section based largely on wells at Jackson and Monroe.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Michigan—Continued.

System.	Subdivision	Maximum thickness (feet).	Lithologic character.	Water supply.
Silurian.	Niagara group.	835	Dolomite and limestone; some shale.	Little information available. Water probably of poor quality.
	(?)	100	Red shale; in some places sandy or green shale.	
Ordovician.	Utica and later Ordovician shales.	±600	Dark shale with some limestone.	Do not yield much water.
	Trenton (?) and older limestones.	271	Dolomite and limestone, shaly at base.	Yield strong brine.
	St. Peter sandstone.	18	White friable sandstone or red clay.	
	"Calciferous."			

Northern Indiana.[g]

System.	Subdivision	Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	"Knobstone" group.	600	Shale with some sandstone and limestone.	Produce little water.
Devonian.	New Albany shale.	100	Shale locally bituminous.	Very poor water bearer.
	Sellersburg limestone.[h] Jeffersonville limestone.[h] Pendleton sandstone.	350	Bedded limestones, with heavy-bedded soft white sandstone (Pendleton sandstone) in certain areas.	Yield considerable water in areas where they are near the surface.
Silurian.	Kokomo limestone ("water lime").[i]		Bedded and jointed limestone.	Furnishes good supplies of water.
	Niagara formation:[i] Upper division.	500	Compact, massive, or bedded limestone, in many parts somewhat crystalline, ranging in color from buff to bluish or greenish shades. Immediately below glacial drift in many places in northern Indiana.	In many places carries considerable amounts of potable water in joints, bedding planes, and solution passages.
	Lower division ("Clinton")	±50	Brownish or reddish limestone.	Poor water bearer.
Ordovician.	Richmond formation. "Lorraine" formation. Utica shale.	1,000	Blue-green shale and blue limestone above and fine-grained brown or black shale below. Do not crop out in northern Indiana.	Yield very little water Nowhere known to furnish sufficient for well supply.

[g] Capps, S. R., The underground waters of north-central Indiana: U. S. Geol. Survey Water-Supply Paper 254, p. 36, 1910.
[h] The Sellersburg and Jeffersonville limestones together are the "Corniferous" of well drillers.
[i] The name "Niagara," as commonly used by well drillers, includes the Kokomo limestone ("water-lime") and the Niagara formation.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Northern Indiana—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply
Ordovician.	"Trenton" limestone.	±500	Massive limestone, in many places dolomitic. Does not crop out in northern Indiana.	Yields large quantities of salt water.
	Shale (formation undetermined).	80		
	St. Peter sandstone.	250	Porous sandstone. Does not crop out in northern Indiana.	Yields abundant water highly mineralized with salt, sulphur, iron, etc.
	"Lower Magnesian" limestone.	±400	Gray sandy dolomitic sandstone. Does not crop out in northern Indiana.	

Wisconsin. [j]

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply
Devonian.	Milwaukee (Hamilton) shale.	138	Magnesian limestone and shale.	Yield only small supplies.
Silurian.	Cayugan (Waubakee beds).	30	Shaly limestone.	
	Niagara limestone.	700	Hard magnesian limestone; nearly pure dolomite.	Generally yields moderate supplies.
	Clinton beds.	60	Shale and iron ore.	Not important.
Ordovician.	Richmond shale. Maquoketa shale.	500	Blue and green shale.	Yields very little water.
	Galena limestone.	250	Gray or buff magnesian limestone.	Yields moderate supplies.
	Decorah shale.	50	Blue and green shales and dolomite.	Yields very small supplies.
	Platteville limestone.	60	Blue and buff limestone.	Yields only small supplies.
	St. Peter sandstone.	200	White and yellow sandstone.	Yields large supplies.
	Shakopee dolomite.	100	Dolomite, in places sandy and shaly.	Yields small supplies.
	Oneota dolomite.	150	Dolomite, in places sandy and cherty.	Yields moderate supplies.
Cambrian.	Madison [k] (Jordan) sandstone.	50	White and yellowish sandstone.	Generally yields large supplies.

[j] Weidman, Samuel, and Schultz, A. R., The underground and surface-water supplies of Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 35, pl. 2, 1915.
[k] According to E. O. Ulrich both the Madison and Mendota are younger than the Jordan sandstone.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Wisconsin—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Cambrian.	Mendota[k] (St. Lawrence) sandstone.	60	Yellowish sandstone, shaly and dolomitic.	Generally yields moderate supplies.
	Franconia sandstone.	160	Sandstone, in places glauconitic and shaly.	Yields large supplies.
	Dresbach sandstone.	100	Coarse friable sandstone.	
	Eau Claire sandstone.	250	Fine sandstone, locally shaly.	Generally yields moderate to large supplies.
	Mount Simon sandstone.	250	Coarse sandstone.	Yields large supplies.

Illinois.[l]

System.	Series.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Pennsylvanian series.	McLeansboro formation.	1,000	Alternating beds of shale, sandstone, and limestone.	Yield small supplies to many shallow wells. Water from considerable depths highly mineralized.
		Carbondale formation.	375		
		Pottsville formation.	700	Conglomerate and sandstone.	Not a valuable source of water because in southern part of State, where it is well developed, it is deeply buried and contains salty water.
	Mississippian series.	Chester group.	1,200	Chiefly sandstone.	Yields water freely but in most places is deeply buried and contains water too salty for use.
		Meramec group.	350	Chiefly limestone.	Not prominent water bearers but yield adequate supplies to many wells of moderate depths.
		Osage group.	400		
		Kinderhook group.	200		
Devonian.		Chattanooga shale.	400	Black shale.	Unimportant as water bearers but yield small supplies to a few wells.
		Limestones of Hamilton, Onondaga, Oriskany, and Helderberg age.	1,025	Limestone with some sandstone.	

[k] According to E. O. Ulrich both the Madison and Mendota are younger than the Jordan sandstone.
[l] Section compiled from various sources. Water-supply data chiefly from Fuller, M. L., Underground waters of eastern United States: U. S. Geol. Survey Water-Supply Paper 114, pp. 248-257, 1905.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Illinois—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Silurian.	Niagara dolomite.	420	Creviced limestone or dolomite.	Yields freely to both shallow and deep wells.
Ordovician.	Maquoketa shale.	275	Chiefly shale.	Yields little water.
	Galena dolomite.[a] Decorah shale. Platteville limestone.	450	Chiefly creviced limestone or dolomite.	Yields freely to both shallow and deep wells in northern part of State.
	St. Peter sandstone.	420	Chiefly porous sandstone.	Yields generous supplies to wells in northern and western part of State.
	Shakopee dolomite including New Richmond(?) sandstone member. Oneota dolomite.	±600	Dolomite and some sandstone.	Yield some water.
Cambrian.	Upper Cambrian sandstone.	1,000	Chiefly porous sandstone.	Yields large supplies of potable water in northern part of State. Farther south this sandstone is deeply buried and its water is largely too salty for use

Southern Minnesota.[b]

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Devonian.		100	Limestone and sandstone.	Locally yields moderate supplies.
Ordovician.	Maquoketa shale.	100	Shale, dolomite, and argillaceous sandstone.	Locally yields small supplies.
	Galena limestone. Decorah shale. Platteville limestone.	350	Limestone and shale.	Yield moderate or large supplies.
	St. Peter sandstone.	200	White or yellow sandstone, with some shale.	Yields large supplies.
	Shakopee dolomite.	±75	Yellow, buff, pink, or red dolomite; some sandstone.	Locally yields small to moderate supplies.
	Oneota dolomite.	200	Buff to reddish dolomite.	Generally yields moderate supplies.
Cambrian.	Jordan sandstone.	200	Coarse-grained white sandstone.	Yields large supplies.

[a] In the southern and central parts of the State the interval between the Maquoketa shale and St. Peter sandstone is occupied by the Fernvale, Kimmswick, Plattin, and Joachim limestones, which have an aggregate thickness of 800 feet.

[b] Adapted from Hall, C. W., Meinzer, O. E., and Fuller, M. L., Geology and underground waters of southern Minnesota: U. S. Geol. Survey Water-Supply Paper 256, pl. 6, 1911

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Southern Minnesota—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Cambrian.	St. Lawrence formation.	225	Dolomite, shale, and sandstone.	Yields little water.
	Franconia sandstone.	100	Fine-grained white sandstone; shaly beds toward base.	Yields large supplies.
	Dresbach sandstone and underlying shales and sandstones.	450	White sandstone, shale, and thin limestone.	Yields freely in some parts.
Algonkian (?).	Red clastic series.	±1,750	Red sandstone and shale. Partly fragmental volcanic rocks.	Yields little water.

Iowa.[a]

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Permian (?) series.			±22	Red shale, sandstone, and gypsum.	
	Pennsylvanian series.	Missouri group.		±700	Shale, limestone, some sandstone, and coal.	Generally yields only meager and uncertain supplies.
		Des Moines group.		±970	Shale, some sandstone and limestone, and coal. Prominent sandstone formation at base.	The chief aquifer of this group is the basal sandstone, which yields moderate supplies. Other parts yield only meager supplies of water that is often too poor for use.
	Mississippian series.	"St. Louis limestone."		500	Limestone, sandstone, and shales.	The median bed of this formation is an important source of water for both shallow and deep wells. The upper and lower parts of the formation are not important as water bearers.
		Osage group.	Keokuk limestone. Burlington limestone.		Limestone, chert, and geodiferous shales.	Generally yield adequate supplies from crevices in the limestone.
		Kinderhook group.		±500	Shale, magnesian and oolitic limestones, and sandstone.	The limestone of this group yields reliable supplies of hard but otherwise excellent water to many wells.

[a] Adapted from Norton, W. H., Hendrixson, W. S., Simpson, H. E., and Meinzer, O. E., Underground-water resources of Iowa: U. S. Geol. Survey Water-Supply Paper 293, pl. 2, 1912.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Iowa—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Devonian.	Lime Creek shale, Sweetland Creek shale, and State Quarry limestone.	±300	Shale and limestone.	Yield small supplies but are not important as sources of water.
	Cedar Valley limestone.		Limestone.	
	Wapsipinicon limestone.		Limestone and some shale.	
Silurian.	Salina (?) formation.	350?	Dolomite, limestone, gypsum and anhydrite marls, and sandstone.	Yields highly mineralized water, much of it too mineralized for use.
	Niagara dolomite.	±345	Dolomite.	Yields abundant supplies to shallow and deep wells and to many springs. Water occurs largely in solution passages.
Ordovician.	Maquoketa shale.	±275	Shale with some limestone near middle.	Is nearly impervious and not a source of water supply, except the limestone at the middle, which furnishes water to a few wells.
	Galena dolomite.	500	Dolomite and limestone.	Yields abundant supplies to shallow and deep wells and to many springs.
	Decorah shale.		Green shale.	Yields practically no water
	Plattville limestone.		Limestone and shale.	Yields little water.
	St. Peter sandstone.	110	Sandstone, white rounded grains.	One of the most reliable and best known of the aquifers in the State. Furnishes abundant supplies to many wells.
	Shakopee dolomite.	±700	Dolomite, in places arenaceous.	Yields considerable water from joints and solution passages.
	New Richmond (?) sandstone, member of Shakopee dolomite.		Sandstone.	Yields water freely.
	Oneota dolomite.		Dolomite.	Yields considerable water from joints and solution passages. Supplies many large springs.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Iowa—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Cambrian.	Jordan sandstone.	100	Sandstone.	One of the chief aquifers of the State. Supplies many springs and flowing wells.
	St. Lawrence formation.	±450	Dolomite, marl, and shale.	Does not yield much water
	Dresbach sandstone.	±1,100	Sandstone.	Yield abundant supplies of good water in eastern part of State. Supply many flowing wells. Farther west the yield is less and the water contains more mineral matter.
	Undifferentiated Cambrian.		Sandstone, marl, and shale.	
Algonkian (?).	Red clastic series.	±430	Red sandstone.	Yields little water.

Missouri. [p]

System.	Series.	Group.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Pennsylvanian series.	Missouri group.		±1,200	Alternating beds of shale, limestone, and sandstone; shale largely predominates.	Yields no good supplies of water, but some water that is salty or otherwise highly mineralized.
		Des Moines group.	Pleasanton formation.	225	Chiefly shale, but with some sandstone and limestone and small veins of coal.	Sandstone and limestone beds yield some water. Springs from this formation are rare.
			Henrietta formation.	125	Sandy shale and thin beds of sandstone and limestone.	Not an important water bearer, but a small supply is obtained by sinking wells to the limestone beds. Does not give rise to any important springs.
			Cherokee shale.	720	Chiefly shale and sandstone; the sandstone usually more abundant at the base. Also contains workable coal beds and a few thin beds of limestone. Yields oil and gas.	Yields brines and other highly mineralized waters.
			Graydon sandstone.	75	Coarse-grained friable sandstone with shale and some gravel or conglomerate.	An important water bearer. Gives rise to many springs.
	Mississippian series.	Chester group.		600	Limestone, sandstone, and shale.	Generally yield good water.
		Ste. Genevieve limestone.[q]		150	Limestone.	

[p] Stratigraphic material compiled from various sources, including Shepard, E. M., U. S. Geol. Survey Water-Supply Paper 195, 1907; Ulrich, E. O., Geol. Soc. America Bull., vol. 22, pp. 281–680, 1911; Lee, Wallace, Missouri Bur. Geol. and Mines, vol. 12, 2d ser., pp. 7–51, 1914; Branson, E. B., Missouri Univ. Bull., vol. 19, No. 15, 1918; and unpublished material. The water-supply data are from Water-Supply Paper 195.

[q] Whether this limestone properly belongs in the Chester or Meramec group is undecided.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Missouri—Continued.

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Mississippian series.	Meramec group.	St. Louis limestone.	375	Evenly bedded cherty gray limestone, locally brecciated.	Yields some water but is not an important source of supply.
			Spergen limestone.	200	Massive oolitic limestone, parts of which afford a handsome building material.	Not important as a source of water.
			Warsaw shale.	75	Chiefly shale, with some limestone and sandstone.	Unimportant as a source of water.
		Osage group.	Keokuk limestone.	20	Compact bluish limestone at base; thinner beds of limestone interbedded with shaly beds farther up.	Not important as a source of water.
			Burlington limestone.	150	Generally coarse-grained crystalline pure limestone. In southwestern part of State it is represented by a thick upper limestone, a less persistent lower bluish limestone, which is very dense and hard, and between the two beds a layer of shattered chert. The limestone contains large sink holes and caves.	One of the great water bearers of the State. Contains large subterranean streams that issue in large springs. Many springs also issue from the shattered chert.
		Kinderhook group.[r]	Chouteau limestone.	70	Compact limestone, in places shaly or sandy.	Too compact to be a reliable source of water. Supplies a few springs.
			Hannibal shale.	70	Bluish to greenish shale impregnated with salts; contains some beds of impure limestone and dolomite; upper part very sandy.	Yields some of the strongest mineral waters in the State
			Louisiana limestone.	40	Dolomitic limestone, with sandy shale at base.	
Devonian.	Chattanooga shale.			60	Black shale. Present in part of southwestern Missouri.	Unimportant as a source of water.
	Craghead Creek shale.			25	Dark-blue to drab sandy shale with calcareous partings, and soft yellow to gray siliceous shale. Present in northeastern Missouri.	
	Callaway limestone.			60	Thin-bedded dark-gray limestone and shaly concretionary limestone.	

[r] Fern Glen, Bushberg, Glen Park, Sulphur Springs, and other names have been applied to local subdivisions of the Kinderhook.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Missouri—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Devonian.	Grand Tower limestone.	60	Compact bluish-gray limestone.	Unimportant as a source of water.
	Clear Creek limestone.	150	Cherty limestone.	
	Bailey limestone.	120	Chiefly dark bluish-gray slightly cherty limestone.	Recognized in only a few well sections in the State.
Silurian.	Bainbridge limestone.[a]	25	Dolomitic argillaceous limestone.	Recognized in only a few well sections in the State.
Ordovician.	Girardeau limestone.	60	Dark fine-grained, hard, brittle limestone.	Not widely distributed and not important as water bearers in the State.
	Maquoketa shale.	100	Chiefly light-blue shale; some arenaceous shale and sandstone.	
	Fernvale limestone.	5		
	Kimmswick limestone.	±450	Coarsely crystalline light-gray to bluish-drab limestone.	
	Plattin limestone.		Compact heavy-bedded limestone.	
	Joachim limestone.	150	White or yellowish dolomitic limestone, in part very soft and white.	
	St. Peter sandstone.	200	Loosely cemented quartz sandstone.	One of the most important water bearers in the State.
	Jefferson City dolomite.	[b]300	Cherty gray dolomite, noncherty dolomite, and white to buff dolomite (cotton rock).	Yields some water. Gives rise to small springs.
Cambrian.	Roubidoux formation.	225	Alternating beds of coarsely crystalline dolomite and sandstone; chert abundant.	The sandstones of this formation are important sources of water and supply most of the large springs in the southeastern part of the State.

[a] The Silurian of northeastern Missouri is divided by T. E. Savage and others into the Sexton Creek limestone (above) and Edgewood formation (below), with a total thickness of 84 feet.
[b] Thickens to 1,000 feet in southern part of State, according to E. B. Branson.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Missouri—Continued.

System.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Cambrian.	Gasconade dolomite.[a]	300	Cavernous cherty dolomite, noncherty. dolomite, and some sandstone.	Important water bearers. Large springs issue from the cavernous beds.
	Proctor dolomite.[a]	100	Noncherty massive dolomite.	
	Eminence dolomite[a]	300	Very cherty dolomite.	
	Potosi dolomite.[a]	±300	Rather massive dolomite.	
	Elvins formation.	260	Shaly beds with some limestone conglomerate and dolomite.	
	Bonneterre dolomite.	±450	Dolomitic limestone, in some places shaly.	
	Lamotte sandstone.	250	Sandstone, generally fine grained, but gravel at the base.	Generally a good water bearer.

North-central Texas.[b]

System.	Series.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Permian series.	Double Mountain formation.	2,200	Red and blue clay, sandy shale, and sandstone, with gypsum and some limestone; gypsum most abundant in the upper beds.	Yield highly mineralized water. Some of the water is good enough for stock, but most of it is too poor for domestic use. The water from limestone beds is better than that from sandstone, shale, or gypsum beds.
		Clear Fork formation.	1,900		
		Wichita formation.	2,000	Red and blue clay and sandstone, with limestone in upper part.	Yields water, nearly all of which is salty.
	Pennsylvanian series.	Cisco group.	1,000	Clay, shale, conglomerate, and sandstone, with some limestone and coal.	Sandstone and limestone yield water in varying amounts. Water from upper part of formation is generally too highly mineralized for use, but water from lower part near outcrop is generally good enough for use and supplies shallow wells.
		Canyon group.	1,100	Alternating beds of limestone and clay, with some sandstone and conglomerate.	Gives rise to many springs. Yields water chiefly from sandstone beds. Water is variable in quality, some being good and some unfit for use.

[a] The Gasconade, Proctor, Eminence, and Potosi formations belong to the Ozarkian system of E. O. Ulrich.

[b] Stratigraphic material compiled from various sources, including Gordon, C. H., Geology and underground waters of the Wichita region, north-central Texas: U. S. Geol. Survey Water-Supply Paper 317, pp. 13-29, 1913; and unpublished material. Water-supply data from U. S. Geol. Survey Water-Supply Paper 317.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

North-central Texas—Continued.

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Pennsylvanian series.	Strawn formation.	1,900	Alternating beds of sandstone and clay with some conglomerate and shale; the lower 1,000 feet consists of blue and black clay locally containing beds of limestone, sandstone, or sandy shale, and a coal seam at top.	Yields water that is too salty for use, except upper part near outcrop, which yields potable water to shallow wells.
		Smithwick shale.	225	Soft very dark or nearly black carbonaceous shale, with some sandstone lentils.	
		Marble Falls limestone.	500	Light-gray, dark-gray, and dark-blue to black limestones.	
	Mississippian series.	"Lower Bend" shale and limestone.	(?)	Black fissile bituminous shale, with limestone at top.	
Ordovician and Cambrian.	Ellenburger limestone or equivalent limestones.		±1,000	Chert-bearing limestone and dolomite.	
Cambrian.	Upper Cambrian sandstones, some limestone.		(?)		

Black Hills region.[w]

Carboniferous.	Permian (?) series.	Minnekahta limestone.	50	Thin-bedded gray limestone.	Too dense to carry much water, although cavernous in some places near surface. Probably will yield only small supplies of water of poor quality.
		Opeche formation.	130	Red slabby sandstone and sandy shale.	
	Pennsylvanian series.	Minnelusa sandstone.	600	Sandstones, locally buff and red, in greater part calcareous; some thin limestone included; red shale at base.	Sandstone generally coarse and water bearing supplying some wells and many springs. In some places the sandstone is fine-grained and will not yield water freely.
	Mississippian series.	Pahasapa limestone.	630	Massive gray limestone.	Apparently too dense to yield water except possibly along some higher slopes where caverns may be penetrated.
		Englewood limestone.	60	Pink slabby limestone.	Apparently too dense to yield much water.

[w] Darton, N. H., Artesian water in the vicinity of the Black Hills, S. Dak.: U. S. Geol. Survey Water-Supply Paper 428, pp. 9-35, 1918; and unpublished material.

Columnar sections of Paleozoic rocks in the United States, with descriptions of their water supplies—Continued.

Black Hills region—Continued.

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.	Water supply.
Ordovician.	Upper Ordovician series.	Whitewood limestone.	80	Massive buff limestone.	Apparently too dense to yield much water.
Cambrian.	Upper Cambrian series.	Deadwood formation.	±500	Red-brown sandstone and quartzite, locally conglomeratic, partly massive; much greenish-gray shale and limestone breccia in middle northern hills.	The upper and lower sandstones of this formation supply many springs and will doubtless also yield considerable water to wells.

Big Horn Basin.[x]

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.	Water supply.
Carboniferous.	Permian.	Embar formation.	480	Gray limestone interbedded with gray and red sandy shale, gypsum, and thin-bedded sandstone.	Will probably yield little water.
	Pennsylvanian.	Tensleep sandstone.	250	Massive gray sandstone, containing thin layers of limestone.	Good water bearer.
	Mississippian.	Amsden formation.	300	Red sandy shale and sandstone, with layers of limestone and chert.	Will probably yield moderate supplies.
		Madison limestone.	1,000	Massive gray limestone.	Will probably yield little water.
Ordovician.	Upper Ordovician.	Bighorn limestone.	300	Siliceous gray limestone, very hard and massive.	
Cambrian.	Upper Cambrian.	Deadwood formation.	900	Sandstone, shale, conglomerate, and limestone.	Will probably yield some water.

[x] Darton, N. H., Geology of the Big Horn Mountains: U. S. Geol. Survey Prof. Paper 51, p. 14, 1906. Fisher, C. A., Geology and water resources of the Big Horn Basin, Wyo.: U. S. Geol. Survey Prof. Paper 53, p. 8, 1906. Lupton, C. T., and Hewett, D. F., Anticlines in the southern part of the Big Horn Basin, Wyo.: U S. Geol. Survey Bull. 656, 1917.

CAMBRIAN SYSTEM.[10]

Cambrian rocks lie at or near the surface in parts of New England and eastern New York and in parts of the Appalachian Mountains in Pennsylvania, Maryland, West Virginia, Virginia, North Carolina, South Carolina, Tennessee, Alabama, and Georgia. Farther west they become deeply buried under younger Paleozoic rocks, but they reappear at or near the surface in an extensive area in Wisconsin, Minnesota, Iowa, and the northern peninsula of Michigan and in another extensive area in Missouri and Arkansas. Still farther west Cambrian rocks appear in many small and widely scattered outcrops. (See fig. 77.)

In New England and the Appalachian Mountain region the Cambrian rocks have been much deformed and metamorphosed and in many places can not be distinguished from the pre-Cambrian crystalline rocks. They consist largely of quartzite, slate, schist, and crystalline limestone. In the southern part of the Appalachian region the system is exposed over extensive areas and has a maximum thickness of many thousands of feet, including thick limestone formations in its upper part. Throughout most of the large Paleozoic area of the eastern and central United States (fig. 76) the Cambrian rocks consist predominantly of sandstone, generally a few hundred feet in aggregate thickness. In the Cambrian of the West quartzite is prominent.

---

[10] The following publications (of the U. S. Geol. Survey, except as otherwise stated) give information relating to water in Cambrian rocks in the United States:

Alabama, Water-Supply Paper 114; Geol. Folio 175; Alabama Geol. Survey cooperative report on underground water.

Connecticut, Water-Supply Paper 374, 470.

Delaware, Water-Supply Paper 106.

Georgia, Water-Supply Paper 114; Georgia Geol. Survey Bull. 15 (cooperative report).

Illinois, Water-Supply Paper 114; Seventeenth Ann. Rept., pt. 2; Monograph 38; Geol. Folios 81, 145, 200.

Iowa, Water-Supply Papers 114, 145, 293; Geol. Folios 145, 200.

Kansas, Geol. Folio 148.

Maine, Geol. Folios 149, 158.

Maryland, Geol. Folios 179, 204; Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).

Minnesota, Water-Supply Papers 114, 256; Geol. Folio 201.

Missouri, Water-Supply Papers 114, 145, 195; Geol. Folio 148.

Nebraska, Prof. Paper 32.

New Mexico, Geol. Folio 199.

New York, Water-Supply Paper 114.

North Carolina, Geol. Folios 124, 147, 151.

Ohio, Water-Supply Paper 259.

Pennsylvania, Water-Supply Papers 106, 110, 114; Geol. Folios 162, 179.

South Carolina, Geol. Folio 147.

South Dakota, Water-Supply Papers 227, 428; Twenty-first Ann. Rept., pt. 4; Prof Papers 32, 65; Geol. Folios 107, 127, 128, 164, 209.

Tennessee, Geol. Folios 124, 151.

Virginia, Water-Supply Paper 114.

West Virginia, Water-Supply Papers 114, 179.

Wisconsin, Water-Supply Papers 114, 145; Geol. Folios 140, 145; Wisconsin Geol. and Nat. Hist. Survey Bull. 35 (cooperative report).

Wyoming, Twenty-first Ann. Rept., pt. 4; Prof. Papers 32, 51, 65; Geol. Folios 107, 127, 128, 150.

The Cambrian sandstones of the Mississippi Valley region rank among the best water-bearing formations in the United States. (See

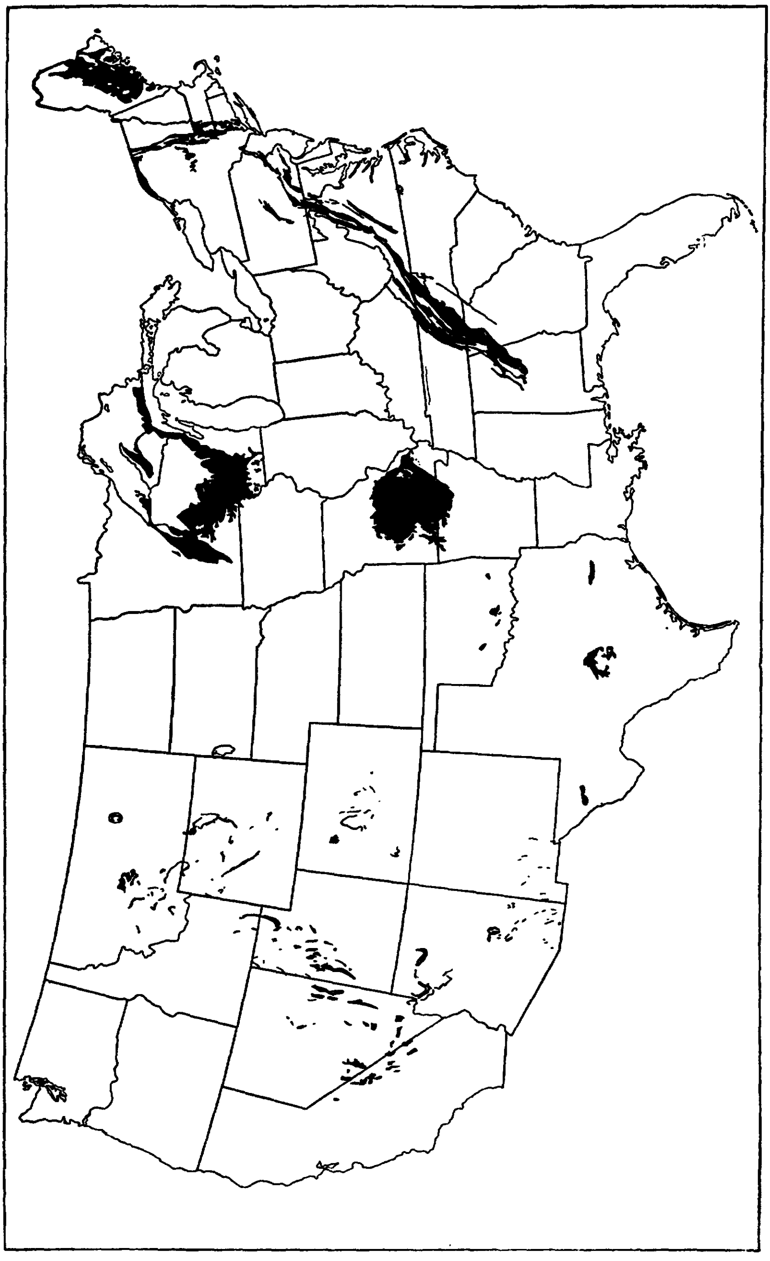


FIGURE 77.—Map of the United States showing areas in which Cambrian or Lower Ordovician rocks are at or near the surface. Cambrian rocks are of most importance as sources of water in the States bordering Mississippi River, where they consist largely of sandstones that yield abundant supplies of potable water and in many places give rise to artesian flows.

statements regarding their mechanical composition on p. 109.) In Wisconsin, Minnesota, Iowa, Illinois, Missouri, and Arkansas they furnish generous yields of fairly good water, which is largely utilized by municipalities for public supplies. They belong to one of the most productive artesian basins in the country and give rise to many flowing wells. In this region there are a good many sucessful wells that tap the Cambrian sandstones at depths of more than 1,000 feet, but some deep wells have salty water.

East of this region, in Indiana, Ohio, and the southern peninsula of Michigan, and in large parts of New York, Pennsylvania, West Virginia, Kentucky, and Tennessee, the Cambrian sandstones are deeply buried and contain only salty water.

Farther east, in New England, New York, and the Appalachian Mountain region, Cambrian rocks of various kinds furnish small supplies of good water to many dug wells and relatively shallow drilled wells. In the southern Appalachian Mountain region the thick limestones give rise to large springs. The conditions in the East are very different from those in the Mississippi Valley region in that there are no well-recognized Cambrian water horizons and no well-recognized artesian basin, such as characterizes the Mississippi Valley region.

West of the Mississippi Valley region of successful Cambrian wells the Cambrian formations pass to greater depths, and their water becomes more highly mineralized. For this reason they do not form a practicable source of supply where they underlie southwestern Minnesota, western Iowa, northwestern Missouri, and regions to the west. In the Black Hills the sandstones of the Deadwood formation supply many springs and will probably give rise to flowing wells over a large area. In the mountains of Oklahoma, and in a great many ranges farther west Cambrian rocks are exposed, but in these places they generally have steep dips and pass quickly to great depths. Consequently they are of very minor importance for water supply in the western half of the United States.

ORDOVICIAN SYSTEM.[11]

The Ordovician rocks lie next above the Cambrian and do not differ greatly from them in distribution within the United States. (See

[11] The following publications (of the U. S. Geol. Survey, except as otherwise stated) give information relating to water in Ordovician rocks in the United States:

Alabama, Water-Supply Paper 114; Geol. Folio 175.
Arkansas, Water-Supply Papers 114, 145.
Colorado, Prof. Paper 32.
Connecticut, Water-Supply Paper 374, 470.
Delaware, Water-Supply Paper 106.
Georgia, Water-Supply Paper 114.
Illinois, Water-Supply Paper 114; Seventeenth Ann. Rept., pt. 2; Monograph 38; Bulletins 438, 506; Geol. Folios 81, 145, 185, 188, 200, 208, 213.
Indiana, Water-Supply Papers 113, 114, 254; Eighteenth Ann. Rept., pt. 4.
Iowa, Water-Supply Papers 114, 145, 293; Geol. Folios 145, 200.
Kansas, Geol. Folios 148, 206.

fig. 78.) Throughout most of the great Paleozoic area of the central and eastern United States they lie buried beneath younger Paleozoic formations, but they come to the surface or near the surface over rather wide belts adjacent to the Cambrian outcrops and also in a few areas where the Cambrian rocks remain entirely concealed.

For the purposes of this paper the areas in which Ordovician formations are at or near the surface can be grouped as follows:

1. A wide belt adjacent to the Cambrian outcrops, occupying much of southeastern Minnesota, northeastern Iowa, northern Illinois, southern and eastern Wisconsin, and the eastern part of the northern peninsula of Michigan (fig. 78). This is the largest and most important area with respect to water supply.

2. A large crescent-shaped belt in southern and eastern Missouri and adjacent parts of Arkansas and Illinois, encircling the Ozark Mountains except to the southeast, where the Paleozoic rocks are overlapped by younger deposits (figs. 77 and 78). This area ranks second in importance with respect to water supply.

3. A large area on the gentle upfold of Paleozoic strata known as the Cincinnati anticline. This anticline extends from northwestern Alabama through central Tennessee and central Kentucky into western Ohio and eastern Indiana, where it forks, one prong extending northeastward into eastern Michigan and the other northwestward toward Chicago (fig. 78). The Ordovician rocks in this area are of comparatively little value for water supply, because most of the water at any considerable depth is too highly mineralized for use. Some of the formations, however, supply potable water to shallow wells.

4. Many detached areas in New England, eastern New York, and the Appalachian Mountain region from Pennsylvania to Alabama. The Ordovician rocks in these areas are closely related to the Cam-

---

Kentucky, Water-Supply Papers 114, 233.
Maine, Geol. Folio 158.
Maryland, Geol. Folio 179; Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).
Michigan, Water-Supply Papers 30, 114.
Minnesota, Water-Supply Papers 114, 256; Geol. Folio 201.
Missouri, Water-Supply Papers 114, 145, 195; Bulletin 438; Geol. Folio 148.
Nebraska, Prof. Paper 32.
New York, Water-Supply Paper 114
North Carolina, Geol. Folio 151.
Ohio, Water-Supply Papers 114, 259; Eighteenth Ann. Rept., pt. 4, Nineteenth Ann. Rept., pt. 4.
Pennsylvania, Water-Supply Papers 106, 110, 114; Geol. Folios 162, 170, 179.
South Dakota, Prof. Paper 32.
Tennessee, Water-Supply Paper 114; Geol. Folio 151; Tennessee Geol. Survey Bull. 26 (cooperative report).
Virginia, Water-Supply Paper 114.
West Virginia, Water-Supply Papers 110, 114; Geol. Folio 179.
Wisconsin, Water-Supply Papers 114, 145; Geol. Folios 140, 145; Wisconsin Geol. and Nat. Hist. Survey Bull. 32 (cooperative report).
Wyoming, Prof. Paper 32.

brian and, like them, are largely deformed and metamorphosed. Like the Cambrian rocks of the region they yield many small supplies

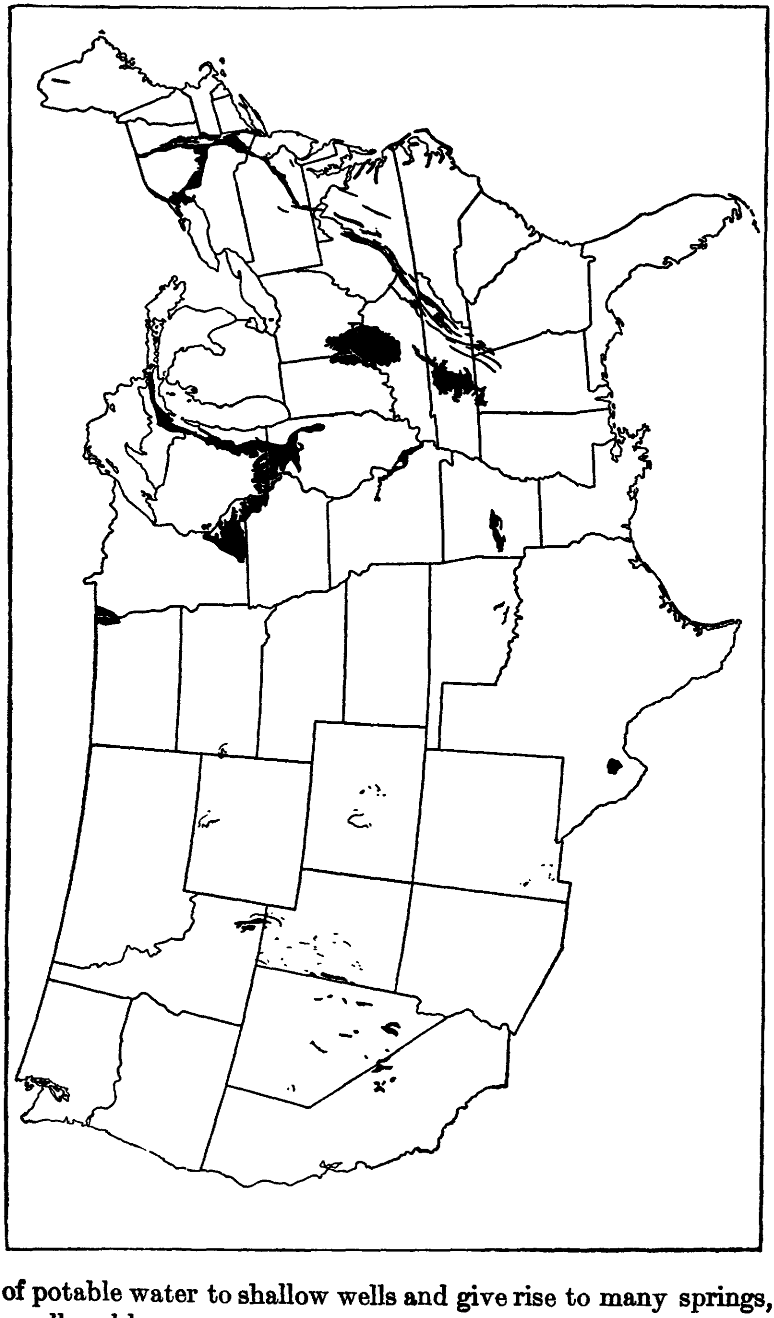


FIGURE 78.—Map of the United States showing areas in which Middle and Upper Ordovician rocks are at or near the surface. The Ordovician system includes the St. Peter sandstone, which in the States adjacent to Mississippi River yields large supplies of potable water and in many places gives rise to artesian flows; the system also includes valuable limestone aquifers.

of potable water to shallow wells and give rise to many springs, both small and large.

5. A rather small and little-known area in northwestern Minnesota and northeastern North Dakota, forming a part of a larger Ordovician area that lies mainly in Canada (fig. 78). The Ordovician rocks of this area are generally covered by glacial drift. They are of little value for water supply because of the salty character of the water.

6. Many rather small outcrops in or near mountain ranges throughout the western part of the United States, generally overlying Cambrian rocks. In the West the Ordovician system is, on the whole, not very well developed nor extensively exposed and is not of much consequence for water supply. There are, however, many outcrops that are not shown in figure 78.

The Ordovician system in the Mississippi Valley region includes the St. Peter sandstone, which is one of the most valuable aquifers in the United States. (See pp. 119, 152.) It is remarkably persistent and widespread, underlying nearly all of Iowa and Missouri, parts of the States adjoining these two on the north, west, and south, nearly all of Illinois and adjacent parts of Wisconsin, nearly all of Indiana, and at least large parts of Michigan, Ohio, and Kentucky. Though varying in character and thickness from place to place, it is not generally more than 200 feet thick and is commonly distinguished as a slightly cemented porous sandstone composed of well-rounded quartz grains. It is almost everywhere water bearing and is a valuable source of supply in most of Illinois, a little of eastern Indiana, southern Wisconsin, southeastern Minnesota, eastern Iowa, a large part of Missouri, and northern Arkansas. In this belt it generally yields potable water in sufficient quantities for public supplies. Farther east its water is too salty for use; farther west it passes to rather great depths and its water is generally highly mineralized. The St. Peter sandstone, like the underlying Cambrian sandstones, forms a prominent aquifer in the great Paleozoic artesian basin of the Mississippi Valley region and gives rise to many flowing wells.

The Ordovician formations below the St. Peter sandstone consist chiefly of limestone or dolomite. In Iowa and Minnesota they are divided into two formations, the Shakopee dolomite above and the Oneota dolomite below. The Shakopee contains beds of sandstone and in some places has a heavy sandstone member at the base that is tentatively correlated with the New Richmond sandstone of Wisconsin. The Oneota usually consists of massive dolomite. It rests on the Cambrian sandstone. The Oneota and the Shakopee furnish considerable water, the Oneota and the New Richmond (?) sandstone member of the Shakopee probably yielding more freely than the remainder of the Shakopee.

Above the St. Peter sandstone is a group of beds consisting chiefly of limestone or dolomite, the upper and thickest part of which is called the Galena limestone or dolomite in Iowa, Minnesota, Wisconsin, and Illinois, where it is a very satisfactory aquifer that yields moderate to large supplies of hard but otherwise good water to numerous wells. East of these States limestones also occur above the St. Peter sandstone, but their water is generally salty except locally in shallow wells.

The upper part of the Ordovician system throughout the eastern and central United States consists chiefly of shale and therefore yields only meager supplies of water.

Ordovician formations are at or near the surface in a considerable part of eastern New York, on both sides of Hudson River and on the southeast, south, and southwest sides of the Adirondack Mountains. Farther west they pass below a thick cover of younger Paleozoic formations. They consist of a great thickness of shale, limestone, and other rocks, which in the eastern part of the State are largely folded and metamorphosed. They yield supplies to many wells, a considerable part of the water from shale or slate. Most of the water is of satisfactory quality, but some is highly mineralized. The ground-water conditions are determined by varying local differences of structure and rock composition. Somewhat similar irregular conditions are found in the Ordovician rocks of the Appalachian Mountains south of New York.

In the southern part of the Appalachian Mountains the Ordovician rocks have a great total thickness. The Knox dolomite, partly of Cambrian and partly of Ordovician age, is several thousand feet thick. It gives rise to some very large springs.

SILURIAN SYSTEM.[12]

The Silurian system is less widely distributed in the United States than the Cambrian and Ordovician systems. It is thin or absent in

[12] The following publications (of the U. S. Geol. Survey, except as otherwise indicated) contain information relating to water in Silurian rocks in the United States:

Alabama, Water-Supply Paper 114; Geol. Folio 175
Arkansas, Water-Supply Paper 114.
Georgia, Water-Supply Paper 114; Georgia Geol. Survey Bull. 15 (cooperative report).
Illinois, Water-Supply Paper 114; Seventeenth Ann. Rept., pt. 2; Monograph 38; Bulletin 506.
Indiana, Water-Supply Papers 113, 114, 245; Eighteenth Ann. Rept., pt. 4.
Iowa, Water-Supply Papers 114, 145, 293.
Kentucky, Water-Supply Papers 114, 233.
Maine, Geol Folio 149.
Maryland, Water-Supply Paper 110; Geol. Folio 179; Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).
Michigan, Water-Supply Papers 30, 31, 114, 182–183; Geol. Folio 205.
Minnesota, Water-Supply Papers 114, 256.
Missouri, Water-Supply Papers 114, 145, 195.
New York, Water-Supply Paper 114.
Ohio, Water-Supply Papers 91, 114, 259; Eighteenth Ann. Rept., pt. 4, Nineteenth Ann. Rept., pt. 4; Geol. Folio 197.
Pennsylvania, Water-Supply Papers 110, 114; Geol. Folio 179.
Tennessee, Water-Supply Paper 114; Tennessee Geol. Survey Bull. 26 (cooperative report).
Virginia, Water-Supply Paper 114.
West Virginia, Water-Supply Paper 114; Geol. Folio 179.
Wisconsin, Water-Supply Paper 114; Geol. Folio 140; Wisconsin Geol. and Nat. Hist. Survey Bull. 35 (cooperative report).

most of the Paleozoic sections of the West. It is present under most of the great Paleozoic area of the eastern and central United States but is absent in large tracts where both older and younger Paleozoic rocks occur. It is also present in parts of the Appalachian Mountains and in certain localities in New England, chiefly in northern Maine. It lies at or near the surface in large areas in northeastern Iowa, northern Illinois, the eastern margin of Wisconsin, the southeastern margin of the northern peninsula of Michigan, northern and eastern Indiana, eastern Ohio, and western New York; also in marginal parts of the southern peninsula of Michigan; in belts adjacent to the Ordovician outcrops on both sides of the Cincinnati anticline in Kentucky, Tennessee, and Alabama; and in areas northeast of the Ozark Mountains in Missouri and Illinois. It appears to be absent from the Paleozoic section in Minnesota and in parts of Kentucky, Tennessee, Alabama, Arkansas, and Missouri west of the Ozark Mountains. (See fig. 79.)

The Silurian system consists chiefly of limestone and dolomite, which are important sources of water and are tapped by numerous wells, especially in Iowa, Illinois, Wisconsin, Indiana, and Ohio. Apparently before the glacial epoch these limestones, like those of the Ordovician, were in large areas above the water table and were thus exposed to weathering, which made them cavernous. Where these areas were later covered by glacial drift the water level rose and the cavernous limestones became good water bearers.

In Iowa, Wisconsin, Illinois, and Indiana the principal Silurian formation is the Niagara limestone or dolomite, which yields water freely and is recognized as an important aquifer. Its water in these States is generally potable, although it may yield poor water where it is struck at considerable depths in central or southern Illinois or in Indiana. In Ohio and adjacent parts of Kentucky the Niagaran limestones are also present and yield satisfactory water to many shallow wells but generally only salty water where they are struck at considerable depths.

In Ohio a thick formation, chiefly limestone, known as the Monroe formation, lies above the Niagara and forms the upper part of the Silurian system. This is the best aquifer in Ohio except the glacial drift. Where it is near the surface it yields abundant supplies of water to many wells. In Michigan the Monroe consists chiefly of dolomite but includes sandstone near the top and is divisible into several formations. It yields some potable water, but where it occurs at some depth below the surface its water is probably generally of poor quality. In Michigan and in northeastern Ohio the Salina formation, which contains many beds of salt and much salty water, intervenes between the Monroe and the Niagara deposits.

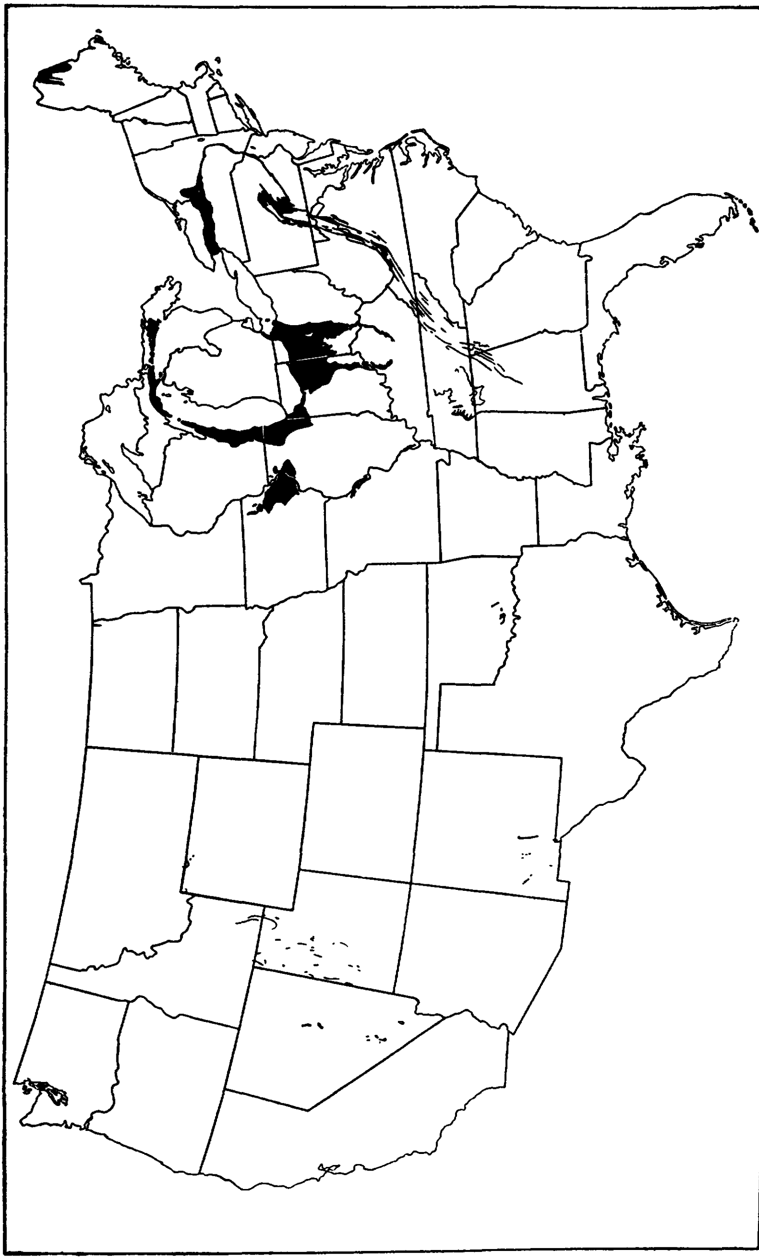


FIGURE 79.—Map of the United States showing areas in which Silurian rocks are at or near the surface. The Silurian system includes the Niagara limestone, which is a valuable aquifer from Iowa to Ohio and Kentucky but which yields salty water where deeply buried in southern Illinois and in Indiana, Ohio, and Kentucky. The system also includes the Monroe formation, which is the best bedrock aquifer in Ohio.

DEVONIAN SYSTEM.[13]

The Devonian system is most extensively developed in New York, Pennsylvania, Maryland, Virginia, and West Virginia, where it attains a thickness of many thousand feet. In New York the maximum thickness of the deposits of Devonian age is about 8,400 feet, in Pennsylvania 14,450 feet, in Virginia 13,700 feet, in Maryland 10,575 feet, and in West Virginia 9,215 feet. In southern New York and adjacent parts of Pennsylvania the Devonian crops out or lies immediately below the glacial drift throughout a wide belt (fig. 80). Its lower part consists of limestone, sandstone, and shale; its upper part comprises a great mass of gray and greenish sandstone and shale overlain by thick deposits of red sandstone and red sandy shale. In this region the Devonian rocks yield moderate supplies of water to many shallow wells but are seldom deeply penetrated for water. In western Pennsylvania the Devonian formations pass beneath the Carboniferous and are likely to yield salty water.

The Devonian system extends westward and southwestward from New York, Pennsylvania, and West Virginia through most of Ohio, Indiana, Michigan, Illinois, Iowa, Kentucky, and Tennessee, and into parts of adjacent States (fig. 80). It thins out rapidly, however, toward the west, and in the western part of the country it is in many places absent from the Paleozoic section, the Carboniferous rocks resting directly on Ordovician or older formations. In the States mentioned the Devonian system consists chiefly of limestone in its lower part and dark shale in its upper part. In none of these States is it an important source of water, although the limestone formations yield moderate supplies in many localities. In Ohio the very thick shale in the upper part of the Devonian system is especially unfavorable with respect to water supplies.

---

[13] The following publications (of the U. S. Geol. Survey, except as otherwise indicated) give information relating to water in Devonian rocks in the United States:

- Alabama, Water-Supply Paper 114; Alabama Geol. Survey cooperative report on underground water.
- Arkansas, Water-Supply Paper 114.
- Illinois, Water-Supply Paper 114.
- Indiana, Water-Supply Papers 26, 114, 254; Eighteenth Ann. Rept., pt. 4.
- Iowa, Water-Supply Papers 114, 145, 293.
- Kentucky, Water-Supply Papers 114, 233.
- Maryland, Water-Supply Papers 110, 114; Geol. Folio 179; Maryland Geol. Survey Special Pub: 10, pt. 2 (cooperative report).
- Michigan, Water-Supply Papers 30, 31, 114, 182, 183: Geol. Folio 205.
- Minnesota, Water-Supply Paper 256.
- Missouri, Water-Supply Papers 114, 195.
- New York, Water-Supply Paper 114.
- Ohio, Water-Supply Papers 91, 114; Eighteenth Ann. Rept., pt. 4, Nineteenth Ann. Rept., pt. 4; Geol. Folio 197.
- Pennsylvania, Water-Supply Papers 110, 114; Geol. Folio 179.
- Tennessee, Water-Supply Paper 114.
- Virginia, Water-Supply Paper 114.
- West Virginia, Water-Supply Papers 110, 114; Geol. Folio 179.

Devonian rocks occur in New England and in the folds of the Appalachian Mountains. Like the rocks of the older systems, they

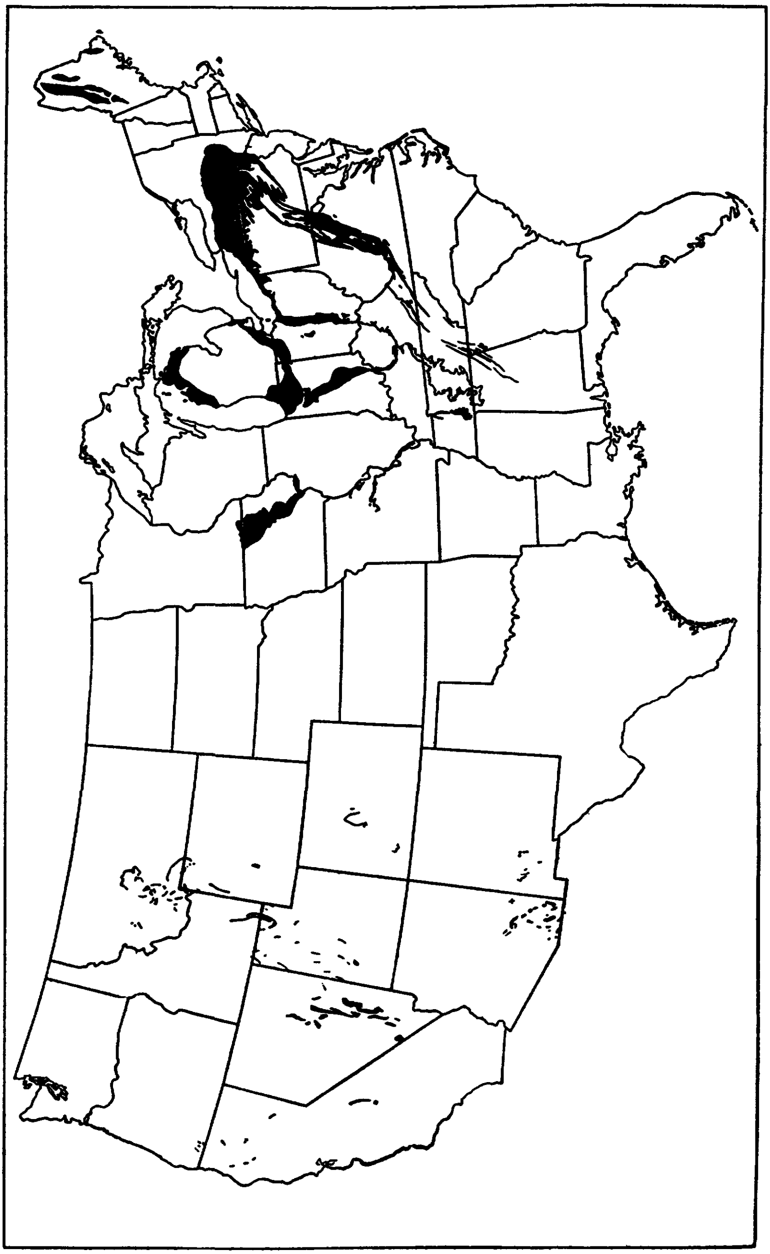


FIGURE 80.—Map of the United States showing areas in which Devonian rocks are at or near the surface. Devonian rocks are relatively unimportant as sources of water. In New York and Pennsylvania they include sandstones and limestones that supply many shallow wells; farther west they include limestones that locally yield potable water and much nonproductive shale.

are here largely metamorphosed. The northern part of Maine is extensively underlain by moderately folded Silurian and Devonian limestone, shale, and sandstone, cut in places by igneous rocks, some of which are volcanic. These formations would probably yield moderate water supplies, but it has not often been necessary to sink wells into them through the overlying drift.

CARBONIFEROUS SYSTEM.[14]

In the United States the Carboniferous is the most extensively developed of the Paleozoic systems. It has an aggregate thickness of many thousands of feet and is widely distributed over both the eastern and western parts of the country. It lies at the surface or immediately below the glacial drift throughout much larger areas than any of the other Paleozoic systems. (See fig. 81.)

Carboniferous rocks are found in New England, in the folds of the Appalachian Mountains, in the great area of flat-lying Paleozoic rocks between the Appalachian and Rocky Mountains, and in a few large areas and many smaller areas in the West.

In Rhode Island and eastern Massachusetts Carboniferous rocks belonging to the Pennsylvanian series attain an aggregate thickness of 12,000 feet, and in many places they rest on rocks of Cambrian

---

[14] The following publications (of the U. S. Geol. Survey, except as otherwise indicated) give information relating to water in Carboniferous rocks in the United States:

Alabama, Water-Supply Paper 114; Geol. Folio 175; Alabama Geol. Survey cooperative report on underground water.
Arizona, Water-Supply Paper 380; Bulletin 435.
Arkansas, Water-Supply Papers 110, 114, 145; Geol. Folios 122, 154.
Colorado, Prof. Papers 32, 52.
Georgia, Water-Supply Paper 114; Georgia Geol. Survey Bull. 15 (cooperative report).
Illinois, Water-Supply Paper 114; Seventeenth Ann. Rept., pt. 2; Bulletin 438, 506; Monograph 38; Geol. Folios 105, 185, 188, 195, 208, 213; Illinois Geol. Survey Bull. 5 (cooperative report).
Indiana, Water-Supply Papers 26, 114, 254; Eighteenth Ann. Rept., pt. 4; Geol. Folio 105.
Iowa, Water-Supply Papers 114, 293.
Kansas, Water-Supply Paper 273; Prof. Paper 32; Bulletin 238; Geol. Folios 148, 159, 206, 212.
Kentucky, Water-Supply Paper 114; Geol. Folios 184, 233.
Maryland, Water-Supply Papers 110, 114; Geol. Folios 160, 179; Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).
Michigan, Water-Supply Papers 30, 31, 114, 182, 183.
Mississippi, Water-Supply Paper 114.
Missouri, Water-Supply Papers 114, 195; Bulletin 438; Geol. Folios 148, 206.
Montana, Water-Supply Paper 221.
Nebraska, Water-Supply Paper 12; Nineteenth Ann. Rept., pt. 4; Prof. Papers 17, 32.
New Mexico, Water-Supply Papers 123, 158, 343; Bulletin 435.
New York, Geol. Folio 172.
Ohio, Water-Supply Papers 91, 114; Eighteenth Ann. Rept., pt. 4. Nineteenth Ann. Rept., pt. 4; Geol. Folio 184.
Oklahoma, Water-Supply Paper 148; Bulletins 641, 691; Geol. Folios 122, 132, 154.
Pennsylvania, Water-Supply Papers 110, 114; Bulletins 300, 531; Geol. Folios 102, 121, 123, 133, 144, 146, 160, 172, 174, 189.
South Dakota, Water-Supply Papers 227, 428; Twenty-first Ann. Rept., pt. 4; Prof. Papers 32, 65; Geol. Folios 107, 127, 128, 164, 209.
Tennessee, Water-Supply Paper 114; Tennessee Geol. Survey Bull. 26 (cooperative report).
Texas, Water-Supply Papers 154, 191, 276, 317; Eighteenth Ann. Rept., pt. 2; Geol. Folio 194
Utah, Water-Supply Paper 380.
Virginia, Water-Supply Paper 114.
West Virginia, Water-Supply Papers 110, 114; Geol. Folios 160, 179, 184.
Wyoming, Twenty-first Ann. Rept., pt. 4; Prof. Papers 32, 51, 53, 65; Bulletin 364; Geol. Folios 107, 127, 128, 141, 150, 173.

age. Carboniferous rocks also occur in other parts of New England, but they consist chiefly of metamorphic and igneous masses.

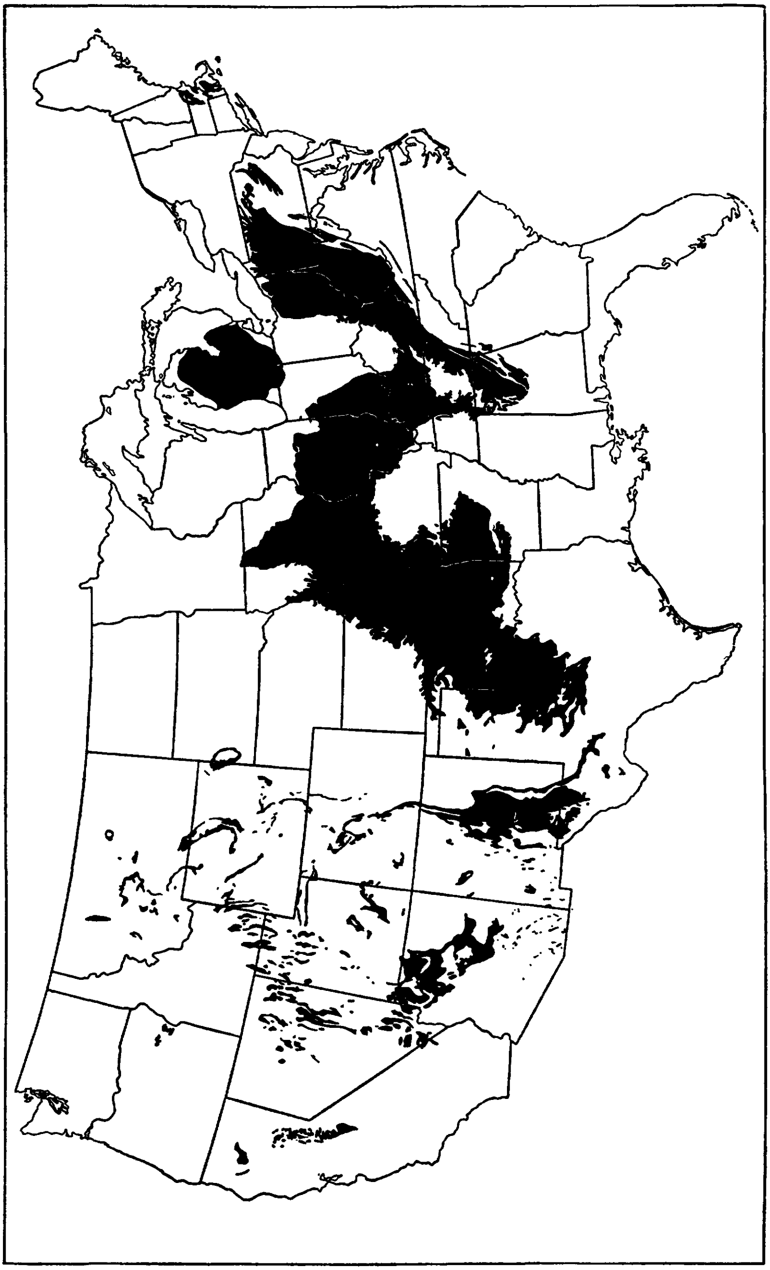


FIGURE 81.—Map of the United States showing areas in which Carboniferous rocks are at or near the surface. The Carboniferous rocks are, on the whole, not good sources of water. The best aquifers are the Mississippian limestones in Iowa, Missouri, and adjacent areas, the basal sandstone or conglomerate of the Pennsylvanian series, and the limestone and sandstone that yield artesian flows in Pecos Valley, N. Mex.

Between the Appalachian and Rocky Mountains the Carboniferous rocks lie at or near the surface in the southern peninsula of Michigan, where they are surrounded by older rocks, and in broad, irregular belts adjacent to the outcrops of older rocks on the north and in the Cincinnati anticline and Ozark Mountain uplift. They also lie at or near the surface throughout a great area extending far southwestward and eventually pass beneath younger deposits to the south and west. Thus, Carboniferous rocks are found at or near the surface in the southern peninsula of Michigan, western Pennsylvania, eastern Ohio, most of West Virginia and Kentucky, central Tennessee, northern Alabama, southwestern Indiana, central and southern Illinois, southern and north-central Iowa, northern and western Missouri, northwestern Arkansas, southeastern Nebraska, eastern Kansas, most of Oklahoma, north-central Texas, and adjacent parts of other States.

Farther west the Carboniferous strata reappear from beneath the younger deposits and occupy large parts of New Mexico and trans-Pecos Texas. In the eastern part of New Mexico they lie nearly level, like the Paleozoic formations throughout most of the large area in the eastern and central United States; but farther west they are commonly inclined at considerable angles and are broken into mountain blocks by faulting. Carboniferous rocks underlie most of the Colorado Plateau in northern Arizona, eastern Utah, and adjacent parts of Colorado and New Mexico, and in large parts of this high plateau region they lie immediately below the surface and are nearly horizontal or only gently inclined. Carboniferous formations, generally steeply inclined, crop out in belts that border or form parts of the Black Hills, the Uinta Mountains, and many of the mountain ranges of the Rocky Mountain system in Colorado, Wyoming, Montana, and Idaho. They also crop out in the escarpments of many of the faulted block mountains of the Basin and Range province and of the Sierra Nevada.

Each of the three series of the Carboniferous system—the Mississippian, the Pennsylvanian, and the Permian—is well developed in the United States, and both the Mississippian and the Pennsylvanian are widely distributed. (See figs. 82, 83, and 84.) In Michigan, in northern Indiana, and east of the Cincinnati anticline the Mississippian series consists largely of sandstone and shale, but farther west it consists predominantly of limestone. It has a maximum thickness in Pennsylvania of about 4,400 feet; in the Mississippi Valley region of about 1,500 feet; and in northern Arizona of about 1,500 feet. The Pennsylvanian series consists, for the most part, of a great succession of relatively thin discontinuous strata of shale, sandy shale, sandstone, limestone, and coal. It attains a thickness of several thousand feet in the East and in the Southwest but is not generally much more than 1,000 feet thick in the Mississippi Valley region. The Permian series occurs in West Virginia and adjacent parts of Pennsylvania and Ohio, where it consists of the Dunkard group, made up of sandstone, shale, limestone, and thin beds of coal. It occurs much more extensively in the Southwest, chiefly in Kansas, Oklahoma, Texas, and New Mexico, where it has a maximum thickness of a few thousand feet and consists of shale and sandstone, largely of red color, with limestone, gypsum, and salt. The portions in which the red shale and sandstone predominate are commonly called "Red Beds." In some parts of the west the Permian series

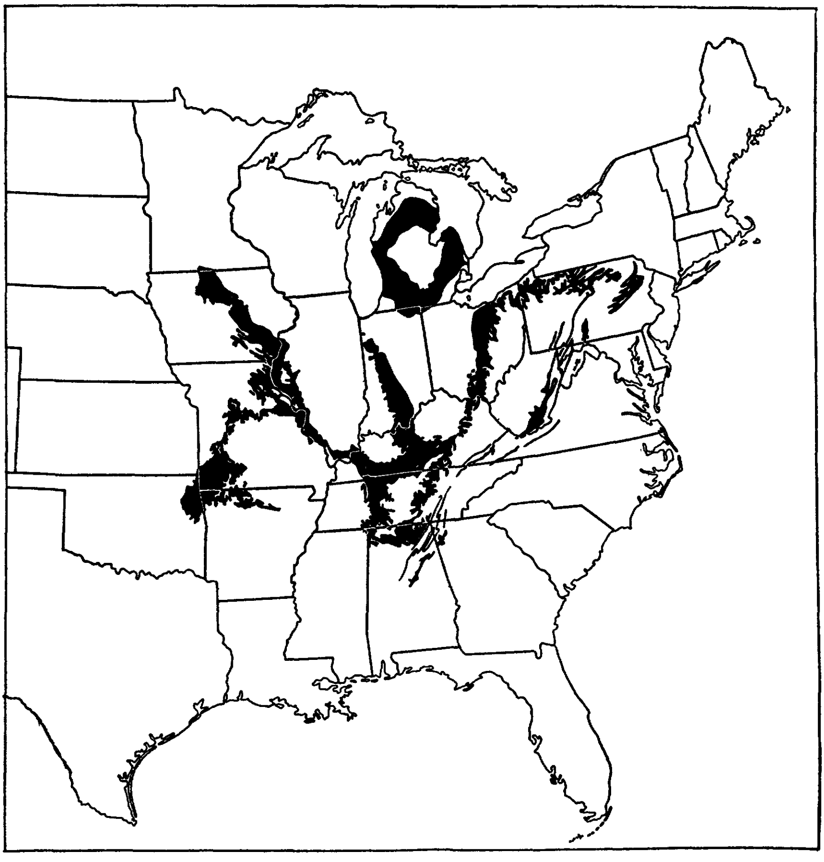


FIGURE 82.—Map of the United States east of longitude 102°, showing areas in which rocks of the Mississippian series are at or near the surface. In parts of Iowa and Missouri and adjacent areas Mississippian limestones and sandstones yield satisfactory water supplies and are largely utilized. In Michigan, Indiana, and farther east the Mississippian series yields some potable water, but as a rule its supplies are small or of poor quality

has not yet been definitely separated from the underlying Pennsylvanian rocks or the overlying Triassic rocks.

On the whole the Carboniferous rocks, especially the Pennsylvanian and Permian, are not good water bearers. The large areas in the United States where they are at the surface are among the most unfavorable in the country with respect to water supply.

In Michigan, Indiana, and farther east (fig. 82) the Mississippian series yields some potable water, but as a rule the quantity is small and the quality poor, the shaly formations being especially unfavorable. West of these States larger and better supplies are obtained from the Mississippian limestone formations. In parts of Iowa and Missouri and adjacent parts of other States some of the Mississippian

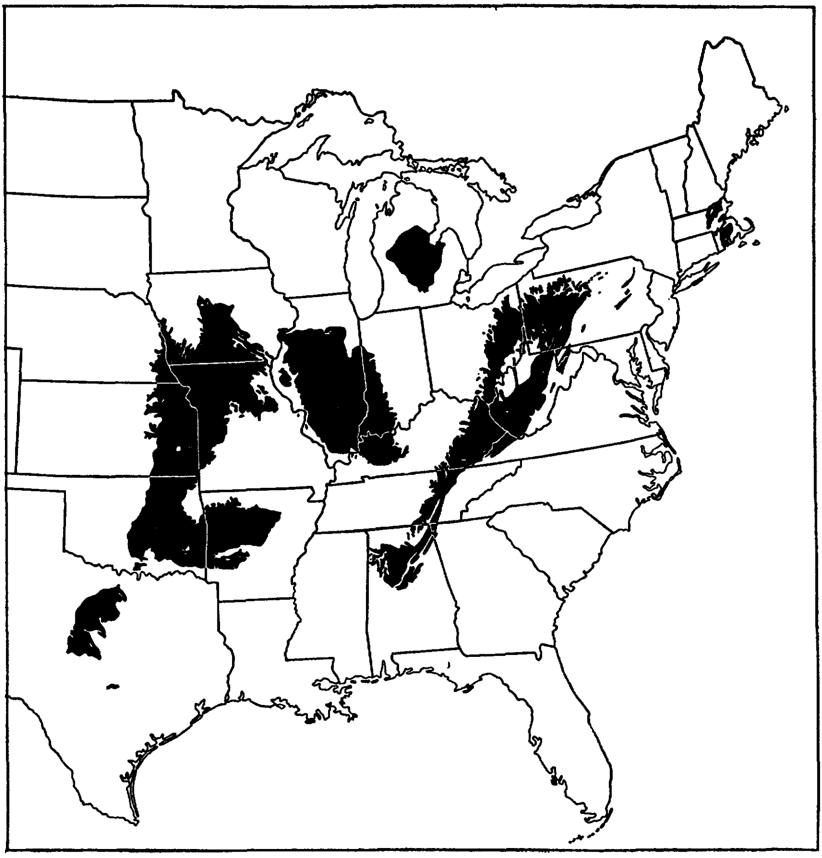


FIGURE 83.—Map of the United States east of longitude 102°, showing areas in which rocks of the Pennsylvanian series are at or near the surface. To a large extent areas underlain by Pennsylvanian rocks lack satisfactory water supplies. The basal sandstone or conglomerate, which occurs from Pennsylvania to Iowa and Missouri, may yield potable supplies where it is not too deeply buried.

limestones and sandstones yield very satisfactory supplies and are tapped by many wells.

The best sources of water in the Pennsylvanian series are the sandstones and conglomerates commonly found at the base of the series throughout the region from Pennsylvania to Missouri and Iowa (fig. 83). They yield fairly satisfactory supplies to many wells in localities where it is difficult to get water from other sources, but where they are deeply buried their water is likely to be too highly mineralized for use. The beds higher up in the series consist so largely of shale and shaly sandstone that they generally yield only meager supplies, and, moreover, their water is generally highly mineralized. Unfortunately, throughout large areas the Pennsylvanian series lies at the surface and has a great thickness. In these areas it is tapped by many wells that yield more or less satisfactory supplies, but in general the problems of water supply are acute, not only

FIGURE 84.—Map of the United States east of longitude 102°, showing areas in which rocks of the Permian series are at or near the surface. The Permian series is unsatisfactory in both quantity and quality of water, especially in Kansas, Oklahoma, and Texas.

for the waterworks of cities and villages but also for domestic and live-stock use on farms. In many localities reliance must be placed chiefly on rain water stored in cisterns and earth reservoirs.

The Permian series is also very unsatisfactory as a source of water. In some parts of its area of outcrop in Kansas, Oklahoma, and Texas (fig. 84) it yields only meager supplies; in other parts it yields large supplies of salty water. The water from many of the springs is so highly mineralized that it is unfit for use. There are, however, many springs in the Quartermaster formation that yield water of satisfactory quality. In general the yield of the Permian "Red Beds" is not large. In this area the water-supply problems are as acute as they are in the areas of Pennsylvanian rocks, and rain water is also stored to a large extent for domestic, stock, and other supplies. In both Pennsylvanian and Permian areas many localities have surficial deposits of one kind or another that yield the needed water.

On the whole, the Pennsylvanian and Permian formations yield more satisfactory supplies in Pennsylvania and other parts of the Appalachian region than farther west, because the surface is more rugged, and hence the water-bearing formations have been leached of their saline matter to greater depths and also crop out more extensively and thus give rise to more springs. Although in the Appalachian region the deeper Carboniferous waters are practically all salty, there is no acute water-supply problem, as in many Carboniferous areas farther west, because good domestic supplies can generally be obtained from springs or shallow wells and municipal supplies from springs or spring-fed streams.

On the high plains or plateaus of eastern New Mexico a number of deep wells have been drilled into the Carboniferous rocks, which here consist of limestone, sandstone, shale, and gypsum. Some of these wells have failed to get water or have struck only salty water. Others have found adequate supplies of very hard gypseous water, which can, however, be used for watering live stock and in many places also for drinking and other domestic uses. Pecos Valley, N. Mex., is underlain by Carboniferous formations which are believed to be Permian, at least in part, The upper 600 to 800 feet is made up of typical red beds, consisting of gypsum, red sandstone, limestone, and shale. Below these red beds there is a formation of gray limestone with some beds of sandstone, shale, and gypsum. The limestone and sandstone of this lower formation yield very large supplies to numerous flowing wells; the water is very hard but is used for drinking, domestic supplies, and irrigation.

In northern Arizona Carboniferous formations are within reach of the drill throughout considerable areas. They apparently rest largely on Cambrian and pre-Cambrian rocks. They consist chiefly of rocks of Pennsylvanian age, but in places they include rocks of Mississippian and probably of Permian age. The Redwall limestone of the Grand Canyon region is a thick, massive Mississippian limestone that is probably not promising as a source of water. In parts of northern Arizona the Mississippian series is apparently absent, but in parts of central and southern Arizona it is well represented. The Pennsylvanian series consists of sandstone, limestone, and variable amounts of shale. The limestone and shale are nearly impervious and are unpromising as sources of water. The sandstone, which occurs at several horizons, is somewhat porous and would doubtless yield some water under favorable conditions. Above the Pennsylvanian rocks is the Moenkopi formation, of either Permian or Triassic age. It consists of shale and thin sandstone containing some water that is, at least in part, salty. Above this formation, in some places, is the De Chelly sandstone, a moderately porous brown sandstone of Triassic age.

MESOZOIC SYSTEMS.

GENERAL CONDITIONS.

At the end of the Paleozoic era great changes took place in the physical geography of North America and hence in the regions in which sediments accumulated. Consequently the areas in the United States where Mesozoic rocks are near the surface are very different from those where Paleozoic rocks are near the surface. In the eastern part of the United States the Mesozoic rocks are less abundant than the Paleozoic. The great interior region extending from the Appalachian Mountains to the Great Plains is, for the most part, underlain by Paleozoic formations, but the marginal regions on the east and south contain Mesozoic formations. In the western part of the United States Mesozoic deposits were spread more widely, and in many places they lie over Paleozoic rocks.

There are three Mesozoic systems—the Triassic, the Jurassic, and the Cretaceous. The Triassic and Jurassic systems are not extensively exposed and are of relatively small importance as sources of water. The Cretaceous system, on the other hand, is extensively developed and widespread and is one of the most important of all rock systems as a source of water.

TRIASSIC SYSTEM.[15]

Triassic rocks occur in three general regions in the United States—in a number of isolated tracts between the Atlantic coast and the

[15] The following publications by the U. S. Geol. Survey give information relating to water in Triassic rocks in the United States:

Arizona, Water-Supply Paper 380; Bulletin 435.
Colorado, Sixteenth Ann. Rept., pt. 2, Seventeenth Ann. Rept., pt. 2; Prof. Paper 52.
Connecticut, Water-Supply Papers 110, 114, 232, 374, 449, 466, 470.
Kansas, Sixteenth Ann. Rept., pt. 2.
Massachusetts, Water-Supply Paper 110.
Maryland, Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).
Nebraska, Sixteenth Ann. Rept., pt. 2.
North Carolina, Water-Supply Paper 114.
New Jersey, Water-Supply Paper 114; Geol. Folios 157, 167, 191.
New Mexico, Water-Supply Paper 380; Bulletin 435.
New York, Water-Supply Paper 114; Geol. Folio 157.
Pennsylvania, Water-Supply Papers 106, 114; Geol. Folios 162, 167.
South Dakota, Geol. Folios 107, 164.
Texas, Water-Supply Papers 154, 191.
Utah, Water-Supply Paper 380.
Virginia, Water-Supply Papers 114, 258.
Wyoming, Bulletin 364; Geol. Folios 107, 150, 173.

Appalachian Mountains, from Massachusetts to North Carolina; in parts of the Great Plains, Rocky Mountains, and Colorado Plateaus;

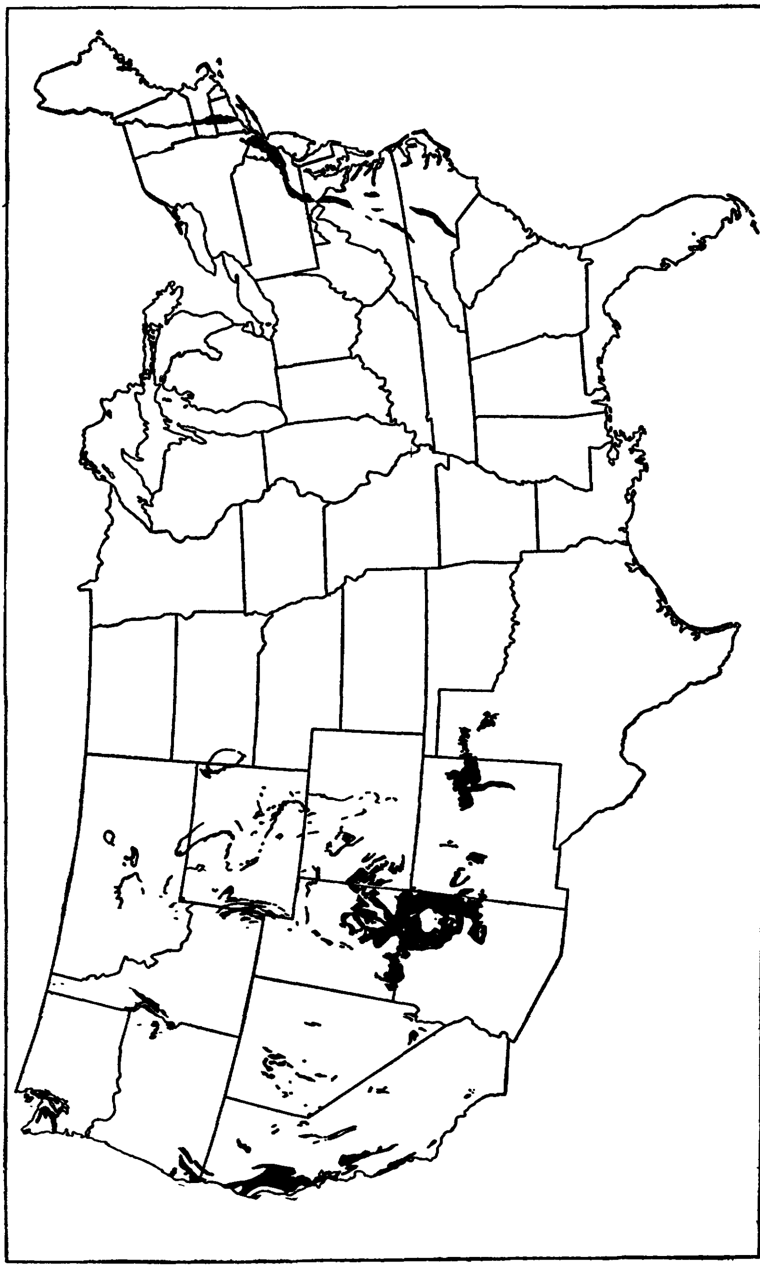


FIGURE 85.—Map of the United States showing areas in which Triassic or Jurassic rocks are at or near the surface. These two systems are relatively unimportant as sources of water. In the East the Triassic yields small to moderate supplies of satisfactory water; in the western areas it locally yields valuable supplies but commonly has only water that is meager in amount or of poor quality. The Jurassic contains sandstones that may yield considerable water.

and in the far West, from the western part of the Basin and Range province to the Pacific coast. (See fig. 85.)

The Triassic rocks between the Atlantic coast and the Appalachian Mountains form the Newark group, which consists of sandstone with some shale and conglomerate, a little coal, and some prominent layers of basic igneous rock commonly called trap. The sandstone, shale, and conglomerate generally have a deep-red color. The igneous rocks are in part extrusive lava flows and in part intrusive dikes and sills. The Newark rocks are commonly tilted, in some places at rather steep angles, and are broken by large normal faults, as a result of which the same sandstone bed or trap sheet may crop out in two or more parallel belts, as shown in figure 86. It is also extensively broken by smaller joints and faults.

The Newark rocks occur in a number of isolated tracts from Canada to North Carolina. The outcrops in the United States are shown in figure 75 (p. 199). A relatively large tract of Triassic rocks extends through the Connecticut Valley in Massachusetts and Connecticut; a very small tract occurs farther west in Connecticut; the largest tract begins in southeastern New York and extends through New Jer-

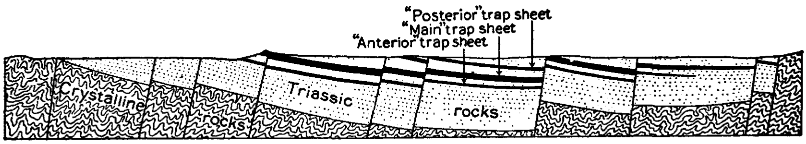


FIGURE 86.—Generalized section across the Triassic area of the Connecticut Valley. (After W. M. Davis.)

sey and Pennsylvania into Maryland; another tract of considerable size begins in Maryland and extends well into Virginia; and several other tracts are found farther south in Virginia and North Carolina. It should be noted that most of these tracts are entirely surrounded by older rocks, showing that the Triassic beds do not extend under cover from one tract to another but occur in isolated basins.

The sandstone and conglomerate of the Newark group yield water in moderate quantities to many dug and drilled wells. Large yields are not often obtained, but the supplies are generally ample for domestic use or for small industrial plants. In New Jersey some rather large supplies for industrial plants and public waterworks are obtained from this group of formations. The sandstone is somewhat porous, but most of the water is derived from joints, as in the surrounding crystalline rocks. Joints occur abundantly within 300 or 400 feet of the surface, but generally grow narrower with increasing depth. The shale is in general less porous than the sandstone but is also traversed by water-bearing joints. It generally occurs in rather small lenses that are soon penetrated by the drill. The trap rocks are generally so compact that they yield little or no water. This is especially true of the intrusive bodies and the deep parts of thick extrusive sheets. Meager supplies may be obtained from joints, and in a few places considerable water has been obtained from vesicular parts of extrusive trap (p. 141). The water of the Newark rocks is of much better quality than most of the Paleozoic water but not quite so free of dissolved mineral matter as the water from the crystalline rocks in the same region.

The Triassic rocks of the Great Plains, Rocky Mountains, and Colorado Plateaus are largely red beds consisting chiefly of irregularly stratified shaly sandstone, sandy shale, and gypsum. The "Red Beds" are in part Permian, in part Triassic, and perhaps in part Jurassic or even younger. In many places their age is not definitely known, and their reference to the Triassic system is tentative. Both the lower and the upper boundaries of the Triassic system in this region are uncertain.

The following section gives the thickness, lithologic character, and water-bearing properties of the Triassic and associated formations at a typical locality in the Panhandle of Texas:

Geologic section on North Branch of North Canyon. Cita Creek, eastern Randall County, Tex.[a]

System.	Subdivision.		Lithologic character.	Thickness (feet).	Water supply.
Tertiary.			Sand and clay.	70	Generally yields large supplies of water.
Triassic.	Dockum group.	Trujillo.	Gray sandstone and conglomerate, cross-bedded, with fossil bones and plates (upper sandstone).	30	Springs in the Triassic "Red Beds" usually issue from under the sandstone ledges, especially those in the Trujillo formation, or from joints and fissures in the red clay. As a rule water from springs in the Triassic is of good quality. Few wells have been sunk in the Triassic formations in this part of the State, but almost all yield relatively soft and pure water. In other places the Triassic may be less satisfactory.
			Red and gray shales.	35	
			Gray cross-bedded sandstone and conglomerate, with fossil bones and plates (middle sandstone).	10	
			Red shale with white bands of soft sandstone.	60	
			Massive cross-bedded gray to brown sandstone, with shaly members, and conglomerate; locally three well-marked ledges with shale lentils between (lower sandstone).	75	
		Tecovas.	Dark-red shale with white bands.	140	
			Yellow shale with iron concretions.	20	
			Maroon shale with iron concretions.	20	
			White to lavender shale.	10	

[a] Gould, C. N., The geology and water resources of the western portion of the Panhandle of Texas: U. S. Geol. Survey Water-Supply Paper 191, pp. 22, 36, 37, 1907. Water-supply data from various sources.

497781 O-59-19

Geologic section on North Branch of North Canyon, Cita Creek, eastern Randall County, Tex.—Continued.

System.	Subdivision.	Lithologic character.	Thickness (feet).	Water supply.
Carboniferous (Permian).	Quartermaster.	Red shale with white bands and ledges of soft sandstone.	150	Most water from Permian "Red Beds" contains large amounts of mineral salts. The water from many of the springs is so highly mineralized that it is unfit for use. There are, however, many springs in the Quartermaster formation which yield water of satisfactory quality. In general, the yield of the Permian "Red Beds" is not large.

Similar "Red Beds" are found in adjacent parts of New Mexico. In some parts of Texas and New Mexico they do not yield much water and their water is not of satisfactory quality. In most places they are overlain by water-bearing Tertiary deposits, but where these are absent wells are sunk into the "Red Beds," frequently, though not always, with disappointing results.

Farther north, especially in the Black Hills and in the mountains of Wyoming, there is a formation of "Red Beds" in some places more than 1,000 feet thick. In the Black Hills it is called the Spearfish formation, and in other localities its approximate equivalent is called the Chugwater formation. The Chugwater is regarded as chiefly Triassic, though the lower part in places is Permian and probably in places also extends down into the Pennsylvanian. It consists of soft, intensely red shale and sandstone, with thick beds of gypsum near the base. It is very unfavorable as a source of water. It may locally be water bearing, but as a rule it yields no water or only small amounts of very poor water.

In the Navajo country of northeastern Arizona and adjacent regions the Shinarump conglomerate of Triassic age, which is generally not more than 100 feet thick, is porous, and the contact between it and the underlying Moenkopi formation is one of the best saturated zones in the region and gives rise to many springs. The Chinle formation, which rests on the Shinarump, has a maximum thickness of about 1,000 feet and lies at the surface throughout extensive areas. It consists of chocolate-colored sandy shale at the base, succeeded by purple, lavender, green, and light-colored variegated shales, overlain by lenses of limestone conglomerate and red shale and shaly sandstone. This formation is notable for the fossil wood which it contains. It has small capacity for water, and in large parts it is destitute of available supplies.[16]

[16] Gregory, H. E., The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, pp. 79, 125, 1916.

In the western part of Nevada, in the Sierra Nevada, and in other parts of the far West there are Triassic formations, of great aggregate thickness, that are very different from the "Red Beds" farther east. They include sandstone, limestone, and shale which have been greatly intruded by igneous magmas and much metamorphosed. They are not extensively exposed, and, so far as known, they are unimportant with respect to water supplies.

JURASSIC SYSTEM.[17]

Jurassic rocks are apparently absent from the eastern part of the United States, but they underlie large areas in the West, where they have a distribution somewhat similar to that of the Triassic (fig. 85). They may be considered as occurring chiefly in two different regions—in the Colorado Plateaus and the Rocky Mountains and in the Pacific Mountain region, including the Coast Ranges and the Sierra Nevada. The Jurassic rocks in these two regions differ in lithologic character and have not been closely correlated.

Jurassic formations occur in large parts of Montana, Wyoming, eastern Utah, central and western Colorado, northeastern Arizona, northwestern New Mexico, and adjacent parts of other States. In most of this region they are deeply buried by younger deposits, but they crop out in narrow bands adjacent to many of the mountain ranges and lie at or near the surface over rather large areas in southeastern Utah and northeastern Arizona and adjacent parts of Colorado and New Mexico.

In the Black Hills uplift the "Red Beds" of probable Triassic age (Spearfish formation) are overlain by the Sundance formation, which is overlain by the Unkpapa sandstone, which is overlain by the Morrison shale. The Sundance and Unkpapa are Jurassic; the Morrison may be Lower Cretaceous. The Sundance formation here ranges between 100 and 300 feet in thickness and consists of dark-gray shale and buff sandstone; the Unkpapa sandstone has a maximum thickness of about 225 feet and consists of massive fine sandstone of white, purple, red, and buff hues; the Morrison shale has a maximum thickness of about 150 feet and consists of massive shale that ranges in color from gray to greenish and maroon. On the whole, these formations are not promising as water bearers. The Morrison shale and the shaly parts of the Sundance formation are practically barren of available

[17] The following publications of the U. S Geol. Survey give information relative to water in Jurassic rocks in the United States:

- Arizona, Water-Supply Paper 380.
- Kansas, Sixteenth Ann. Rept., pt. 2.
- Nebraska, Sixteenth Ann. Rept., pt.2; Geol. Folio 108.
- New Mexico, Water-Supply Paper 380.
- South Dakota, Water-Supply Paper 428; Prof. Paper 32; Geol. Folios 107, 127, 164.
- Utah, Water-Supply Paper 380; Bulletin 628; Prof. Paper 56.
- Wyoming, Prof. Papers 32, 56, 65; Bulletins 471, 543; Geol. Folios 107, 108, 127, 150.

water. The sandstone members of the lower part of the Sundance will yield small or moderate supplies. The Unkpapa sandstone, in the eastern and southeastern part of the Black Hills, may prove to be water bearing, but apparently it is too fine grained or compact to carry a large volume.[18]

The Sundance formation and the Morrison shale extend over a considerable area. They have been identified in the Laramie and Big Horn basins. They are prevailingly clayey except the lower part of the Sundance, which consists chiefly of soft sandstone.

In southwestern Wyoming the Jurassic is represented by the Nugget sandstone, a light-colored sandstone, by the Twin Creek limestone, and by at least the lower part of the Beckwith formation.[19] The water-bearing properties of the Nugget sandstone have not, so far as is known, been tested by drilling, but its physical character suggests that it may be water bearing. The Twin Creek, which overlies the Nugget, consists of black and gray shale and shaly limestone, with occasional beds of yellow sandstone. It is not promising as a source of water. Above the Twin Creek is the Beckwith formation, which attains a great thickness. The lower part of the Beckwith has been shown by fossil evidence to be Jurassic, but the upper part is probably Lower Cretaceous. Where best developed the Beckwith consists of a lower red-bed member, composed of interbedded clay, sandstone, and conglomerate, 2,500 feet thick, and of an upper member, composed of rather light-colored interbedded sandstone and clay over 3,000 feet thick. The sandstones and conglomerates of this formation may be important water bearers. Some of the water is highly mineralized, but some of it may be of satisfactory quality.[20]

In southeastern Utah, northeastern Arizona, and adjacent parts of Colorado and New Mexico is the La Plata group, of Jurassic age, which consists mainly of two massive cross-bedded friable sandstone formations—the Navajo sandstone above and the Wingate sandstone below. Between these two sandstones in many places is a band of limestone or of calcareous shale and sandstone called the Todilto formation.[21] Above the Navajo sandstone lie the McElmo formation, consisting of sandstone and some shale, and other beds of sandstone, which thicken toward the west. In central Utah the beds assigned to the McElmo formation attain a thickness of about 1,850 feet and

[18] Darton, N. H., Artesian waters in the vicinity of the Black Hills, S. Dak.: U. S. Geol. Survey Water-Supply Paper 428, pp. 32, 33, 1918.

[19] Schultz, A. R., Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, table opposite p. 24, 1920.

[20] Veatch, A. C., geography and geology of a portion of southwestern Wyoming, with special reference to coal and oil: U. S. Geol. Survey Prof. Paper 56, pp. 162-163, 1907. Schultz, A. R., Geology and geography of a portion of Lincoln County, Wyo.: U. S. Geol. Survey Bull. 543, pp. 49-54, 135, 1914.

[21] Gregory, H. E., The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, pp. 79, 125-126, 1916.

consist chiefly of variegated sandstone and sandy shale. The lower 800 feet is here mainly red and contains gypsum. Above the red beds is a gray to white sandstone about 200 feet thick.[22] The McElmo is of either late Jurassic or early Cretaceous age. There is still much uncertainty as to the correlation of the beds at about this horizon in different localities.

The massive sandstones of the La Plata group are porous and permeable and will doubtless yield water in considerable quantities. Where they crop out they give rise to many springs and seeps.[23] The McElmo formation in Arizona is similar to the Navajo sandstone. Supplies of fairly good water are obtained from conglomeratic sandstone of the McElmo formation in the vicinity of the town of Green River, Utah, and the sandstone beds are probably water bearing in other places.[24]

In California the Franciscan formation is of either Jurassic or Lower Cretaceous age, probably Jurassic. It is several thousand feet in aggregate thickness and comprises sandstone, conglomerate, shale, limestone, bedded radiolarian chert, and schist, much altered, shattered, and metamorphosed by intrusive and extrusive igneous rocks. This formation is too compact to be of much importance as a source of water. However, a large yield has recently been obtained on Angel Island by drilling to a depth of 300 feet and tapping sandstone beds that apparently belong to the Franciscan.

CRETACEOUS SYSTEM.[25]

GENERAL CONDITIONS.

The Cretaceous system is well developed and widely distributed in the United States. It has been divided into two rather distinct rock series known as the Lower Cretaceous and the Upper Cretaceous, both of which are important with respect to water. (See figs. 87 and 88, pp. 264, 266.) For convenience in describing the Cretaceous system it

[22] Lupton, C. T., Geology and coal resources of Castle Valley in Carbon, Emery, and Sevier counties, Utah: U. S. Geol. Survey Bull. 628, pp. 23-26, 1916.

[23] Gregory, H. E., op. cit., p. 126.

[24] Lupton, C. T., op. cit., p. 17.

[25] The following publications (of the U. S. Geol. Survey, except as indicated) give information relating to water in Cretaceous rocks in the United States:

Alabama, Water-Supply Paper 114; Alabama Geol. Survey cooperative report on ground water.
Arizona, Water-Supply Paper 380; Bulletin 435.
Arkansas, Water-Supply Papers 114, 399; Prof. Paper 46.
California, Water-Supply Papers 375, 446, 495.
Colorado, Seventeenth Ann. Rept., pt. 2; Monograph 27; Prof. Papers 32, 52; Bulletins 265, 350; Geol. Folios 36, 58, 68, 71, 135, 153, 186, 203.
Delaware, Water-Supply Papers 106, 114; Bulletin 138; Geol. Folios 137, 162, 211.
District of Columbia, Bulletin 138; Water-Supply Paper 114; Geol. Folios 70, 152.
Georgia, Water-Supply Papers 67, 114, 341, Bulletins 138, 164; Georgia Geol. Survey Bull. 15 (cooperative report).
Iowa, Water-Supply Papers 114, 293; Geol. Folio 156.

(Footnote continued on page 252.)

may be regarded as occurring in three regions in the United States—the Atlantic Coastal Plain (including the coastal plain adjacent to the Gulf of Mexico), the western interior (parts of the Great Plains, the Rocky Mountains, and the Colorado Plateaus), and the Pacific coast region. The first two of these regions contain valuable Cretaceous aquifers.

COLUMNAR SECTIONS.

The following tables give the generalized geologic columns, with reference to ground water, for the Cretaceous and overlying rocks in eight different parts of the country—three in the Atlantic Coastal Plain and five in the western interior. The Tertiary and Quaternary formations are given for reference in connection with the description of those systems (pp. 271–309).

(Footnote continued from page 251.)

Kansas, Water-Supply Papers 6, 273; Prof. Paper 32, Geol. Folio 212.
Kentucky, Water-Supply Papers 114, 164.
Louisiana, Water-Supply Paper 114; Prof. Paper 46.
Maryland, Water-Supply Paper 114; Bulletin 138; Geol. Folios 13, 137, 152, 182, 204; Maryland Geol. Survey Special Pub. 10, pt. 2 (cooperative report).
Minnesota, Water-Supply Papers 114, 256; Monograph 25; Geol. Folio 117.
Mississippi, Water-Supply Papers 114, 159.
Montana, Water-Supply Papers 221, 518; Geol. Folios 55, 128.
Nebraska, Water-Supply Papers 12, 70, 215, 425; Nineteenth Ann. Rept., pt. 4; Prof. Papers 17, 32; Geol. Folios 85, 87, 88, 108, 156.
New Jersey, Water-Supply Papers 106, 114; Bulletin 138; Geol. Folios 137, 157, 162, 167, 211.
New Mexico, Water-Supply Papers 123, 343, 380; Bulletin 435; Geol. Folios 199, 214.
New York, Water-Supply Paper 114; Prof. Paper 44; Bulletin 138; Geol. Folio 157.
North Carolina, Water-Supply Paper 114; Bulletin 138; Geol. Folio 80; North Carolina Geol. and Econ. Survey, vol. 3 (cooperative report).
North Dakota, Monograph 25; Bulletin 575; Geol. Folios 117, 168, 181.
Oklahoma, Water-Supply Paper 148.
Pennsylvania, Water-Supply Paper 106; Bulletin 138; Geol. Folios 162, 167, 211.
South Carolina, Water-Supply Paper 114; Prof. Paper 90; Bulletin 138.
South Dakota, Water-Supply Papers 34, 90, 227, 428; Seventeenth Ann. Rept., pt. 2, Twenty-first Ann. Rept., pt. 4; Prof. Papers 32, 65; Bulletins 575, 627; Geol. Folios 85, 96, 97, 100, 107, 108, 113, 114, 127, 128, 156, 164, 165, 209.
Tennessee, Water-Supply Papers 114, 164; Tennessee Geol. Survey Bull. 26 (cooperative report).
Texas, Water-Supply Papers 190, 191, 276, 317, 335, 375; Eighteenth Ann. Rept., pt. 2; Twenty-first Ann. Rept., pt. 7; Geol. Folios 42, 64, 76, 183.
Utah, Prof. Paper 56; Bulletins 541, 628.
Virginia, Water-Supply Paper 114; Bulletin 138; Geol. Folios 13, 80; Virginia Geol. Survey Bull. 5 (cooperative report).
Wyoming, Water-Supply Papers 70, 425; Twenty-first Ann. Rept., pt. 4; Prof. Papers 32, 51, 53, 56, 65; Bulletins 364, 471, 543, 621, 641, 656; Geol. Folios 107, 127, 128, 141, 142, 150, 173.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies.

Maryland and Delaware.[a]

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Quaternary.	Recent series.				Clay, loam, sand, gravel, peat, and ice-borne boulders, forming veneer on a series of terraces of which the Sunderland is highest and oldest and the Talbot is lowest and youngest.	Small supplies of water are obtained rather generally at base of blanket of Pleistocene deposits, especially of Wicomico and Talbot formations. Water from Talbot formation is likely to be salty.
	Pleistocene series.	Columbia group.	Talbot formation. Wicomico formation. Sunderland formation.			
Tertiary.	Pliocene (?) series.		Brandywine formation.	±50	Ferruginous clay, loam, sand, and gravel occurring in erosion remnants unconformably on older formations at high levels.	Supplies many springs and shallow wells. Locally beds of clean sand and gravel yield rather copious supplies.
	Miocene (?) or Pliocene (?).		Cohansey (?) or Yorktown (?) formation.	Several hundred feet.	Sandy formation with gravel and clay lenses, encountered in wells in southern Delaware and throughout Worcester County, Md.	Yields water in many places but is very irregular.
	Miocene series.	Chesapeake group.	St. Marys formation.	±150	Clay, sand, and greenish-blue sandy clay.	Yields rather large supplies, chiefly from basal beds.
			Choptank formation.		Sand, clay, and marl.	Probably yields water from upper beds.
			Calvert formation.	+200	Sand, clay, marl, and diatomaceous earth.	Yields moderate supplies from beds between 35 and 75 feet above base of formation.
	Eocene series.	Pamunkey group.	Nanjemoy formation.	+125	Clayey greensand with some gypsum.	Yields abundant supplies from deposits near base and also important supplies from beds near top of formation.
			Aquia formation.	100	Greensand and greensand marl.	
Cretaceous.	Upper Cretaceous series.		Rancocas formation.	20	Greensand marl.	
			Monmouth formation.			
			Matawan formation.	+50	Dark micaceous sandy clay.	Not a water horizon.

[a] Clark, W. B., and others, The surface and underground water resources of Maryland, including Delaware and the District of Columbia: Maryland Geol. Survey special publication, vol. 10, pt. 2, 1918.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Maryland and Delaware—Continued.

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Cretaceous.	Upper Cretaceous series.		Magothy formation.	90	Sand and clay which change rapidly both horizontally and vertically.	Widely water bearing. Yields rather large supplies.
			Raritan formation.	200	Thick-bedded light-colored sand, grading into gravel and clay.	Yields rather large supplies from the lower beds. Locally water is found at higher horizons.
	Lower Cretaceous series.	Potomac group.	Patapsco formation.	200	Highly colored and variegated clay, grading into lighter sandy clay and some sand.	Yields moderate supplies to many shallow wells, and rather large supplies to deeper wells.
			Arundel formation.	125	Lenses of iron-bearing clay, large, tough, and dark.	Not a water horizon
			Patuxent formation.	350	Sand, sandy clay, and clay. The sand is in part pure and gritty; in part containing kaolinized feldspar. Cross-bedded and irregularly bedded.	Yields rather large supplies from basal deposits, and somewhat smaller supplies from deposits near top of formation.

Georgia.[b]

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Quaternary.	Recent series.				Flood-plain deposits, alluvial sand, marsh mud, swamp deposits, and beach sand.	
	Pleistocene series.	Columbia group.	Satilla formation.	50	Near coast mud and sand containing marine shells. Fluviate phase, coarse sand, gravel, and clay.	Yield moderate supplies of nonartesian water to many shallow dug and driven wells.
			Okefenokee formation.	40	Coastal-terrace phase, gray sand of perhaps beach origin; argillaceous sand and small amount of gravel. Fluviate phase, coarse sand and gravel.	
Tertiary.	Pliocene (?) series.	Charlton formation.		(?)	Soft white argillaceous limestone and laminated fossiliferous greenish clay.	Unimportant as a source of water.

[b] Stephenson, L. W., and Veatch, J. O., Underground waters of the Coastal Plain of Georgia: U. S. Geol. Survey Water-Supply Paper 341, 1915. Cooke, C. W., The age of the Ocala limestone: U. S. Geol. Survey Prof. Paper 95, pp. 107–177, 1916. Cooke, C. W., and Shearer, H. K., Deposits of Claiborne and Jackson age in Georgia: U. S. Geol. Survey Prof. Paper 120, pp. 41–81, 1919.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Georgia—Continued.

System.	Series.	Subdivision.		Maximum thickness (feet).	Lithologic character.	Water supply.
Tertiary.	Miocene series.	Duplin marl.		15	Sandy shelly marl, slightly phosphatic.	Conditions not well known, but these formations probably supply some artesian wells.
		Marks Head marl.		45	Very sandy greenish and drab clay, fine gray and brownish phosphatic sand, and sandy laminated clay with calcareous nodules.	
		Alum Bluff formation.		200	Marine fossiliferous, greenish or gray argillaceous sand and sandy laminated clay.	Contains local water-bearing beds.
	Oligocene series.	Chattahoochee formation.		150	Gray and drab compact fossiliferous limestone.	Contains beds yielding large quantities of artesian water suitable for domestic use and for most industrial purposes.
		Vicksburg formation.		300	Mainly heavy-bedded soft white fossiliferous limestone, extensively silicified, overlain by red residual sand containing flint fragments. Contains some sand and clay beds.	Contains beds yielding large quantities of artesian and nonartesian water suitable for domestic use and for most industrial purposes.
	Eocene series.	Ocala limestone (in southwestern Georgia). Contains Jackson fossils.	Contemporaneous.	150	White granular fossiliferous limestone.	Contains beds yielding artesian water suitable for domestic use and for most industrial purposes.
		Barnwell formation (in eastern Georgia). Contains Jackson. fossils.		100	Mainly red and varicolored fossiliferous marine sand; thin beds of silicified limestone or chert and sandstone and quartzite. Twiggs clay member at base.	Contain numerous beds yielding large quantities of good water.
		McBean formation. Contains Claiborne fossils.		400	Variable in lithologic character, mainly clayey and sandy fossiliferous marl, drab sandy clay, and fuller's earth.	
		Wilcox formation.		150	Dark lignitic and glauconitic clay of the nature of fuller's earth and varicolored unconsolidated sand and clay.	Contains water-bearing beds; importance not ascertained.
		Midway formation.		400?	Ferruginous sand and local beds of white clay, together with fossiliferous limestone, marl, clay, and calcareous quartzite.	Contains beds yielding fairly large quantities of good water.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Georgia—Continued.

System.	Series.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Cretaceous.	Upper Cretaceous series.	Ripley formation.	±950	Gray calcareous micaceous sand, dark-gray to black sandy clay and shell marl, fine to cross-bedded sand with subordinate lenses of clay.	The upper and lower parts of the formation contain numerous sand beds yielding large quantities of good water; the clayey and marly beds near the middle contain some water-bearing beds.
		Eutaw formation.	560	Calcareous sand, sandy limestone, and more or less sandy clay of marine origin; cross-bedded sand and clay at base.	The lower part contains beds yielding fairly large quantities of good water
	Lower Cretaceous series.	Not differentiated.	600	Coarse-grained cross-bedded arkosic sand with subordinate lenses of light-colored to pure-white clay, approaching kaolin in composition.	Contains numerous beds yielding large quantities of good water.
Pre-Cambrian.				Crystalline rocks.	

Eastern Texas.[c]

System.	Series.	Subdivision.	Maximum thickness (feet).	Lithologic character.	Water supply.
Quaternary.	Recent series.		50	Fluviatile and beach deposits.	Yields small supplies of potable water to some shallow wells where the deeper water is salty.
	Pleistocene series.	Beaumont clay.	800	Blue calcareous clay, with lenses of sand and sandy clay.	Yields small supplies from sandy lenses. Much of the water is too salty for use.
		Lissie gravel.	900	Gravel and coarse sand, with lenses of clay.	One of the most important water-bearing formations in the region.
		Deposits of highest Pleistocene terrace.	50	Fluviatile deposits consisting in part of gravel.	Relatively unimportant for water supply.
Tertiary (?).	Pliocene (?)	Reynosa formation.	100	Fluviatile deposits consisting of flint gravel and limestone débris embedded in a clay matrix.	Not important in eastern part of State, but in the area in which it crops out, west of Brazos River, it yields potable water from sand and gravel members.

[c] Gordon, C. H., Geology and underground waters of northeastern Texas: U. S. Geol. Survey Water-Supply Paper 276, pp. 37–44, 1911. Deussen, Alexander, Geology and underground waters of the southeastern part of the Texas Coastal Plain: U. S. Geol. Survey Water-Supply Paper 335, pp. 27–29, 1914. Matson, G. C., The Pliocene Citronelle formation of the Gulf Coastal Plain: U. S. Geol. Survey Prof. Paper 98, pp. 167–192, 1916. Stephenson, L. W., A contribution to the geology of northeastern Texas and southern Oklahoma: U. S. Geol. Survey Prof. Paper 120, pp. 129–163, 1918. Trowbridge, A. C., Reconnaissance of Gulf Coastal Plain of Texas: U. S. Geol. Survey Prof. Paper 131, pp. 85–107, 1923.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Eastern Texas—Continued.

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Tertiary.	Pliocene series.		Dewitt formation.	1,500	Cross-bedded coarse gray semi-indurated, highly calcareous sandstone with lenses of clay.	Yields water freely from sandstone beds.
	Miocene series.		Pascagoula clay.	300	Marine and nonmarine blue, green, and gray clay; locally calcareous; some large calcareous concretions and many small nodules; some layers of sand and sandstone.	Do not yield much water.
			Hattiesburg clay.	350	Nonmarine blue and gray clay, some layers calcareous; thin layers of sand and sandstone.	
	Oligocene series.		Catahoula sandstone.	±475	Nonmarine gray sand, sandstone, fine conglomerate, quartzite, and clay. For statement regarding mechanical composition see p. 120.	Yield water freely to flowing and nonflowing wells.
	Eocene series.		Fayette sandstone.	160	Marine gray sand, sandstone, quartzite, and dark calcareous clay.	
			Jackson formation.	50	Calcareous blue clay with large limestone concretions.	Does not yield much water.
		Claiborne group.	Yegua formation.	750	Green clay with concretions of selenite and lenses of sand and lignite.	Yields considerable water
			Cook Mountain formation.	400	Lenticular masses of yellow sand and clay; in places lenses of green calcareous, glauconitic, fossiliferous marl; beds of iron ore and lignite.	Yields water freely from lower part of formation.
			Mount Selman formation.	350	Red ferruginous indurated green sand, with lenses of lignite and clay; beds and concretions of iron ore.	Yields water freely to flowing and nonflowing wells.
			Wilcox formation.	1,100	At the top 50 to 200 feet of white porous loose water-bearing sand with some interstratified clay. Farther down lenticular masses of sand, clay, and lignite and beds of marl.	Yields water freely to flowing and nonflowing wells.
			Midway formation.	500	Black and blue clay with interbedded strata of limestone and some lenses of sand.	The clay yields no water. Some sandy beds yield meager supplies.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Eastern Texas—Continued.

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.	Water supply.
Cretaceous.	Upper Cretaceous or Gulf series.	Navarro formation.	1,000	Shaly clay, fine gray sand, and sandy clay.	The clay and marl are not water-bearing except locally where they are sandy. The sand beds are important water bearers in Arkansas but of doubtful value in Texas.
		Taylor marl.	600	Chiefly gray or bluish-gray calcareous shaly clay or marl. At top Pecan Gap chalk member, 50 feet thick, underlain by Wolfe City sand member, 100 feet thick.	
		Austin chalk.	600	Chalk.	Not of value as a source of water. The more porous parts yield some very hard water.
		Eagle Ford clay.	600	Chiefly clay. Contains sand strata near top.	Sand strata yield water. The clay yields none or only meager supplies of highly mineralized water.
		Woodbine sand.	800	Sand and shale.	The sand strata at several horizons yield water freely.
	Lower Cretaceous or Comanche series.	Washita group.		Impure limestone and marl, some sand.	Generally yields no water or only small supplies. Locally considerable water from sand lenses.
		Fredericksburg group.		Massive white chalky limestone and calcareous clay.	Yields little water in eastern Texas but supplies many springs and wells farther west, chiefly from Edwards limestone.
		Trinity group.		Sand and clay with thin beds of limestone and some shale.	One of the most important sources of water in the region.

Northwestern Nebraska and adjacent parts of Wyoming and South Dakota.[d]

Quaternary.	Alluvium.		50	Gravel.	Yields freely in the larger stream valleys.
Tertiary	Pliocene series.	Ogalalla formation.	250	Calcareous grit, sandy clay, sand, and gravel.	Yields large supplies of good water to many wells.
	Miocene series.	Arikaree formation.	800	Gray sand with beds of pipy concretions.	Yields moderate supplies especially from coarse basal beds.
		Gering formation.	+200	Coarse sand, soft sandstone, and conglomerate.	Yields water but is not an important source of supply.

[d] Compiled from various sources, chiefly U. S. Geol. Survey Prof. Papers 17 and 32, by N. H. Darton.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Northwestern Nebraska and adjacent parts of Wyoming and South Dakota—Continued.

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Tertiary.	Oligocene series.	White River group.	Brule clay.	600	Hard pinkish clay, more or less sandy and jointed.	Generally yields only small supplies, but in some places it yields rather freely. Some of water is highly mineralized.
			Chadron formation.	100	Pale greenish-gray sandstone and shale.	Yields water in a few places.
Cretaceous.	Upper Cretaceous series.	Montana group.	Fox Hills sandstone.	700	Sandy and shaly beds.	Yields moderate supplies in some localities.
			Pierre shale.	±1,200	Dark-gray shale.	Yields no water or at best only meager supplies of water of poor quality.
		Colorado group.	Niobrara formation	400	Chalk and calcareous shale.	Yields small supplies in some places.
			Benton shale.	±1,000	Gray and dark shale, thin sandstone, limestone, and concretions.	Generally yields but little water.
		Dakota sandstone.		200	Massive buff sandstone.	Widespread artesian aquifer. Gives rise to a large number of wells, including numerous strong flowing wells.

Black Hills region. [e]

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Tertiary.	Oligocene series.	White River group.	Brule clay.	200	Similar to preceding section.	
			Chadron formation.	100		
Cretaceous.	Upper Cretaceous series.	Montana group.	Pierre shale.	1,200		
		Colorado group.	Niobrara formation.	225		
			Carlile shale.	600	Gray shale with thin sandstone, limestone, and concretions.	Generally yield but little water. Best water bed is a sandstone near top of the Carlile shale.

[e] Darton, N. H., Artesian waters in the vicinity of the Black Hills, S. Dak.: U. S. Geol. Survey Water-Supply Paper 428, pp. 9, 16–23, 29–32, 1918.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Black Hills region—Continued.

System.	Subdivision			Maximum thickness (feet).	Lithologic character.	Water supply.
Cretaceous.	Upper Cretaceous series.	Colorado group.	Greenhorn limestone.	65	Impure slabby limestone.	
			Graneros shale.	1,150	Dark shale with some lenses of massive sandstone in its lower part.	Generally not water-bearing, but yields some water from sandstone lenses.
		Dakota sandstone.		200	Massive buff sandstone.	Widespread artesian aquifer. Gives rise to a large number of wells, including numerous strong flowing wells.
	Lower Cretaceous series.	Fuson shale.		150	Massive white to purple shale and very fine grained sandstone.	Yields little or no water.
		Minnewaste limestone.		30	Gray limestone.	
		Lakota sandstone.		300	Massive buff sandstone, with some intercalated shale.	Yields large supplies of water. Gives rise to strong flowing wells.
Cretaceous (?).	Morrison shale.			150	Massive gray, greenish, and maroon shale.	Yields little or no water.

Central Montana.[f]

System.	Subdivision		Maximum thickness (feet).	Lithologic character.	Water supply.
Quaternary.				Alluvium	Coarser types are water-bearing and supply shallow dug wells; finer types are non water-bearing or yield meager supplies of poor quality. Some municipal supplies are obtained from alluvium. The most abundant yields are obtained in the valleys of large streams.
Tertiary.	Miocene (?) series.	Terrace deposits.	200	Gravel.	Water-bearing where sufficiently thick and not exposed to rapid drainage. Supplies drilled wells 100 to 200 feet deep near base of Big Snowy Mountains.

[f] Bowen, C. F., Anticlines in a part of the Musselshell Valley, Mont: U. S. Geol. Survey Bull. 691, pp. 188–189, 1918; Woolsey, L. H., Richards, R. W., and Lupton, C. T., The Bull Mountain coal field, Musselshell and Yellowstone counties, Mont.: U. S. Geol. Survey Bull. 647, pp. 18–32, 1917; and unpublished material, chiefly by A. J. Ellis. The water-supply data are by A. J. Ellis, and G. M. Hall.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Central Montana—Continued.

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Tertiary.	Eocene series.	Fort Union formation.		+2,000	Alternating beds of massive resistant yellowish to buff sandstone, clay, shale, and coal. At base is Lebo shale member, consisting of dark olive-green to brown sandy shale and thin-bedded arkosic sandstone with beds of carbonaceous sandstone and coal.	Generally water-bearing, but yields are for the most part small. Principal sources of water are sandstone lenses and coal beds. Shale lenses are non water-bearing or furnish small supplies of poor quality. Some lenses of fine-grained sandstone present obstacles to finishing wells. Lebo shale member generally non water-bearing.
Tertiary (?).	Eocene (?) series.	Lance formation.		1,500	Alternating beds of massive yellowish-brown and gray sandstone and buff to gray shale.	Generally water-bearing. Principal sources of water are sandstone beds, especially the basal member (Colgate sandstone member in the eastern part of the State), which in structurally favorable places supplies flowing wells. Shale beds are generally non water-bearing or furnish meager amounts of highly mineralized water.
Cretaceous.	Upper Cretaceous series.	Montana group.	Lennep sandstone (local around Crazy Mountains).	400	Lower part, massive light-colored sandstone, in places cross-bedded; middle part, brown andesitic beds; upper part contains abundant tufaceous material. Not widespread.	Probably locally water-bearing, but no record of developed supplies from this source.
			Bearpaw shale.	±1,000	Dark shale, with some sandstone near base.	Generally non water-bearing. Meager supplies of water, nearly all unsuitable for domestic use, have been obtained in a few places from somewhat sandy layers.
			Judith River formation.	±550	Sandstone and shale. Lower part chiefly sandstone.	Generally water-bearing Water of fair quality and adequate for domestic use except where the formation is very thin. Where the formation is thin supplies from this source resemble those from the Bearpaw and Claggett.
			Claggett formation.	490	Dark shale and sandstone.	Non water-bearing in Musselshell County but contains sandstone members in Stillwater County that are probably water-bearing.
			Eagle sandstone.	±300	Chiefly sandstone but with considerable shale.	Generally water-bearing. Supplies flowing wells in structurally favorable places.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Central Montana—Continued.

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.	Water supply.
Cretaceous.	Upper Cretaceous series.	Colorado shale.	±2,200	Chiefly shale but with several beds of sandstone and conglomerate. In some areas a thin sandy limestone called the Mosby sand occurs 675 feet below the top. At the base is found 30 to 50 feet of thin-bedded sandstone, called the Cat Creek sand, which is approximately equivalent to the top sandstone of the Cloverly formation and the Dakota sandstone, which underlies the Colorado group.	Generally non water-bearing. Water unfit for domestic use is obtained from the Mosby sand and other sandy layers. The Cat Creek sand yields artesian flows of potable water in structurally favorable areas.
	Lower Cretaceous series.	Kootenai formation.	±500	Red, gray, and white shale with thick beds of sandstone in the upper part. Contains several beds of coal in the Lewistown and Great Falls coal fields.	Generally yields potable water. In structurally favorable areas it yields large supplies of artesian water under considerable pressure. In some places south of the Big Snowy Mountains highly mineralized thermal waters have been obtained from the Kootenai by drilling through the Colorado.

Southwestern Wyoming.[a]

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply.
Quaternary.				430	Clay, silt, sand, and gravel, composing flood-plain and terrace deposits.	Will yield water in some places.
Tertiary.	Eocene series.		Bridger formation.	1,800	Greenish sand and clay, composed largely of volcanic ash with occasional calcareous white bands.	
			Green River formation.	±2,000	Thin-bedded shale, sandstone, and limestone, for the most part light colored.	
		Wasatch group.	Knight formation.	±1,500	Red and yellow sandy clay and shale interlaminated with white, gray, yellow, or reddish sandstone. Local areas of concretionary limestone.	Water bearing.
			Fowkes formation.	+2,500	Light-colored rhyolitic ash beds with interbedded limestone.	
			Almy formation.	±2,200	Red and yellowish-white conglomerate, sandstone, and sandy clay.	Water bearing.
Cretaceous or Tertiary.	Evanston formation.			+1,600	Gray, yellow, and black carbonaceous shale and clay interbedded with sandstone and containing several small coal beds.	

[a] Compiled chiefly from Veatch, A. C., Geography and geology of a portion of southwestern Wyoming with special references to coal and oil: U. S. Geol. Survey Prof. Paper 56, table opp. p. 50 and pp. 162–163, 1907.

Columnar sections of the Cretaceous, Tertiary, and Quaternary rocks in the United States, with descriptions of their water supplies—Continued.

Southwestern Wyoming—Continued.

System.	Subdivision.			Maximum thickness (feet).	Lithologic character.	Water supply
Cretaceous.	Upper Cretaceous series.	Montana group.	Adaville formation.	+4,000	White, gray, yellow, and brown carbonaceous clay and shale with irregularly bedded brown and white sandstone and numerous beds of coal.	Probably water bearing.
			Hilliard formation.	6,800	Gray and black sandy shale, with some clay and shaly sandstone.	
		Colorado group.	Frontier formation.	2,600	Alternating beds of gray and yellow clay, shale, and sandstone containing numerous beds of coal. Forms prominent ridges or hogbacks. Near top of formation a pronounced bed of coarse sandstone, in places conglomeratic.	Probably water bearing.
			Aspen formation.	2,000	Gray and black shale, shaly sandstone, and beds of compact gray sandstone.	
		Bear River formation.		±5,000	Black shale, shaly sandstone, and shaly limestone. Several thin beds of coal and bituminous shale.	

Northeastern Arizona and northwestern New Mexico [a].

Tertiary.	Eocene series	Chuska sandstone.	900	White and gray porous cross-bedded sandstone.	Ranks next to the Dakota sandstone in its capacity to yield water.
		Tohachi shale.	1,100	Dark-brown and white shale and subordinate sandstone.	Yields some artesian water.
Cretaceous.	Upper Cretaceous series.	Mesaverde and later formations.	1,100	Light-colored sandstone containing shale and seams of coal.	The sandstones of the Mesaverde formation have considerable porosity and constitute some of the chief water bearers of the region.
		Mancos shale.	800	Gray calcareous shale at base, changing to buff and drab and becoming sandy above.	The shale is impervious. The sandstone strata may yield some water.
		Dakota sandstone.	[illegible]	Conglomerate, consisting mostly of quartzite pebbles. Largest pebbles are 2 inches in diameter. Contains petrified wood. Sandstone above.	Has large capacity for holding water, both between the constituent grains and in cavities. Will probably yield water freely. In some places the water may be highly mineralized.

[a] Gregory, H. E., The Navajo country — a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, pl. 21 and p. 126, 1916.

LOWER CRETACEOUS SERIES.

Lower Cretaceous formations crop out along the inner edge of the Atlantic Coastal Plain from New Jersey to Texas except in parts of

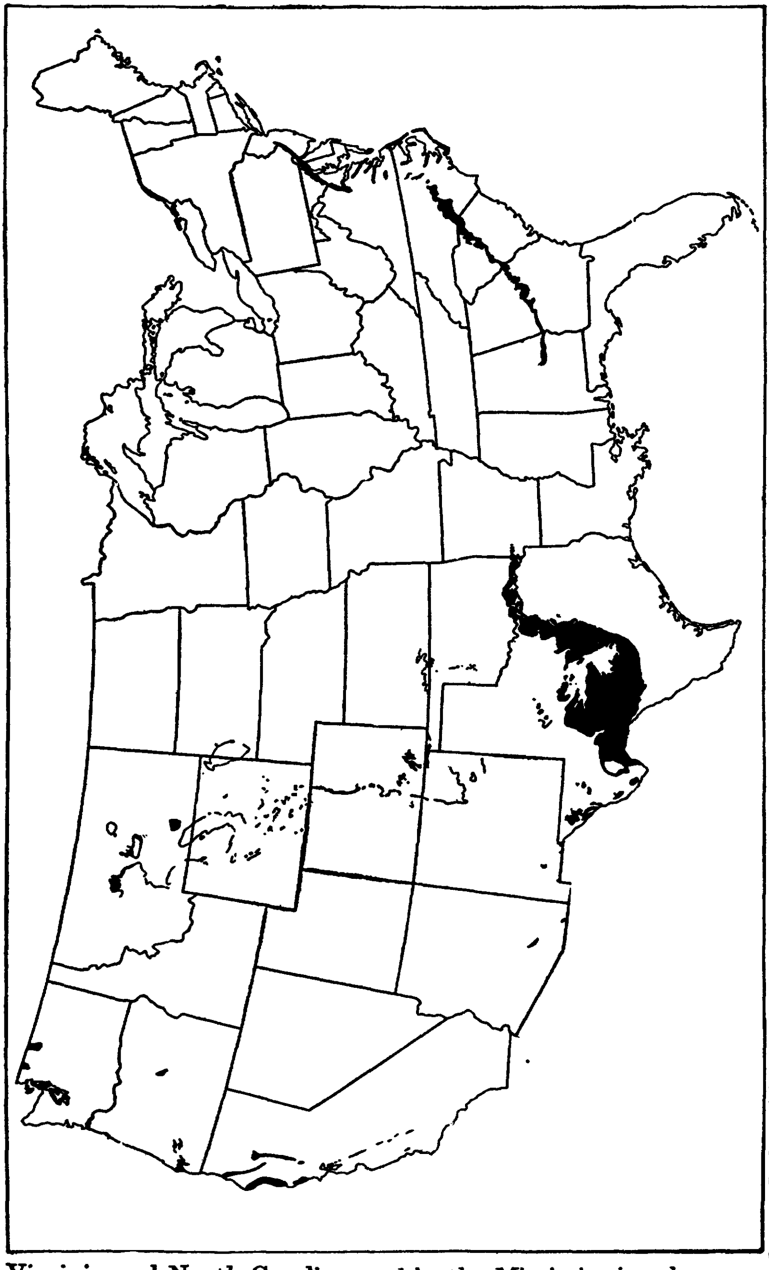


FIGURE 87.—Map of the United States showing areas in which rocks of the Lower Cretaceous series are at or near the surface. Includes some rocks that may prove to be basal Upper Cretaceous. In the eastern part of the United States and in Texas the Lower Cretaceous contains important aquifers; in the western interior (chiefly Montana, Wyoming, South Dakota, and Colorado) it yields considerable water but is not of leading importance; in the Pacific coast region it is unimportant as a source of water.

Virginia and North Carolina and in the Mississippi embayment from Alabama to Arkansas, where they are overlapped by younger formations. (See fig. 87.) The areas of outcrop are relatively narrow except in Texas, where Lower Cretaceous formations are at the surface over a wide area. The Lower Cretaceous formations rest with pronounced unconformity on rocks ranging in age from pre-Cambrian to Triassic. They dip gently seaward and in that direction pass beneath younger formations that dip in the same general direction.

The Lower Cretaceous series east of Mississippi River consists of several hundred feet of irregular gravelly, sandy, and clayey beds and contains some of the leading aquifers of the country. It yields supplies in variable amounts to many wells in its areas of outcrop and for some miles beyond, where it is still within reach of the drill. Although it dips very gently—generally much less than 1°—it soon passes too far below the surface to be commonly reached in drilling. Moreover, at considerable depths the water is likely to be salty.

West of the Mississippi the Lower Cretaceous series thickens until it attains a thickness of more than 2,000 feet. It also becomes more calcareous, about one-half of it being limestone or chalk. The Lower Cretaceous of this region includes a number of good aquifers and is a very important source of water. It is divided into three parts—at the bottom the Trinity group of formations, consisting largely of sand, but with some clay and limestone; in the middle the Fredericksburg group, consisting largely of limestone; and at the top the Washita group, consisting chiefly of impure limestone and marl. The clay and compact limestone do not yield much water, but the beds of porous sand and fissured limestone are good water bearers. The best water beds are the sands of the Trinity group.

Lower Cretaceous formations underlie considerable parts of the western interior region, but they are here not so widespread and not nearly so important for water supply as the Upper Cretaceous. They are found mostly in the northern part of the region. They consist chiefly of shale and sandstone. Some of the sandstones are water bearing, notably the Lakota sandstone, in the vicinity of the Black Hills, and the Cloverly sandstone, in the Big Horn and Laramie mountain regions in Wyoming. The Purgatoire formation in Colorado contains water-bearing sandstone but generally lies too deep to be reached by wells. In Montana the Kootenai formation, which is at least in part Lower Cretaceous, includes beds of sandstone that yield water. In the Great Falls region it is the principal water-bearing formation and gives rise to numerous springs and flowing wells. Below the Lakota, Cloverly, Purgatoire, and Kootenai is the Morrison shale, which yields little or no water.

In the Pacific coast region Lower Cretaceous formations (Knoxville and Horsetown) are well developed, attaining a thickness of several thousand feet, and consist chiefly of shale and sandstone. These formations, however, carry little water and supply but few wells.

UPPER CRETACEOUS SERIES.

The Upper Cretaceous series is more widespread in the United States than the Lower Cretaceous and is more important as a source

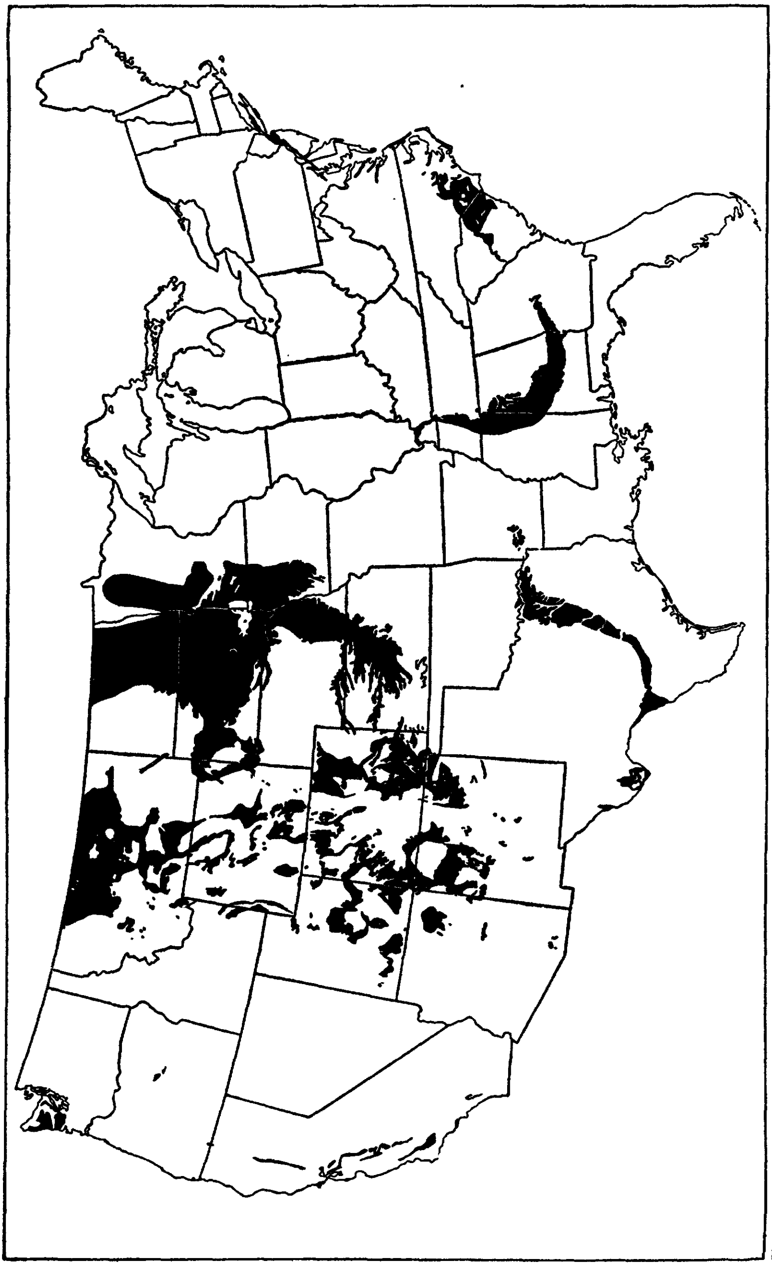


FIGURE 88.—Map of the United States showing areas in which rocks of the Upper Cretaceous series are at or near the surface. In the Atlantic Coastal Plain (Long Island to Texas) this series contains several important aquifers; in the western interior (Great Plains, Rocky Mountain region, and Colorado Plateaus) its basal formation is the Dakota sandstone, one of the most valuable aquifers in the United States and a notable artesian reservoir.

of water. It is of great value for water supply in the Atlantic Coastal Plain and in the western interior, including the Great Plains, the Rocky Mountain region, and the Colorado Plateaus. (See fig. 88.)

In the Atlantic Coastal Plain the Upper Cretaceous series rests on the Lower Cretaceous, except locally, where it overlaps the Lower Cretaceous and rests on older rocks. It crops out or lies immediately below surficial deposits from Massachusetts to the Mexican border in an irregular belt with a few interruptions, chiefly in Virginia and North Carolina and in the Mississippi embayment. It dips gently seaward like the Lower Cretaceous and in that direction passes beneath a cover of younger deposits that gradually increases in thickness toward the sea. Where it fails to crop out, in Virginia and North Carolina and in the Mississippi embayment, it is overlapped by younger formations and can generally be reached in drilling.

The Upper Cretaceous changes considerably from place to place in its extensive occurrence beneath the Atlantic Coastal Plain, but it practically everywhere contains some good water-bearing beds. Its water is generally of satisfactory quality, except at considerable depths, where it may be salty. It consists chiefly of clay, sand, limestone, and greensand marl. The greensand marl is characteristic of the series in this region.

The Upper Cretaceous section in Maryland and Delaware is shown in the table on pages 253–254. About the same formations extend through New Jersey, where they have a somewhat greater aggregate thickness.

In the southern part of North Carolina and in the adjacent part of South Carolina the Upper Cretaceous has an extensive area of outcrop. In North Carolina it has been divided into the Black Creek formation, 500 or 600 feet thick, at the bottom, and the Peedee formation, of still greater thickness, at the top.[26] The Black Creek formation consists of sand, clay, and some marl; the Peedee consists of clayey and calcareous sand and some greensand. Both yield large supplies of water to many wells but are irregular with respect to the distribution of water-bearing sands.

Westward through Georgia and Alabama the Upper Cretaceous thickens and includes much marl, chalk, and soft limestone. In this region it also yields much water, especially from the beds of sand.

West of the Mississippi embayment the Upper Cretaceous becomes still thicker, attaining a maximum thickness of about 3,000 feet in eastern Texas. Here also it consists of alternating beds of sand, clay or shale, limestone and marl, as shown in the section on page 258. The beds of sand are generally good aquifers, but the clayey and calcareous beds either do not yield water or yield only small supplies of very hard water. The best water horizons are in the Woodbine sand, which is the basal formation of the series in Texas.

The Upper Cretaceous underlies the central and northern parts of the Great Plains, extending eastward to central Minnesota and Iowa

[26] Stephenson, L. W., The Coastal Plain of North Carolina (the Cretaceous formations): North Carolina Geol. and Econ. Survey, vol. 3, pp. 73-171, 1912; prepared in cooperation with U. S. Geol. Survey.

and southward into New Mexico. It underlies large parts of the Rocky Mountain region and crops out in numerous ranges of that region. It also underlies most of the plateau region of western Colorado, eastern Utah, northwestern New Mexico, and northeastern Arizona. Throughout most of these regions the basal formation of the Upper Cretaceous is the Dakota sandstone, one of the most valuable aquifers in the United States and a notable source of artesian water. It is approximately equivalent in age to the Woodbine sand of Texas. Above the Dakota sandstone, which is generally not much more than 100 feet thick, lie Upper Cretaceous formations which in some places aggregate several thousand feet in thickness. These overlying formations are predominantly shaly and include much dense, plastic, impervious shale that will yield no water but is very effective in confining the copious supplies of the Dakota sandstone under artesian pressure. There are, however, several fairly good water-bearing beds at various horizons above the Dakota.

The Dakota sandstone is found in most of North Dakota, South Dakota, and Nebraska, in the western parts of Minnesota, Iowa, and Kansas, and in considerable parts of Montana, Wyoming, Colorado, New Mexico, Utah, and Arizona. (See sections on pp. 258–263.) In all these States it includes beds of sandstone and is recognized as a prominent aquifer, although in some parts it also includes much non water-bearing shale. It gives rise to strong flowing wells where it is under cover in low-lying parts of North Dakota, South Dakota, Minnesota, Nebraska, Kansas, Wyoming, and Colorado. Elsewhere it supplies numerous pump wells. Much of the water is highly mineralized. Toward the west, in Montana and Wyoming, it disappears or at least loses its identity as a water-bearing sandstone.

A typical section of the Cretaceous formations above the Dakota sandstone on the Great Plains is the Black Hills section, given on pages 259–260. The Graneros shale, Greenhorn limestone, and Carlile shale correspond to the Benton shale of other areas and collectively have in some reports been called the Benton group. They include a great thickness of impervious shale but yield some water from sandstone beds. The Niobrara formation yields small supplies. The Niobrara and Benton formations together constitute the Colorado group. The Pierre shale is thick and impervious and is notable for its failure to yield water. In many of the areas where the Pierre lies at the surface it is difficult to obtain water supplies even for domestic and stock use. The Fox Hills sandstone is generally water bearing but is absent in much of the region. The Pierre shale and Fox Hills sandstone together form the Montana group. The Laramie formation, which in eastern Colorado lies next above the Montana group, also contains some water-bearing sandstone. In eastern Montana the Lance formation occurs stratigraphically above the Fox Hills sandstone and in places rests on the Pierre shale. It is from 200 to 1,100 feet thick there and consists of somber beds of clay, with lenses of sandstone and a little lignite, and locally a basal sandstone called the Colgate sandstone member, which may possibly be equivalent to the Fox Hills.[27] This basal sandstone, which in places is 175 feet thick, is an aquifer of considerable importance, and the overlying beds also furnish some water. The Lance formation is of either late Cretaceous or early Tertiary age.

In central Montana the Colorado group is represented by a thick shale formation that yields very little potable water except from sandstone near the base, which gives rise to some flowing wells. The Montana group, however, contains more sandstone in central Montana than it does in the area farther east, as is seen by comparing the section for central Montana with the Black Hills section (pp. 259–262). The Eagle sandstone, Claggett formation, Judith River formation, and Bearpaw shale are the equivalents of the Pierre shale. They include several recognized water-bearing sandstones interbedded with thick beds of impervious shale. In the section in southwestern Wyoming shown on pages 262–263 there are beds of porous sandstone that will probably yield water in both the Montana group and the Colorado group of formations. Much of the water is highly mineralized.

On the Colorado Plateaus (western Colorado, eastern Utah, northwestern New Mexico, and northeastern Arizona) the generally distributed Upper Cretaceous deposits are commonly divided into three formations—the Dakota sandstone, at the bottom; the Mancos shale, in the middle; and the Mesaverde formation, at the top. Locally in western Colorado and northwestern New Mexico the Lewis shale, the Pictured Cliffs sandstone, and a series of coal-bearing nonmarine Cretaceous deposits are present above the Mesaverde formation. The Dakota sandstone is generally a few hundred feet thick and contains considerable water-bearing sandstone or conglomerate. Much of its water is, however highly mineralized. The Mancos shale, several thousand feet thick, is an immense body of impervious shale with some sandstone in the lower part. The Mesaverde formation, in many places more than a thousand feet thick, consists of alternating beds of sandstone and shale of which the sandstones are usually water bearers.

In the Pacific coast region the Upper Cretaceous is represented by sedimentary beds having an aggregate thickness of about 4,000 feet. It is exposed largely in the Coast Ranges. It is not important as a source of water. In San Diego County, Calif., a considerable thick-

[27] Calvert, W. R., Geology of certain lignite fields in eastern Montana: U. S. Geol. Survey Bull. 471, pp. 194–198, 1912.

ness of beds supposed to be Upper Cretaceous have been penetrated in drilling, and some water-bearing beds have been encountered.[28]

CENOZOIC SYSTEMS.

GENERAL CONDITIONS.

The Cenozoic era followed the Mesozoic and includes the present time. This era is notable for the deformation and uplift of the earth's crust in the western part of the United States and to a less extent in the eastern part, the voluminous outpouring of lava in the West, and the invasion of the northern part of the country by huge ice sheets in comparatively recent times. At the beginning of the era the territory now occupied by the United States was for the most part a low-lying, partly submerged region. Deformation, uplift, and volcanic activity have produced practically all the mountains and plateaus that exist in the country at present. These highlands were rapidly eroded by the streams, and much of the resulting rock waste was deposited by the streams on the lowlands, producing thick and widespread alluvial deposits that contain numerous irregular beds of water-bearing gravel. Volcanic activity produced very thick and extensive sheets of lava, consisting largely of water-bearing basalts. The great ice sheets eroded the bedrocks and brought with them and deposited vast quantities of rock waste called glacial drift, much of which was assorted by the waters that flowed copiously from the ice sheets, producing abundant deposits of water-bearing gravel. Sediments were also accumulating in parts that were still submerged by the sea, notably in much of the region now occupied by the Atlantic Coastal Plain.

The Cenozoic formations therefore comprise glacial drift, alluvial and lacustrine deposits not related to glaciation, marine deposits, and volcanic rock—all of which contains much water-bearing material. The Cenozoic formations, being the last deposited, immediately underlie the surface throughout much larger areas than the older formations. Hence they are readily recharged by rain and surface water and are conveniently reached by wells. As they consist largely of gravel and other porous and permeable materials, and as they have not been submitted to much compacting or cementation, they include much material that absorbs, transmits, and yields water freely. The Cenozoic formations are therefore more valuable as sources of water than the formations of any of the older eras. They supply more wells and as a rule furnish more water.

The Cenozoic formations are divided into two systems—the Tertiary, which is the older, and the Quaternary, which is the younger.

[28] Ellis, A. J., and Lee, C. H., Geology and ground waters of the western part of San Diego County, Calif.: U. S. Geol. Survey Water-Supply Paper 446, pp. 61-57, 175-181, 1919.

Both are important as sources of water. The Quaternary, which includes the glacial drift and most of the water-bearing alluvial deposits of the West, is without question the most valuable of all the geologic systems as a source of water.

TERTIARY SYSTEM.[29]

GENERAL CONDITIONS.

The Tertiary system is probably the most important system in the United States as a source of water, except the Quaternary.

---

[29] The following publications (of the U. S. Geol. Survey, except as indicated), give information in regard to water in the Tertiary rocks in the United States:

Alabama, Water-Supply Paper 114; Alabama Geol. Survey cooperative report on underground water.
Arizona, Water-Supply Paper 380.
Arkansas, Water-Supply Papers 114, 145, 399: Prof. Paper 46.
California, Water-Supply Papers 225, 375, 495; Geol. Folios 66, 138.
Colorado, Sixteenth Ann. Rept., pt. 2, Seventeenth Ann. Rept., pt. 2, Twenty-first Ann. Rept., pt. 4, Twenty-second Ann. Rept., pt. 4; Monograph 27; Prof. Papers 32, 52; Bulletin 531; Geol. Folios 71, 135, 198.
Delaware, Water-Supply Paper 114; Bulletin 138; Geol. Folios 137, 162.
District of Columbia, Geol. Folio 152.
Florida, Water-Supply Papers 114, 319.
Georgia, Water-Supply Papers 114, 341; Bulletin 138; Georgia Geol. Survey Bull. 15 (cooperative report).
Idaho, Water-Supply Papers 53, 54, 78; Bulletin 199; Geol. Folios 45, 103, 104.
Illinois, Water-Supply Papers 114, 164; Seventeenth Ann. Rept., pt. 2; Monograph 38.
Indiana, Water-Supply Paper 114.
Kansas, Water-Supply Papers 6, 273, 345; Sixteenth Ann. Rept., pt. 2, Twenty-first Ann. Rept., pt. 4, Twenty-second Ann. Rept., pt. 4; Prof. Paper 32; Geol. Folio 212.
Kentucky, Water-Supply Papers 114, 164.
Louisiana, Water-Supply Papers 101, 114; Prof. Paper 46.
Maryland, Water-Supply Paper 114; Bulletin 138; Geol. Folios 13, 23, 136, 137, 152, 182, 204; Maryland Geol. Survey special publication, vol. 10, pt. 2 (cooperative report).
Mississippi, Water-Supply Papers 114, 159.
Missouri, Water-Supply Papers 114, 195.
Montana, Water-Supply Paper 518.
Nebraska, Water-Supply Papers 12, 70, 215, 216, 425; Sixteenth Ann. Rept., pt. 2, Nineteenth Ann. Rept., pt. 4, Twenty-first Ann. Rept., pt. 4, Twenty-second Ann. Rept., pt. 4; Prof. Papers 17, 32; Geol. Folios 87, 88.
Nevada, Water-Supply Paper 423.
New Jersey, Water-Supply Paper 114; Bulletin 138; Geol. Folios 137, 162.
New Mexico, Water-Supply Paper 380; Twenty-first Ann. Rept., pt. 4, Twenty-second Ann. Rept., pt. 4; Geol. Folio 214.
North Carolina, Water-Supply Paper 114; Bulletin 138; Geol. Folio 80; North Carolina Geol. and Econ. Survey, vol. 3 (cooperative report).
North Dakota, Geol. Folio 181.
Oklahoma, Water-Supply Papers 148, 345; Twenty-first Ann. Rept., pt. 4, Twenty-second Ann. Rept., pt. 4.
Oregon, Water-Supply Papers 53, 54, 78, 220, 231; Bulletin 252; Geol. Folio 103.
Pennsylvania, Water-Supply Paper 144; Geol. Folio 162.
South Carolina, Water-Supply Paper 114; Bulletin 138.
South Dakota, Water-Supply Paper 227; Prof. Paper 32; Bulletin 627.
Tennessee, Water-Supply Papers 114, 164.
Texas, Water-Supply Papers 154, 190, 191, 276, 335, 375; Twenty-first Ann. Rept., pts. 4 and 7, Twenty-second Ann. Rept., pt. 4; Geol. Folio 64.
Utah, Bulletin 285; Prof. Paper 56.
Virginia, Water-Supply Paper 114; Bulletin 138; Geol. Folios 13, 23, 80, 136; Virginia Geol. Survey Bull. 5 (cooperative report).
Washington, Water-Supply Papers 53, 54, 55, 111, 118, 316, 425; Bulletin 108; Geol. Folios 86, 106.
Wyoming, Water-Supply Paper 70; Twenty-first Ann. Rept. pt. 4, Twenty-second Ann. Rept., pt. 4; Prof. Papers 32, 51, 56; Bulletins 285, 364, 425, 543; Geol. Folio 173.

Next to it probably ranks the Cretaceous. The Tertiary system is not, as a rule, as thick as some of the older rock systems, but it

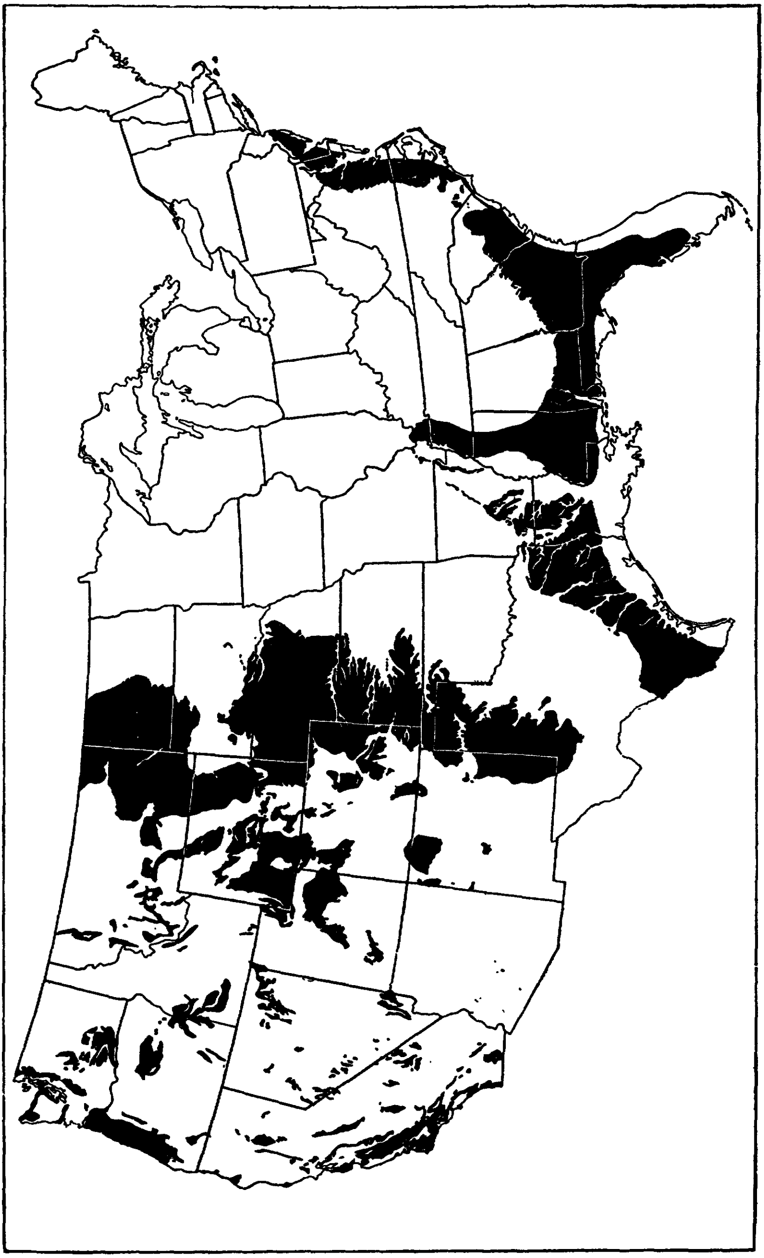


FIGURE 89.—Map of the United States showing areas in which Tertiary sedimentary formations are at or near the surface. In the Atlantic Coastal Plain and the Great Plains and also in parts of the Rocky Mountain region and the Colorado Plateaus the Tertiary system contains valuable aquifers that yield large supplies to many wells.

consists largely of porous materials, and it lies at or near the surface throughout extensive areas. (See figs. 89 and 94.)

The sedimentary deposits of the Tertiary system have been divided into the following four series, the oldest being given first: Eocene, Oligocene, Miocene, and Pliocene. All these series are of considerable importance in the United States as sources of water supply; the Pliocene is most important and the Eocene or Miocene ranks next. In addition to the Tertiary sedimentary formations there are in the western part of the United States vast areas of volcanic rocks of Tertiary age, largely water-bearing basalt (fig. 94).

With respect to water supplies there are four important groups of Tertiary formations in the United States—the sedimentary formations of the Atlantic Coastal Plain, the sedimentary formations of the central and southern parts of the Great Plains, the sedimentary

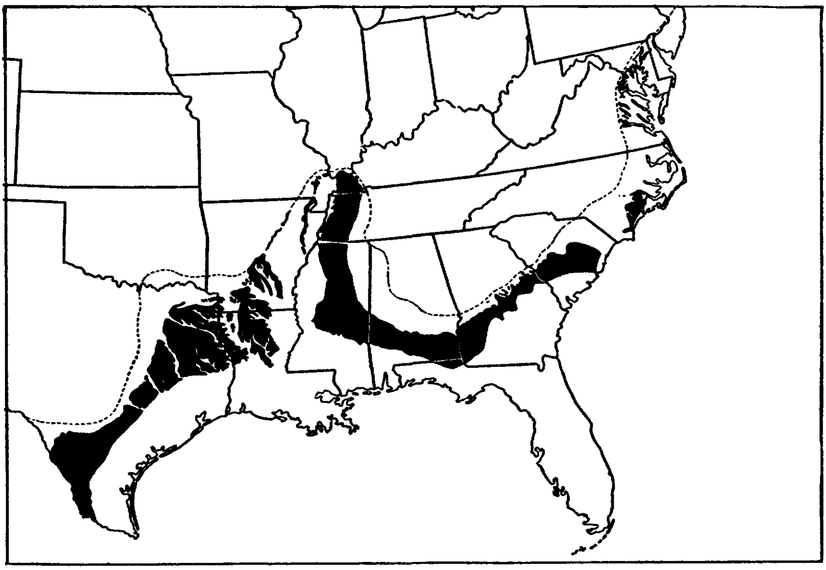


FIGURE 90.—Map of the Atlantic Coastal Plain showing areas in which beds of the Eocene series are at or near the surface. The Eocene, especially from South Carolina to Texas, includes valuable artesian aquifers. The boundary of the Coastal Plain is shown by the broken line.

formations of the northern part of the Great Plains and of parts of the Rocky Mountain region and the Colorado Plateaus, and the lava beds and associated sedimentary beds of the Columbia Plateaus (chiefly in Washington, Oregon, and Idaho). In addition there are many detached areas of Tertiary rocks in the West—both sedimentary and igneous—that yield more or less water.

FORMATIONS OF THE ATLANTIC COASTAL PLAIN.

The Tertiary formations of the Atlantic Coastal Plain were nearly all laid down in the sea, not very far from the shore. They consist mainly of beds of sand, clay, and soft limestone. They overlie the

Cretaceous formations and, like the Cretaceous, dip gently seaward. They include a number of good aquifers, chiefly the beds of sand, which supply many flowing and nonflowing wells. Their water is generally of good quality in the areas of outcrop and for some distance down the dip but is likely to become salty where the formations pass to considerable depths in the direction of the sea. Certain high-level terrace deposits are probably also of Tertiary age. (See p. 307.)

All four of the Tertiary series are present in the Atlantic Coastal Plain and contain water-bearing beds. The areas in which the different series are at or near the surface are shown in figures 90 to 93. Some localities that have only a thin deposit of a younger Tertiary series overlying an older Tertiary series are included in the map of each series. The Eocene is represented in Delaware, Maryland, and Virginia by the Pamunkey group of formations, about 225 feet thick, which contain sand and greensand that yield rather large supplies. In North Carolina the Eocene has been divided into a lower formation, called the Trent marl, approximately 150 feet thick, and an upper formation, called the Castle Hayne limestone, approximately 50 feet thick. Both formations consist largely of beds of marl, limestone, and sand. Both yield abundant supplies of hard water from the sandy beds and from solution openings in the limestone. From South Carolina to the Mexican border the Eocene deposits occur continuously and increase greatly in thickness and in width of outcrop. Throughout this long belt they include prominent artesian aquifers of great value. A good idea of the Eocene of this part of the Atlantic Coastal Plain is given by the typical sections for Georgia and eastern Texas on pages 254–258. In southwestern Texas the water is highly mineralized, and much of it is too salty for use.

The areas in the Atlantic Coastal Plain in which Oligocene beds are at or near the surface are shown in figure 91. The Oligocene underlies extensive areas in South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, and Texas. In Georgia, Florida, and South Carolina it consists largely of limestone but includes considerable sand and other materials. (See section, p. 255.) In these States it contains several important water-bearing formations. The Oligocene limestones of Florida and Georgia give rise to many large springs, including some of the largest in the United States. In Mississippi the Oligocene is represented by the Vicksburg group, which is calcareous and clayey and yields little water, and by the Catahoula sandstone. In Louisiana and eastern Texas, as shown in the section on page 257, it is represented by the Catahoula sandstone, which is a good aquifer.

The Miocene series is represented throughout most of the Atlantic Coastal Plain (fig. 92). From Delaware to North Carolina it con-

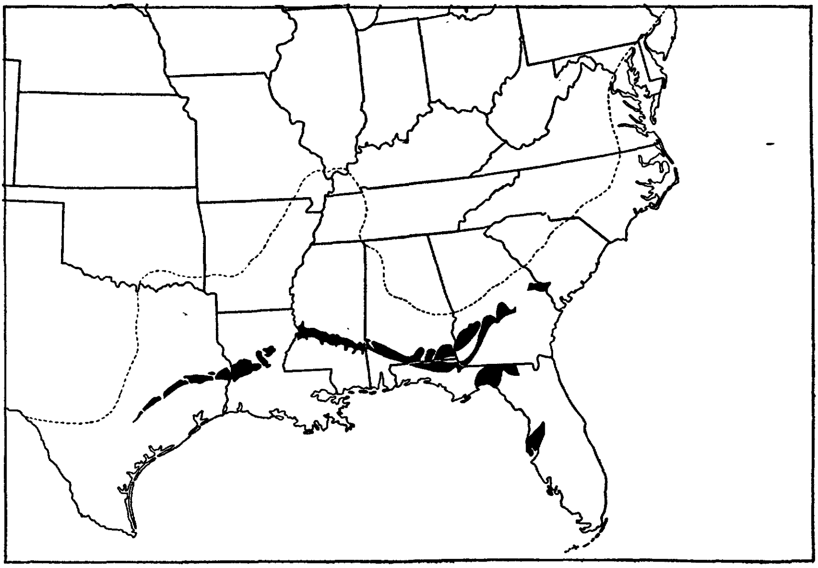


FIGURE 91.—Map of the Atlantic Coastal Plain showing areas in which beds of the Oligocene series are at or near the surface. The Oligocene includes the Catahoula sandstone, which is a good aquifer in Texas and Louisiana, and the Chattahoochee formation and Vicksburg group, which yield water chiefly in Georgia, Florida, and South Carolina. The boundary of the Coastal Plain is shown by the broken line.

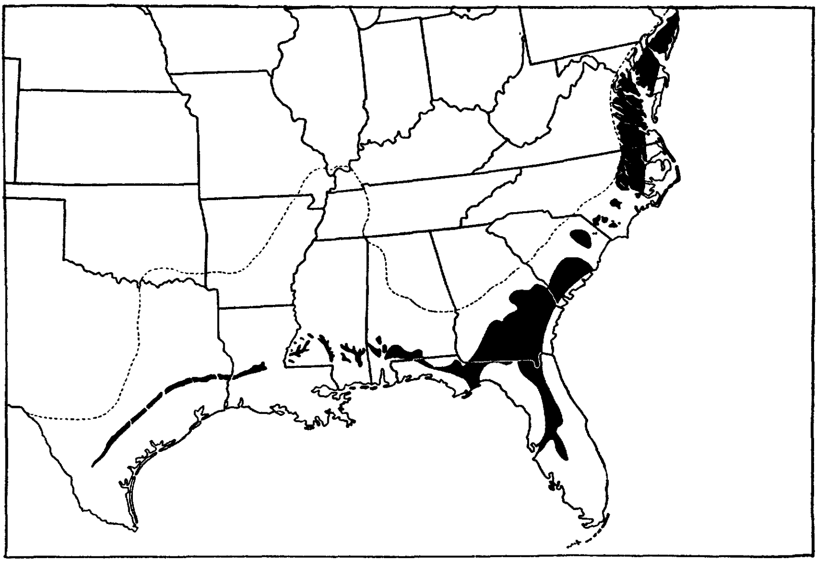


FIGURE 92.—Map of the Atlantic Coastal Plain showing areas in which beds of the Miocene series are at or near the surface. Yields water from sandstone aquifers at several horizons from New Jersey to North Carolina and from the Oakville sandstone in Texas. The boundary of the Coastal Plain is shown by the broken line.

sists of the Chesapeake group, which contains several beds of water-bearing sand. (See section, p. 253.) In New Jersey the overlying Cohansey sand is an important aquifer. West of Brazos River in Texas the Oakville sandstone, which has a maximum thickness of at least 600 feet, yields abundant supplies of potable water to flowing and nonflowing wells.

The Pliocene formations of the Atlantic Coastal Plain apparently comprise deposits of two very different kinds—marine deposits and high-level terrace deposits. The marine deposits are similar to the Miocene beds, on which they rest in regular succession. They are

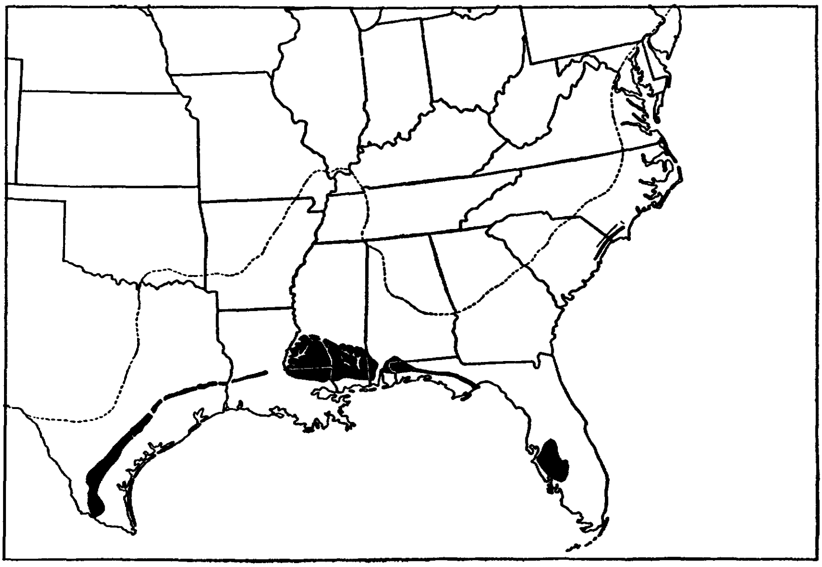


FIGURE 93.—Map of the Atlantic Coastal Plain showing areas in which Pliocene marine beds are at or near the surface. These beds are relatively thin and not very important as sources of water. The Pliocene terrace deposits are found farther inland, in the Atlantic Coastal Plain, as erosion remnants at high levels. Locally they supply many shallow wells. The boundary of the Coastal Plain is shown by the broken line.

the uppermost of the succession of Coastal Plain sedimentary formations thus far considered and are exposed nearest to the present seashore (fig. 93). The terrace deposits are younger and lie farther inland, at higher levels, unconformably on the eroded surfaces of the older formations of the Coastal Plain, like the Pleistocene deposits described on pages 306–307. Both the marine deposits and the terrace deposits are relatively thin and unimportant as sources of water, although they furnish some water in many places. In eastern Texas, however, the Dewitt formation, which is now regarded as Pliocene, attains a great thickness and yields much water.

SEDIMENTARY FORMATIONS OF THE GREAT PLAINS, ROCKY MOUNTAIN REGION, AND COLORADO PLATEAUS.

The great deformation, uplift, and volcanic activity that affected the western part of the United States about the end of the Mesozoic era and has continued or recurred at intervals to the present time produced highlands in association with tracts that were relatively low. The highlands were rapidly eroded by the streams, and the lowlands received great deposits of rock waste washed down from them. Most of these deposits were laid down by the streams themselves and have the usual characteristics of alluvial material—irregular bedding and imperfect assortment but with abundant lenses and stringers of porous gravel. In part, however, the material consists of beds laid down in lakes, swamps, or playas or by the wind. As there were successive epochs of disturbance there are several more or less distinct series of these deposits ranging in age from late Cretaceous or early Eocene to the present. As the major disturbances of the successive epochs occurred in different parts of the West the predominant deposits of different regions are not of the same age.

The oldest Tertiary deposits are found mainly in the northern and central parts of the Great Plains (western North Dakota, western South Dakota, eastern Montana, eastern Wyoming, and parts of Colorado near the mountains), in the Rocky Mountain region (Wyoming and parts of Montana, Colorado, and Utah), and in the Colorado Plateaus (western Colorado, eastern Utah, and northwestern New Mexico). (See fig. 89.) The youngest Tertiary deposits are found mainly in the central and southern parts of the Great Plains (western and central Nebraska, adjacent parts of South Dakota and Wyoming, western and central Kansas, eastern Colorado, western Oklahoma, northwestern Texas, and eastern New Mexico). (See fig. 89.) The bulk of the Quaternary deposits are farther west, in the Basin and Range province. (See pp. 291–303 and fig. 100, p. 293.)

In eastern and central Montana the impervious Pierre shale is overlain by the Lance formation, which is of late Cretaceous or early Tertiary age; and the Lance is overlain by the Fort Union formation, which is early Tertiary. The Lance is in most places several hundred feet thick and consists of somber clay, lenticular beds of sandstone, and a little coal, with locally a basal sandstone known as the Colgate sandstone member. The Fort Union formation, 2,000 feet or more in maximum thickness, consists of an irregular complex of beds similar to those of the Lance. The Lance and the Fort Union are both irregular in their water-bearing properties, but generally yield moderate supplies of fairly good water.[30] A sharp

[30] For description of water in the Fort Union and Lance formations and in the underlying Cretaceous formations in eastern and central Montana see Ellis, A. J., and Meinzer, O. E., Ground water in Musselshell and Golden Valley counties, Mont.: U. S. Geol. Survey Water-Supply Paper 518 (in press).

contrast therefore exists between the areas underlain by the Lance or Fort Union, where domestic and stock supplies are generally obtainable, and the adjacent areas, where the Pierre shale is at the surface and satisfactory water supplies are hard to get. All these formations extend into North Dakota, South Dakota, and Wyoming, where similar contrasts exist as to water supply. In different parts of the Great Plains, the Rocky Mountain region, and the Colorado Plateaus the latest Cretaceous and early Tertiary beds differ in thickness and succession of strata and in the names applied to them, but in general they form thick irregular formations that contain considerable water-bearing material. Good examples are given in the section for southwestern Wyoming and for the Navajo country of northeastern Arizona and northwestern New Mexico. (See pp. 262–263.)

The Great Plains are largely underlain by gravelly, sandy, and clayey materials that were spread smoothly over them in the later part of the Tertiary period by streams from the Rocky Mountains. These alluvial deposits, nowhere more than a few hundred feet thick, are in most areas porous enough to furnish at least some water, and they contain abundant irregularly distributed lenses and stringers of gravel and sand that yield large quantities of good water to many wells. They constitute one of the most valuable aquifers in the United States, ranking among the first in quantity of water, quality of water, number of wells supplied, and extent of productive area. The water supply of these beds is one of the most attractive features and one of the leading assets of the great semiarid region which they underlie. They give rise to only a few flowing wells, but the pumping lifts are generally not great.

In southwestern Nebraska, eastern Colorado, western Kansas, western Oklahoma, northwestern Texas, and eastern New Mexico these beds, called the Ogalalla formation, rest on Cretaceous or older formations. In northwestern Nebraska and adjacent parts of Wyoming and South Dakota they are underlain by older Tertiary formations—the Arikaree, Gering, Brule, and Chadron, as shown in the section on pages 258–259. Towad the north the Ogalalla formation disappears and the underlying formations successively come to the surface. The Arikaree formation, which is of Miocene age, consists largely of sandstone and is a fairly satisfactory aquifer. The Brule clay and the Chadron formation constitute the White River group, of Oligocene age, which forms the principal badlands of South Dakota. They supply some wells but are in general unsatisfactory as to both quantity and quality of water.

In some upland localities in northeastern Montana north of Missouri and Milk rivers water is obtained from shallow wells that end in the Flaxville gravel—a deposit of probable upper Miocene age, about 100 feet in maximum thickness, which rests unconformably on older formations.[31] Water is also obtained in other parts of Montana from terrace gravels, some of which are probably Miocene.

SEDIMENTARY FORMATIONS OF THE BASIN AND RANGE PROVINCE, COLUMBIA PLATEAUS, AND PACIFIC COAST REGION.

Farther west, in the Basin and Range province, the Columbia Plateaus, and the Pacific coast region, there are many Tertiary sedimentary formations of diverse character, all of which can not be separately mentioned here. They yield water in many places but are of minor importance in comparison with the Quaternary alluvial deposits, which are the great water bearers of the Basin and Range province and the Pacific coast region, and also in comparison with the Tertiary lavas of the Columbia Plateaus.

In Nevada Tertiary sedimentary formations underlie many of the desert basins in somewhat synclinal structure and are exposed along the borders of the basins, in some places greatly deformed. They have an aggregate thickness of several thousand feet and consist largely of lake deposits of soft shale, fine-grained sandstone, marl, and tuff. In general they are too dense to be promising as sources of water, and they have thus far been of little consequence in the water supply of the State.

In California and the coast region of Oregon and Washington Tertiary sedimentary beds attain an aggregate thickness of many thousand feet. They were laid down in part in the sea and in part in lakes or on land. They include much shale, sandstone, and tuff. Much of the sandstone is compact and of fine grain, but some is coarse and well assorted.

The Tejon formation, more than 4,000 feet thick, the Monterey group of formations, more than 5,000 feet thick, and the Ione formation are important Tertiary formations of California, but they have no great value as sources of water. In the vicinity of Puget Sound there are Tertiary beds, called the Puget group, aggregating many thousand feet in thickness. They consist largely of sandstone but include conglomerate, shale, and thick beds of coal. They would doubtless yield water, but as they are overlain by thick deposits of water-bearing glacial drift and as the region receives a heavy rainfall their supply is not much needed.

In central and eastern Oregon, western and south-central Idaho and central Washington there are thick Tertiary formations, including lake beds and alluvial and wind-blown deposits. They are

[31] Collier, A. J., and Thom, W. T., jr., The Flaxville gravel and its relation to other terrace gravels of the northern Great Plains: U. S. Geol. Survey Prof. Paper 108, pp. 179-184, 1918. Collier, A. J., Geology of northeastern Montana: U. S. Geol. Survey Prof. Paper 120, pp. 17-39, 1919.

intimately related to the Tertiary lavas of the region and contain much volcanic débris. They include many porous beds and on the whole have considerable promise as producers of water. In many localities they give rise to flowing artesian wells and in some of these localities the artesian water is hot. The following two generalized columnar sections for central Washington give an idea of the prominence of the Tertiary formations in this region, their relations to the volcanic rocks, and the large proportions of sand and gravel that they include. The Ellensburg formation is a recognized artesian aquifer.

Generalized columnar sections of the sedimentary and volcanic rocks in central Washington.[a]

Mount Stuart quadrangle, northern part.

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.
Tertiary.	Pliocene: Rhyolite.		800	Compact lava and tuff, with scattered crystals of quartz; weathers white and rusty yellow.
	Eocene.	Roslyn formation.	+3,500	Massive yellow sandstone, with clay and bony shale. Roslyn seam of coal in upper portion of formation, with other less valuable seams.
		Teanaway basalt.	4,000	Lava flows with interbedded tuffs. Lava black and dark gray, compact or vesicular, in some places weathering brown or red.
		Swauk formation.	5,000	Well-stratified conglomerate, arkose and quartzose sandstone, and shale, light and dark gray. In eastern part of area sandstone more purely quartzose and white and yellow. Cut by numerous dikes of diabase.
Pre-Tertiary.				

Mount Stuart quadrangle, southern part.

System.	Subdivision.		Maximum thickness (feet).	Lithologic character.
Tertiary.	Miocene.	Ellensburg formation.	1,500	Light-colored sandstone, shale, and conglomerate, usually very friable, with many pumice fragments and pebbles, and exhibiting stream bedding.
		Yakima basalt.	2,000	Black lava, weathering gray or brown, compact or scoriaceous, with typical columnar partings common. Tuffs present but not important.
		Taneum andesite.	300	Loose-textured lava, with tuff and tuff-breccia, pink, green, gray, and brown.
	Eocene: Manatash formation.		+1,000	Massive light-colored sandstone and pebbly conglomerate, with shale and seams of bone.
Pre-Tertiary.	Easton schist.			

[a] Smith, G. O., U. S. Geol. Survey Geol. Atlas, Mount Stuart folio (No. 106), 1904.

VOLCANIC ROCKS.

The Tertiary period was characterized throughout the western part of the country not only by great deformation but also by the pouring out of enormous floods of lava (fig. 94) that spread over

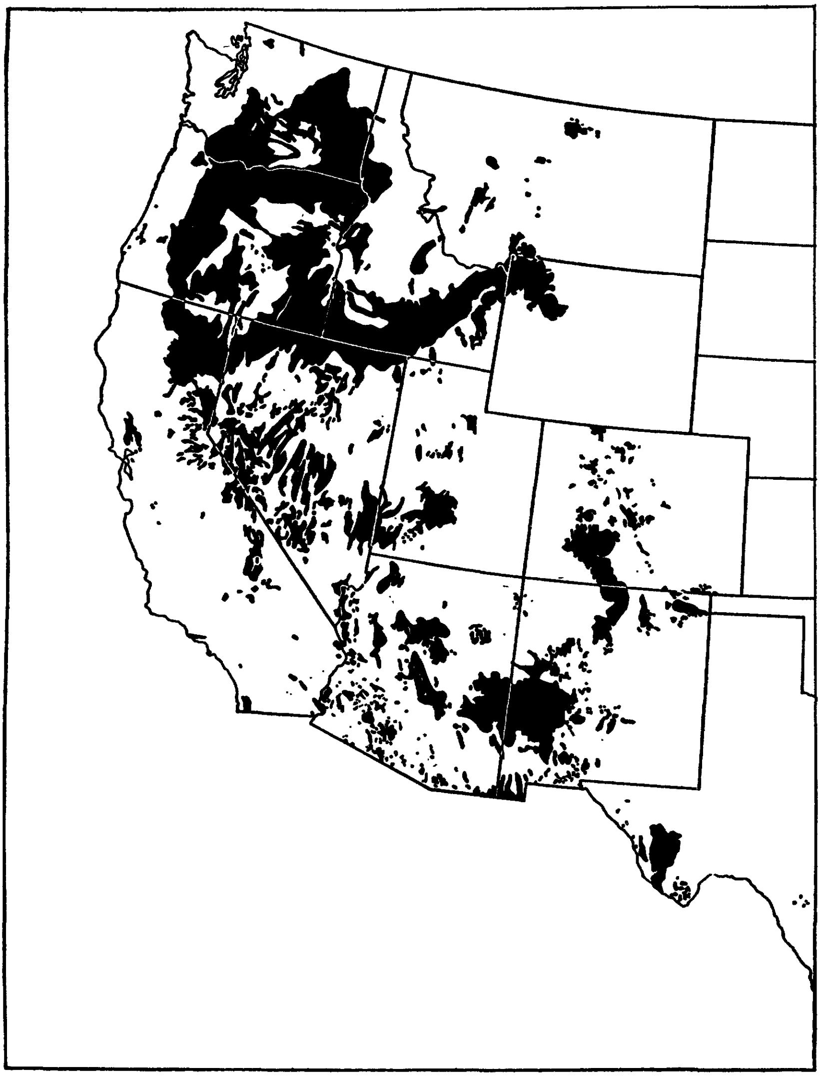


FIGURE 94.—Map of the western part of the United States showing areas in which Tertiary or Quaternary volcanic rocks are at or near the surface. The extensive lava beds, especially in Idaho, Washington, and Oregon, consist chiefly of basalt; they yield abundant supplies to many drilled wells and give rise to numerous springs, some of which are very large. No Tertiary or Quaternary volcanic rocks are exposed in the eastern part of the United States.

large areas and produced expanded sheets like the stratified sedimentary formations. Basalt lies at the surface over vast areas, including large parts of Idaho, Washington, and Oregon and considerable parts of the other Western States. Nearly all of the Columbia Plateaus, more than 200,000 square miles in extent, is underlain by volcanic rock, chiefly basalt. Over much of the region this rock ranges from a few hundred to several thousand feet in thickness and consists of numerous beds laid down one upon another with intervening scoria and volcanic fragments.

On the whole the basalt yields water freely from its joints and other large openings and from the porous zones between successive beds. It ranks as one of the important aquifers of the United States. It supplies numerous wells but is especially notable for the many large perennial springs to which it gives rise; the great springs of the Snake River valley are the best examples (pp. 138–141). Obsidian and jointed rhyolites also yield freely; they give rise to the Big Springs, in Idaho (pp. 142–143). Many of the rhyolites and other volcanic rocks of persilicic or mediosilicic composition do not, however, yield much water (pp. 141–142). The beds of volcanic rock are in most places horizontal or gently warped. Where they are warped into synclines they may form artesian basins. The water from volcanic rocks is usually of good quality.

QUATERNARY SYSTEM.

GENERAL CONDITIONS.

The Quaternary is by far the most important system in the United States with respect to water supply. Indeed, it would probably not be an exaggeration to say that it is as important as all other systems taken together. It lies at the surface throughout the largest area, supplies the most wells, and affords the greatest quantities of water.

The Quaternary deposits in the United States are for the most part included in three groups—glacial drift (fig. 95), the valley fill of the West (fig. 100), and the deposits of the Atlantic Coastal Plain (fig. 109). Both glacial drift and valley fill are of especial importance as sources of water, the drift being the principal source of ground water in the northern part of the country and the fill being the principal source in the western part. Some of the water-bearing basalts are also of Quaternary age, particularly in Idaho, where they have recently been studied by H. T. Stearns, of the United States Geological Survey.

The Quaternary period has been divided into two epochs—the Pleistocene or glacial epoch and the Recent or postglacial epoch. Most of the water-bearing deposits of Quaternary age are sand and gravel beds laid down during the Pleistocene epoch.

GLACIAL DRIFT.[32]

The glacial drift consists chiefly of till, or boulder clay, deposited directly by the glaciers or great continental ice sheets; alluvium deposited by streams issuing from the ice; stratified beds laid down in glacial lakes; and loess and dune sand, consisting largely of glacial materials picked up and redeposited by the wind. (See pp. 117–129.)

The bulk of the material is till. As it is unassorted, it has low porosity and does not yield water freely. It varies greatly, however, in its water-yielding capacity according as it is composed predominantly of coarse or fine material. It supplies a large number of shallow dug wells throughout the drift-covered area, as shown in figure 95. The yield of these wells is generally small but commonly adequate for domestic use. The water of many of the wells is polluted by household and barnyard wastes and by near-by privies.

The gravelly and sandy deposits made by the streams that issued from the ice are the great water bearers of the glacial drift. They yield copious supplies to many drilled and driven wells and are largely drawn upon for public, industrial, and live-stock uses, for which the yields from the till are inadequate. These alluvial deposits consist largely of gravel but also include much sand. They occur in abundant irregular lenses and stringers of gravel and sand

---

[32] The following publications (of the U. S. Geol. Survey, except as indicated) give information regarding water in the glacial drift of the United States:

Arkansas, Water-Supply Paper 145; Geol. Folio 140

Connecticut, Water-Supply Papers 114, 232, 374, 397, 449, 466, 470.

Eastern United States, Water-Supply Paper 114.

Illinois, Water-Supply Paper 114; Seventeenth Ann. Rept., pt. 2; Monograph 38; Geol. Folios 67, 105, 185, 188, 195, 208; Illinois Geol. Survey Bull. 5 (cooperative report).

Indiana, Water-Supply Papers 21, 26, 113, 114, 254; Eighteenth Ann. Rept., pt. 4; Geol. Folios 67, 105.

Iowa, Water-Supply Papers 114, 293.

Kansas, Water-Supply Paper 273; Geol. Folio 206.

Maine, Water-Supply Papers 145, 223; Geol. Folio 149.

Massachusetts, Water-Supply Papers 114, 145.

Michigan, Water-Supply Papers 30, 31, 114, 182, 183; Geol. Folios 155, 206.

Minnesota, Water-Supply Papers 114, 256; Monograph 25; Geol. Folios 117, 201, 210.

Missouri, Water-Supply Paper 195; Geol. Folio 206.

Montana, Water-Supply Papers 221, 400.

Nebraska, Water-Supply Paper 12; Geol. Folio 156.

New Jersey, Geol. Folios 157, 161.

New York, Water-Supply Papers 110, 114, 145; Geol. Folios 157, 169, 190.

North Dakota, Seventeenth Ann. Rept, pt. 2; Monograph 25; Geol. Folios 117, 168.

Ohio, Water-Supply Papers 114, 259; Eighteenth Ann. Rept., pt. 4, Nineteenth Ann. Rept., pt. 4; Geol. Folio 197.

Pennsylvania, Water-Supply Paper 114.

Rhode Island, Water-Supply Paper 114.

South Dakota, Water-Supply Papers 34, 90, 227; Seventeenth Ann. Rept., pt. 2; Geol. Folios 96, 97, 99, 100, 113, 114, 156, 165.

Washington, Water-Supply Paper 425.

Wisconsin, Water-Supply Paper 114; Wisconsin Geol. and Nat. Hist. Survey Bull. 35 (coöperative report).

intimately intermingled with the till; in outwash aprons that extend out from the moraines, where the edges of the ice sheets once stood

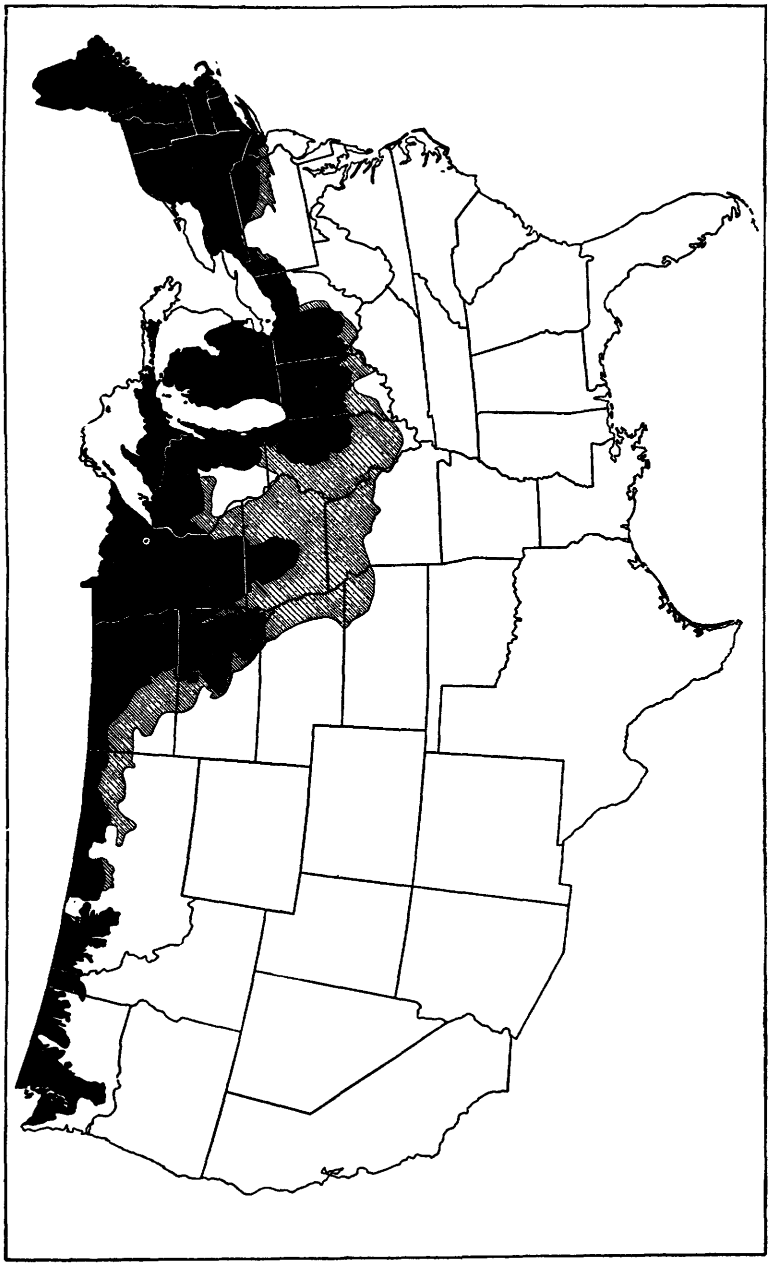


FIGURE 95.—Map of the United States showing principal areas underlain by glacial drift. (After unpublished map compiled by W. C. Alden.) Black indicates the Wisconsin or latest drift sheets; light shading indicates older drift. Many small patches covered by drift of local glaciers in the western mountains are not shown on this map. Outwash deposits and deposits of loess beyond the drift sheets are not shown. The glacial drift is the most important source of water supply in the northern part of the United States.

pouring out great débris-laden floods; and in valley trains, consisting of glacial débris deposited for many miles along the streams that headed in the ice sheets.

The irregular lenses and stringers intermingled with the till in many places consist of imperfectly assorted gravel or sand, and, as a rule, they are not very thick or continuous. One or more of these water-bearing beds is, however, commonly encountered by drilled wells, and they generally yield reliable and rather large supplies under good pressure and protected from pollution to some extent by overlying drift. They furnish water to many successful wells throughout the glaciated area, especially from Ohio to the Dakotas, for livestock and general farm supplies, for industrial supplies, and for public supplies of villages and small cities.

The outwash aprons and valley trains are generally large deposits of coarse and well-assorted gravel or sand that yield water very freely and in large quantities. They occur abundantly in the glaciated area and for many miles along nearly all the streams that rise in that area. Plate XXIX and figure 96 give a good idea of the distribution of these deposits in relation to the drift sheets.

Glacial outwash deposits are the chief water bearers of New England. Until the Catskill system of the New York City waterworks was completed virtually the entire supply for Brooklyn was drawn from the extensive outwash apron on the south side of the terminal moraine on Long Island. (See fig. 97 and p. 117.) The outwash deposits are also extensively developed in the drainage basin of Mississippi River from Pennsylvania to the Dakotas and in the drainage basin of Columbia River in Montana, Idaho, and Washington. Throughout the Mississippi basin they furnish large supplies of good water to many cities, villages, and industrial plants.

Extensive stratified deposits were laid down in a number of large lakes that were produced by ice dams in the Pleistocene epoch, and smaller deposits in lakes and ponds produced by irregularities in the surfaces of the till sheets. Some of the largest deposits of this sort were made in a series of ancient lakes in the drainage basin of the Great Lakes, in the ancient Lake Agassiz, which occupied the drainage basin of the Red River of the North, and in the ancient Lake Missoula, which lay in the Clark Fork drainage basin. The lake deposits consist largely of stratified clay, which, however, in many places overlies or embraces beds of sand or gravel containing artesian water.

Loess is found chiefly in the drainage basin of the Mississippi, west of Indiana. It occurs in and adjacent to the areas covered by the older drift sheets in Illinois, western Wisconsin, southeastern Minnesota, Iowa, Missouri, Nebraska, and Kansas. It also extends far west of the drift on the Great Plains in Kansas and Nebraska and borders the Mississippi southward nearly to the Gulf of Mexico. It is thickest on the uplands bordering the streams that lead from the drift sheets. It yields small supplies to some wells, but on the whole it is very unimportant as a source of water. (See pp. 122–123.)

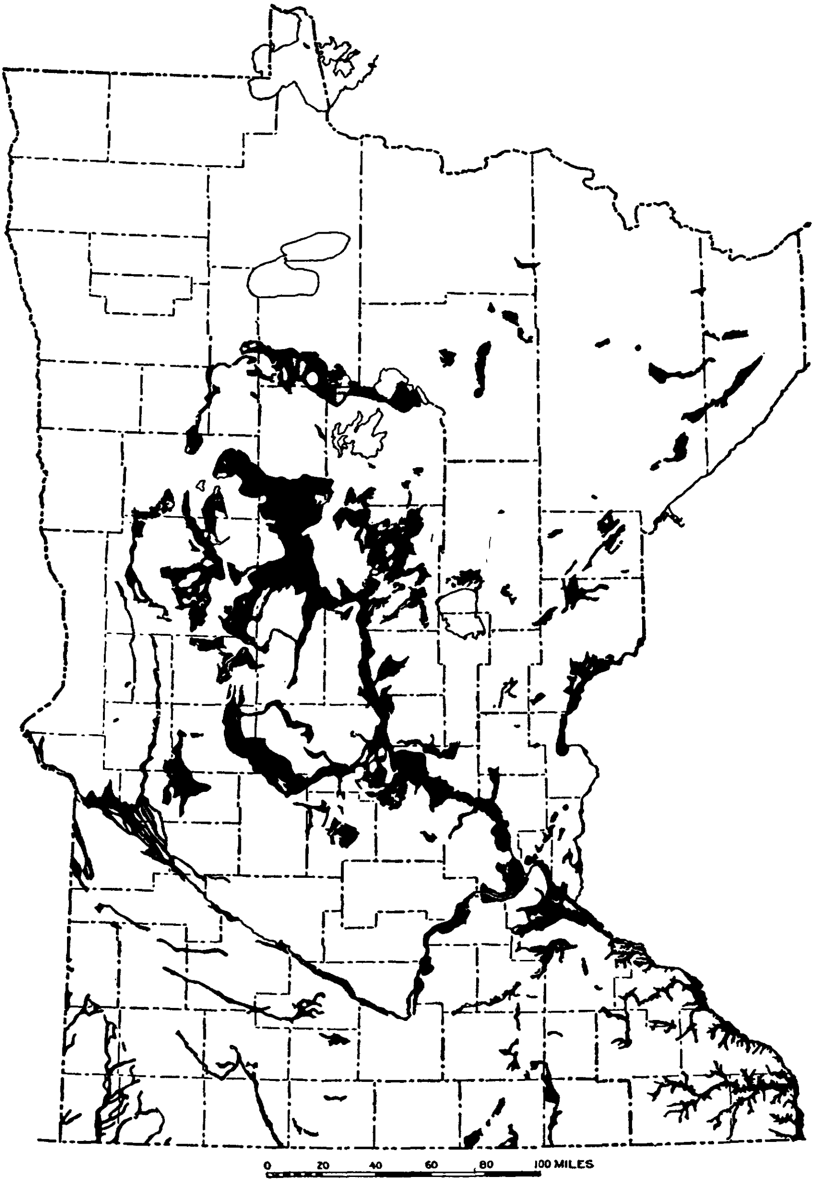


FIGURE 96.—Map of Minnesota showing glacial outwash gravel in plains or aprons. In most places this gravel yields water freely. (Compiled from maps by Frank Leverett and F. W. Sardeson, Minnesota Geol. Survey Bulls. 12, 13, and 14.)

Figure 95 shows approximately the southern limit of the glacial drift in the United States, except for the valley trains and the drift of many relatively small glaciers that existed in the mountains of the West during the Pleistocene epoch. It will be seen that the glacial drift covers a large part of the most productive and best-developed agricultural and industrial section of the country. Hence, its ample water supplies are extensively utilized and very valuable. Some idea of the thickness of the drift may be gained from the map of southern Minnesota (fig. 98).

The glacial drift is not all of the same age but consists of at least five sheets of different ages, superimposed upon one another like the successive formations of older rocks. Between the successive drift

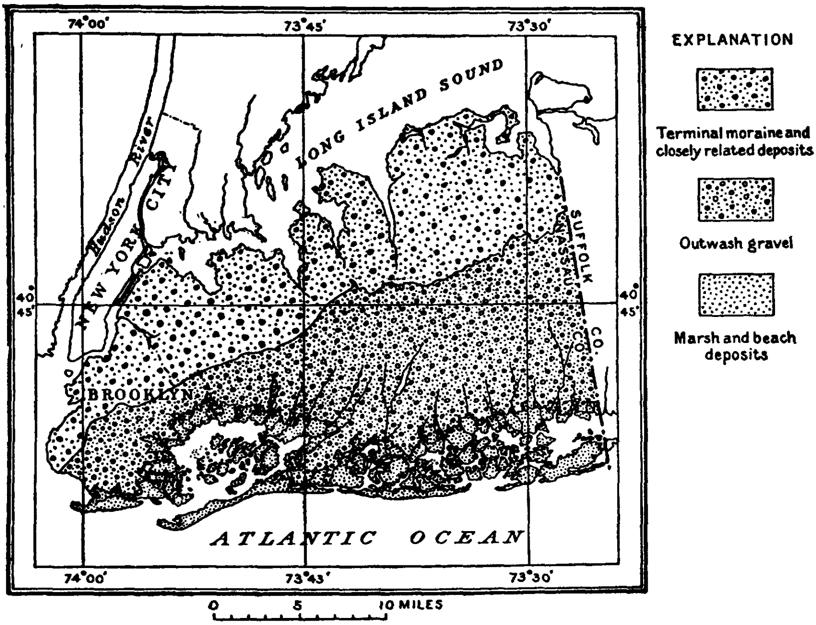


FIGURE 97.—*Map of Nassau County, Long Island, N. Y., showing water-bearing outwash gravel and its relation to the terminal moraine.* (After M. L. Fuller.)

sheets are old soils and various stream and wind deposits. The most important of these deposits with respect to water supplies are beds of gravel laid down by the streams from the melting ice as the ice front retreated or by the streams from the advancing ice which later deposited the drift sheet that covers the gravel. Thus, the base of the lowest drift and the horizons between successive drift sheets are in many places the most productive water horizons.

These different drift sheets are best exposed and best known in Iowa, Illinois, and adjacent States. The Wisconsin drift, which is the youngest, lies at the surface throughout the largest area (fig. 95); the Iowan drift is an exceptionally thin sheet in northeastern Iowa; the Illinoian and Kansan are thick deposits and also widely exposed.

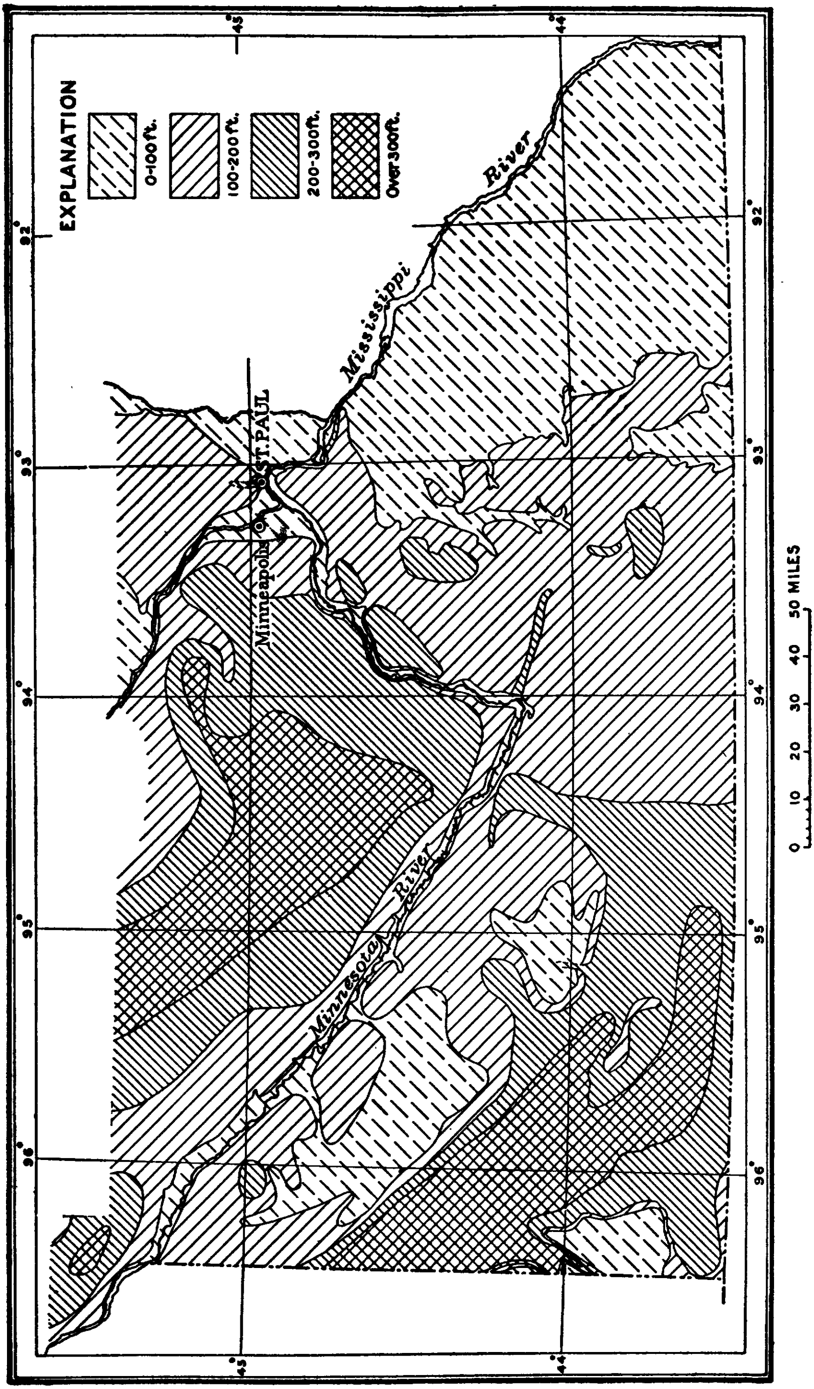


FIGURE 98.—Map of southern Minnesota showing thickness of glacial drift. (From U. S. Geol. Survey Water-Supply Paper 256, pl. 2.)

The Nebraskan is a thick sheet but is apparently exposed only in small areas where the overlying Kansan has been removed by erosion. The Montauk till occurs principally on Long Island. The Jerseyan drift sparsely covers parts of New Jersey and Pennsylvania. The Montauk till and the Jerseyan drift probably correspond in age to the Illinoian and Nebraskan, respectively.

The succession, lithologic character, and water-bearing properties of the various drift sheets and of the intervening deposits are outlined in the following generalized section for Iowa, in which all the five drift sheets of the Mississippi Valley region are found. The distribution of the drift sheets in Iowa is shown in figure 99. The most important difference with respect to water supplies is between the Wisconsin drift and the older drift sheets, or rather between the areas underlain by Wisconsin drift and those underlain only by older drift. The Wisconsin drift was deposited so recently that it is as yet very little eroded, and hence the areas in which it is found are generally poorly drained and have ground water very near the surface; the areas underlain only by older drift have been more extensively eroded and drained since their last glaciation, and hence they are less favorable for obtaining shallow water. The till is so difficultly permeable that it is likely to remain saturated with water nearly to the surface even where it is dissected by deep valleys, but the more permeable gravel beds are likely to be drained where they occur at much higher levels than the streams. The Wisconsin drift is commonly underlain by one or more of the older drift sheets, and much of the water drawn from the glacial drift in the Wisconsin drift area comes from one of the older sheets or from intervening or basal gravel beds.

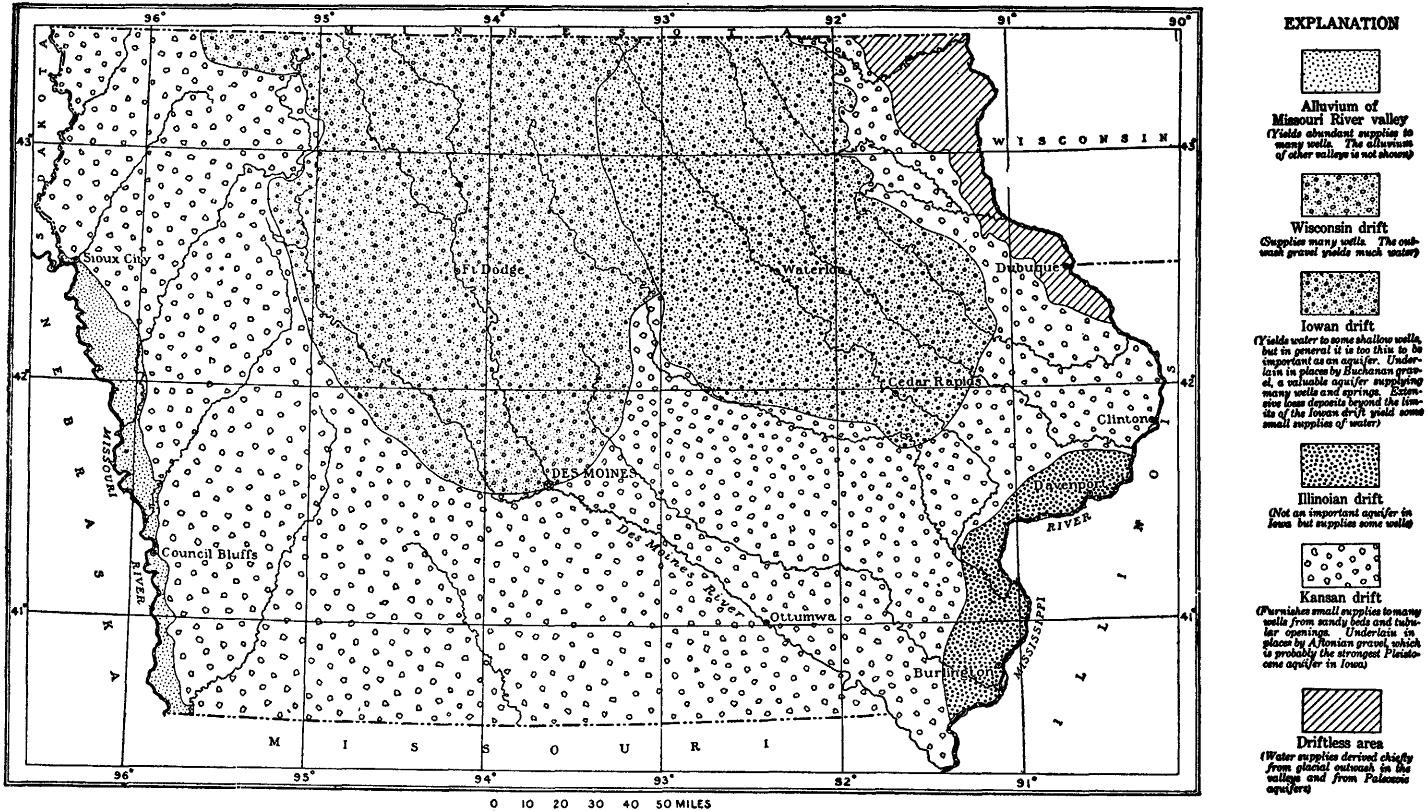


FIGURE 99.—Map of Iowa showing glacial drift sheets. (After Samuel Calvin.)

Generalized columnar section of the Quaternary deposits in Iowa.[a]

Subdivision.		Lithologic character.	Water supply.
Recent series.		Chiefly alluvium. Most of the alluvium is doubtless of glacial origin.	Not important.
Pleistocene series.	Wisconsin drift.	Unweathered calcareous till with sandy and gravelly beds and large amounts of outwash sand and gravel.	Supplies many wells. The outwash gravels yield much water.
	Peorian deposits (loess).	Old soil; much loess.	Yields some small supplies from loess.
	Iowan drift.	A thin sheet of light-yellow clayey till, with numerous large granite boulders.	Yields some small supplies from sandy layers and from small crevices.
	Sangamon deposits.	Soil and vegetal deposits.	Unimportant.
	Illinoian drift.	Clayey till, not quite so dense as the Kansan.	Resembles the Kansan drift in water-bearing properties. Supplies some wells.
	Yarmouth deposits (including Buchanan gravel).	The Buchanan gravel consists of extensive irregular gravel deposits between the Kansan and Iowan drifts.	Very valuable aquifer, supplying many springs and wells.
	Kansan drift.	Tough, hard clayey till, with some sandy beds, especially in upper part.	Because of its extensive occurrence at the surface, this drift probably supplies more wells than any other aquifer in the State. However, the supply is generally small and somewhat uncertain. The water occurs in sandy beds and tubular openings.
Aftonian gravel.		Irregular beds of gravel; also old soil and muck.	Probably the strongest Pleistocene aquifer in the State. Supplies many wells and springs.
Nebraskan drift.		Dark plastic till with old soil and beds containing much wood; sand and gravel chiefly underlying till.	Till yields but little water, often having offensive odor; sand and gravel layers yield large supplies, generally under artesian pressure.

[a] Norton, W. H., and others, Underground water resources of Iowa: U. S. Geol. Survey Water-Supply Paper 293, 1912; and other sources. Based chiefly on the work of Samuel Calvin.

VALLEY FILL OF THE WEST.[33]

In the western part of the United States the broad basins or valleys that lie between the mountain ranges generally contain great deposits of rock waste that has been washed down from the mountains. These deposits are commonly called valley fill. The deposits that can be seen at the surface or in dug wells generally lie in their

[33] The following publications (of the U. S. Geol. Survey, except as indicated) give information relating to water in the fill of the mountain valleys of the western part of the United States:

Arizona, Water-Supply Papers 104, 136, 320, 375, 380, 425, 450; Bulletin 352; Geol. Folios 111, 112, Arizona Agr. Exper. Sta. Bull. 64.

California, Water-Supply Papers 89, 137, 138, 139, 142, 219, 222, 225, 278, 294, 345, 375, 398, 400, 429; 446, 450, 468, 495; Geol. Folios 163, 193; California Conservation Comm. Rept. for 1912, pp. 335–429 (cooperative report).

Colorado, Water-Supply Paper 240.

(Footnote continued on page 292.)

original positions or are only slightly deformed and are for the most part of Quaternary age. In most places, however, the valley fill has not been deeply eroded, so that the lower beds are generally concealed and there is much uncertainty as to their structure and age. In part they are of Tertiary age and have been deformed and eroded before the upper beds were deposited. If the entire valley fill were exposed in outcrops its stratigraphy and structure would doubtless prove to be much more complicated than is suggested by well records and by the shallow exposures found in most localities. In much of the southern part of Big Smoky Valley, Nev., the undeformed Quaternary fill is known to be underlain at slight depths by poorly consolidated sandy and clayey beds of Tertiary age. In some parts of the valley the Tertiary beds seem to be about in their original position; in other parts they are greatly deformed and are separated from the Quaternary by a pronounced unconformity.[34] In the San Pedro Valley, Ariz., Bryan[35] has found that the bulk of the so-called valley fill consists of somewhat deformed beds that are shown by abundant fossil evidence to be of Pliocene age. In this valley the Quaternary formations, which rest unconformably on the Pliocene and older rocks, are probably not much over 100 feet thick.

All the deposits that have been laid down since the intermontane troughs came into existence in about their present form can properly be regarded as valley fill, regardless of whether they are Quaternary or older. But whether specific beds are included which are known to be considerably deformed or whose structure is uncertain must rest on a somewhat arbitrary decision. The undeformed Quaternary fill is doubtless a few hundred feet thick in many places, and fill of undetermined age has in many localities been penetrated to depths of more than 1,000 feet. In many valleys, however, the upper parts of the smooth valley slopes have been formed by the erosion of the bedrocks and have only a thin mantle of detrital material.[36]

The valley fill underlies perhaps one-half of the entire Basin and Range Province, which includes nearly all of Nevada and large parts

(Footnote continued from page 291.)

Idaho, Water-Supply Paper 78.

Montana, Water-Supply Papers 345, 400.

Nevada, Water-Supply Papers 365, 375, 423, 425, 450, 467; Bulletin 530.

New Mexico, Water-Supply Papers 123, 158, 188, 260, 275, 343, 345, 422, 425; Bulletin 618; Geol. Folios 199, 207.

Oregon, Water-Supply Papers 78, 220, 231; Bulletin 252.

Texas, Water-Supply Paper 343; Geol. Folios 166, 194; Texas Univ. Mineral Survey Bull. 9 (cooperative report).

Utah, Water-Supply Papers 157, 199, 217, 277, 333.

[34] Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring valleys: Nev.: U. S. Geol. Survey Water-Supply Paper 423, pp. 53–58, 1917.

[35] Bryan, Kirk, unpublished data.

[36] Bryan, Kirk, Erosion and sedimentation in the Papago country, Ariz., with a sketch of the geology: U. S. Geol Survey Bull. 730, pp. 52–65, 1923. Paige, Sidney, Rock-cut surfaces in the desert ranges: Jour. Geology, vol. 20, pp. 442–450, 1912.

of southern Idaho, southern Oregon, western Utah, eastern California, southern Arizona, central and southwestern New Mexico, and trans-Pecos Texas (Pl. XXVIII, p. 196). It also underlies the Great Valley of California (Sacramento and San Joaquin valleys) and nearly all the

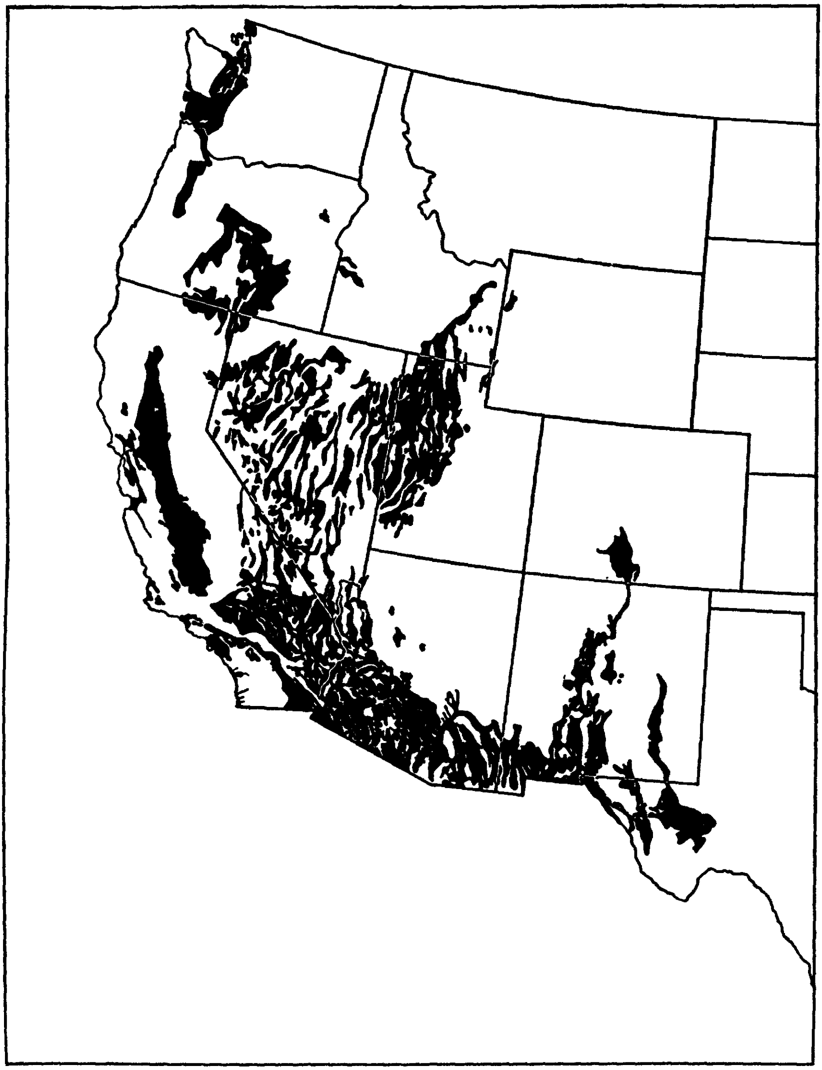


FIGURE 100.—Map of the western part of the United States showing principal areas underlain by Quaternary valley fill. This fill includes much gravel that yields water freely in large quantities. It is the most valuable aquifer in the West.

valleys in California nearer the coast, and many valleys in the Rocky Mountain region and in other parts of the West. Most of the areas underlain by valley fill are shown in figure 100.

The valley fill is the great water bearer of the arid part of the United States. Like the glacial drift, it is very irregular in distribution, thickness, and structure and in the yield, head, and quality of its water, but in most places it yields some water, and in many places it furnishes very large supplies of satisfactory quality. In many desert regions where surface streams are lacking the valley fill is practically the only source of water. It is heavily drawn upon for irrigation, especially in the valleys of California and Arizona—for example, in the valley of southern California, San Joaquin Valley, Sacramento Valley, Santa Clara Valley, and Salinas Valley, in California, and in the Gila River valley and Salt River valley, in Arizona. For this reason it doubtless ranks first among all the formations or groups of formations in the United States in the quantity of water delivered through wells.

The valley fill consists almost entirely of rock waste washed down from the mountains. It was deposited largely by streams or by sheet floods into which the streams expanded on the even lowlands. A small part of the rock waste, chiefly fine-grained material, was carried into lakes or playas that occupied the lowest areas of some of the depressions and was deposited as stratified lake beds or as playa clay. In some places lake deposits are interbedded with stream deposits. A small part of the material has been handled by the wind and has been redeposited as dune sand, or loesslike silt, or, in a few localities, chiefly in New Mexico, as gypsum sand or gypseous clay. The valley fill also contains considerable mineral matter deposited by water from solution, such as caliche, travertine, gypsum, and salt, and in some valleys it contains interbedded sheets of volcanic rock.

The stream deposits are of two general types—unassorted or imperfectly assorted materials consisting of a clayey matrix and embedded pebbles and boulders, and assorted materials, consisting chiefly of gravel and sand. (See pp. 117, 129–131.) The imperfectly assorted materials form the bulk of the valley fill. They are produced by rapidly fluctuating torrential streams and sheet floods. Where they are saturated they generally yield water slowly, and they are the source of supply for many dug wells that extend only a few feet below the water table. The assorted materials are the deposits in ancient beds of streams of more sustained flow. They consist largely of trains of gravel that radiate from the mouths of the canyons, where the mountain streams have throughout the Quaternary period discharged into the valleys. These gravel trains are incased in the clayey matrix of the poorly assorted fill. They are in a peculiarly favorable position to receive the water of the mountain streams and to transmit it to all parts of the valley fill. The gravel in an ancient stream bed of this character is coarsest near the mouth of the canyon from which the train heads and becomes increasingly fine grained as it extends beneath the valley. However, the beds formed by the larger streams may contain clean water-bearing gravel at points many miles from the canyon mouths. Excellent examples are afforded by the clean gravels with very large yields of water that were deposited by Salt River near Phoenix, Ariz.; by the streams that flow across the valley of southern California from the high mountains to the north and east; by the numerous streams that flow into the Great Valley of California from the well-watered Sierra Nevada; and by streams in many other valleys bordered by relatively well-watered mountains. Even in smaller drainage basins with more arid climate remarkably productive gravel trains are found, as, for example, in Steptoe Valley, Nev., where much water-bearing gravel was found in exploratory drilling by the United States Geological Survey.[37]

The sections of wells drilled into the stream deposits of valley fill consist chiefly of the poorly assorted materials which drillers commonly call clay and regard as non water-bearing. In most drilled wells, however, one or more beds of assorted gravel or sand are penetrated, and these are the recognized water-bearing beds. They occur at various levels, and the beds revealed by the sections of different wells at the same locality can often not be correlated. These conditions are well illustrated in figure 45 (p. 157).

Shore features and stratified deposits of extinct or nearly extinct lakes are found in the lowest parts of many of the closed drainage basins, the deposits being at or near the surface. These extinct lakes presumably existed in the times of cold humid climate, in the Pleistocene epoch, when the great continental ice sheets extended far south. The distribution of these lake beds in the Basin and Range province, in so far as they have been discovered, is shown in figure 101. The outlines of the lake beds shown in the map were determined chiefly from the ancient shore features. In some places lake beds are interstratified with alluvium, as illustrated in the artesian-well section shown in figure 102. The lake deposits, except in their marginal parts, are generally too fine grained to yield water freely, but they may form effective confining beds and give rise to artesian flows.

The playas are flats which at the present time occupy the lowest parts of most of the valleys that do not have drainage outlets and to some extent the lowest parts of valleys that have outlets. Underlying the flats is fine-grained material that has been deposited from thin, temporary sheets of roily water which is for the most part derived from heavy floods. Before this water reaches the flats its velocity is reduced so much that it loses all of its load except the fine material which it holds in suspension. The material deposited on the

[37] Clark, W. O., and Riddell, C. W., Exploratory drilling for water and use of ground water for irrigation in Steptoe Valley, Nev.: U. S. Geol. Survey Water-Supply Paper 467, pp. 50–58, 1920.

playas ranges from fine sand to dense clay and includes large amounts of silt. Near the surface it is generally more or less yellow or brown, but at greater depths it may have a bluish hue or may be quite black. The playa deposits are too dense to furnish much water, and such meager supplies as they may yield in some localities are likely to be too poor for use.

The dune sands are porous and permeable and will generally yield water freely. They are, however, not widely enough distributed to

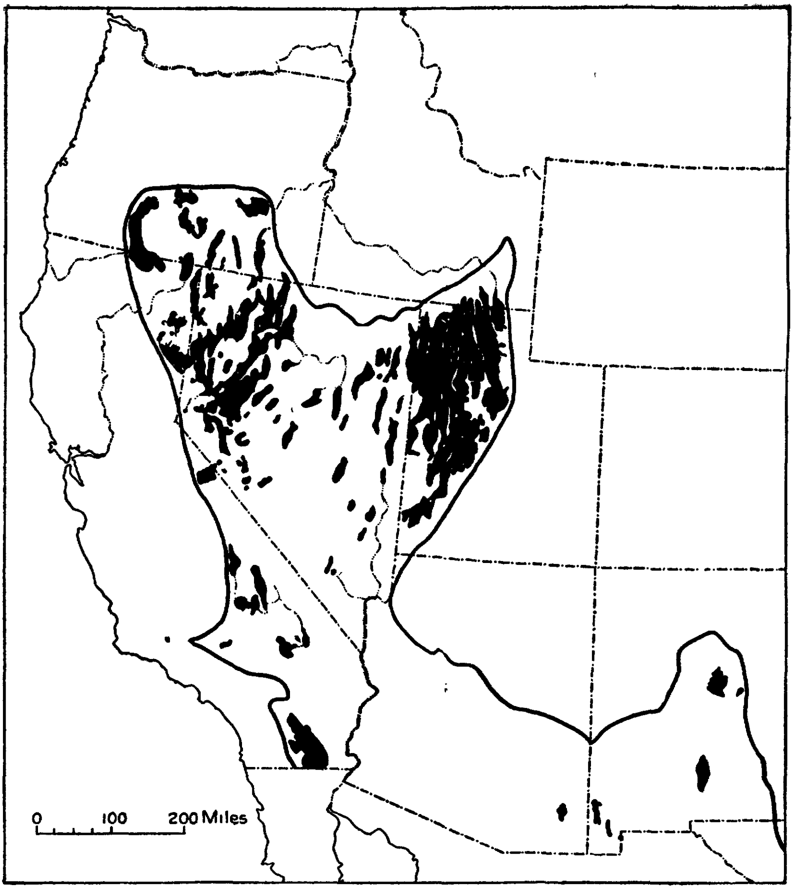


FIGURE 101.—Map of the Basin and Range province showing Pleistocene lake beds. (For a list of these ancient lakes and a brief discussion of them see Geol. Soc. America Bull., vol. 33, pp. 541–552, 1922.)

be of much consequence for water supply. Gypsum sands yield very hard water.

The mineral matter deposited from solution is largely disseminated through the valley fill, but to some extent it forms separate beds. Its effect on the water-bearing properties of the fill is unfavorable. The calcareous material forms hard layers of caliche (fig. 45, p. 157) and a cement that partly occupies the interstices, especially of the lower part of the fill (fig. 71, p. 190), greatly reducing in many places its yield of water. The gypsum and salt, chiefly deposited in the lowest parts of the valleys, are detrimental to the quality of the water.

In many places the deep valley fill yields less water than the fill lying within a few hundred feet of the surface. This is apparently due partly to original differences and partly to greater cementation and compacting of the deeper fill. In some valleys the fill comprises at least two distinct formations, the lower of which is nearly impervious, whereas the upper yields water freely. Such a condition occurs in Animas Valley, N. Mex.,[38] and is shown in figure 103. Similar conditions exist in the valley of southern California[39] (fig. 54, p. 173) and in the Rillito Valley, Ariz.[40] In some places, however, the deep fill yields water abundantly, as,

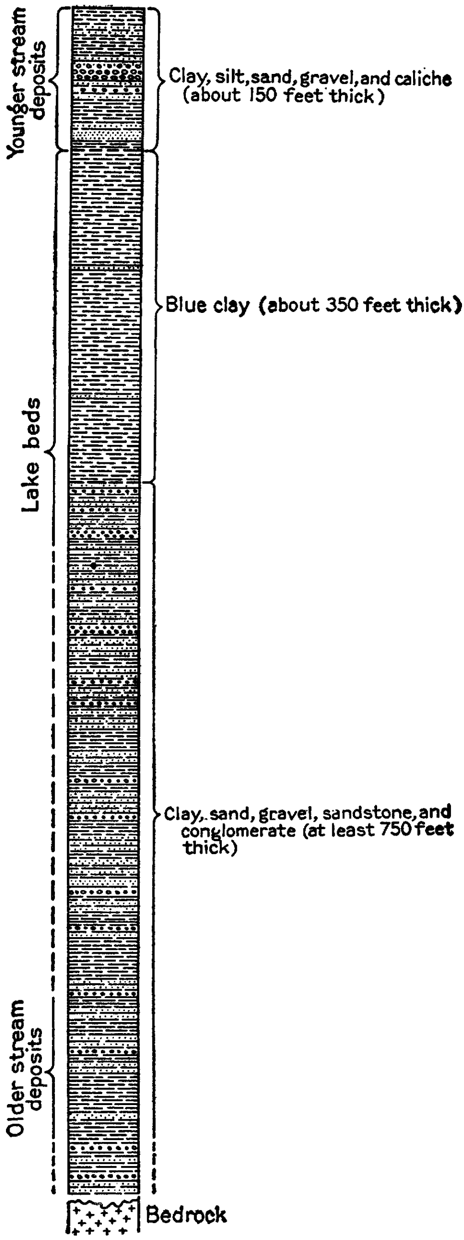


FIGURE 102.—Generalized columnar section of San Simon Valley, Ariz.-N. Mex., showing valley fill in which lake beds are interstratified with alluvium. (After A. T. Schwennesen.)

[38] Schwennesen, A. T., Ground water in the Animas, Playas, Hachita, and San Luis basins, N. Mex.: U. S. Geol. Survey Water-Supply Paper 422, pp. 78–81, 1918.

[39] Mendenhall, W. C., Ground waters and irrigation enterprises in the foothill belt, southern California: U. S. Geol. Survey Water-Supply Paper 219, pp. 34–39, 1908.

[40] Smith, G. E. P., Ground-water supply and irrigation in Rillito Valley, Ariz.: Arizona Agr. Exper. Sta. Bull. 64, p. 86, 1910.

for example, in parts of Coachella Valley north of the Salton Sea, where there are strong wells more than 1,000 feet deep and where one flowing well obtains a large supply from a depth of 1,400 feet.[41]

The water-bearing properties of the valley fill depend very largely on the kind of rocks from which it is derived, as has been explained on page 118.

The occurrence of water in the valley fill is so distinctive and of so much practical importance that it seems worth while to give the following concise description of a typical desert valley underlain by water-bearing fill.[42] (See Pl. XXX and figs. 104 and 105.)

Big Smoky Valley is a typical Nevada desert valley—a plain hemmed in by mountain ranges and underlain by porous rock waste eroded from these ranges and saturated with water discharged from them. Like most of the valleys of the State, it has a general north-south elongation and an interior drainage. A low, gentle alluvial swell divides the area draining to Big Smoky Valley into a north basin, which contains the upper valley (figs. 104 and 105), and a south basin, which contains the

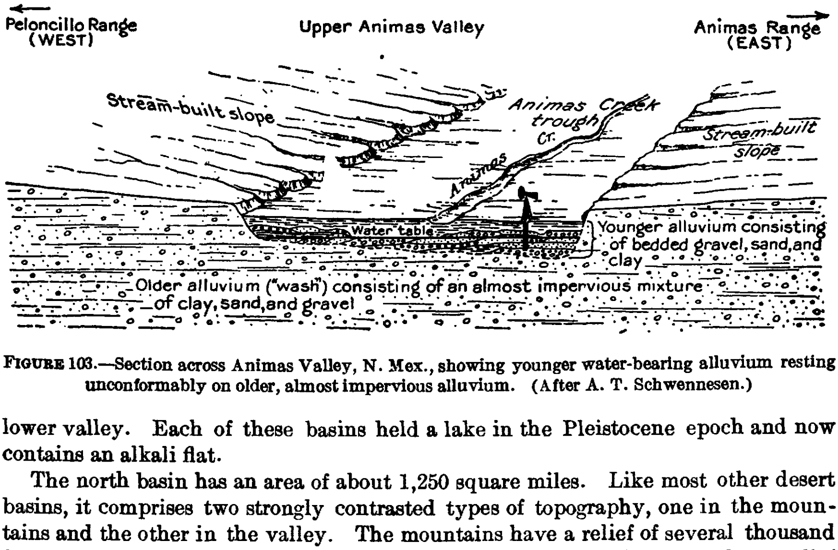


FIGURE 103.—Section across Animas Valley, N. Mex., showing younger water-bearing alluvium resting unconformably on older, almost impervious alluvium. (After A. T. Schwennesen.)

lower valley. Each of these basins held a lake in the Pleistocene epoch and now contains an alkali flat.

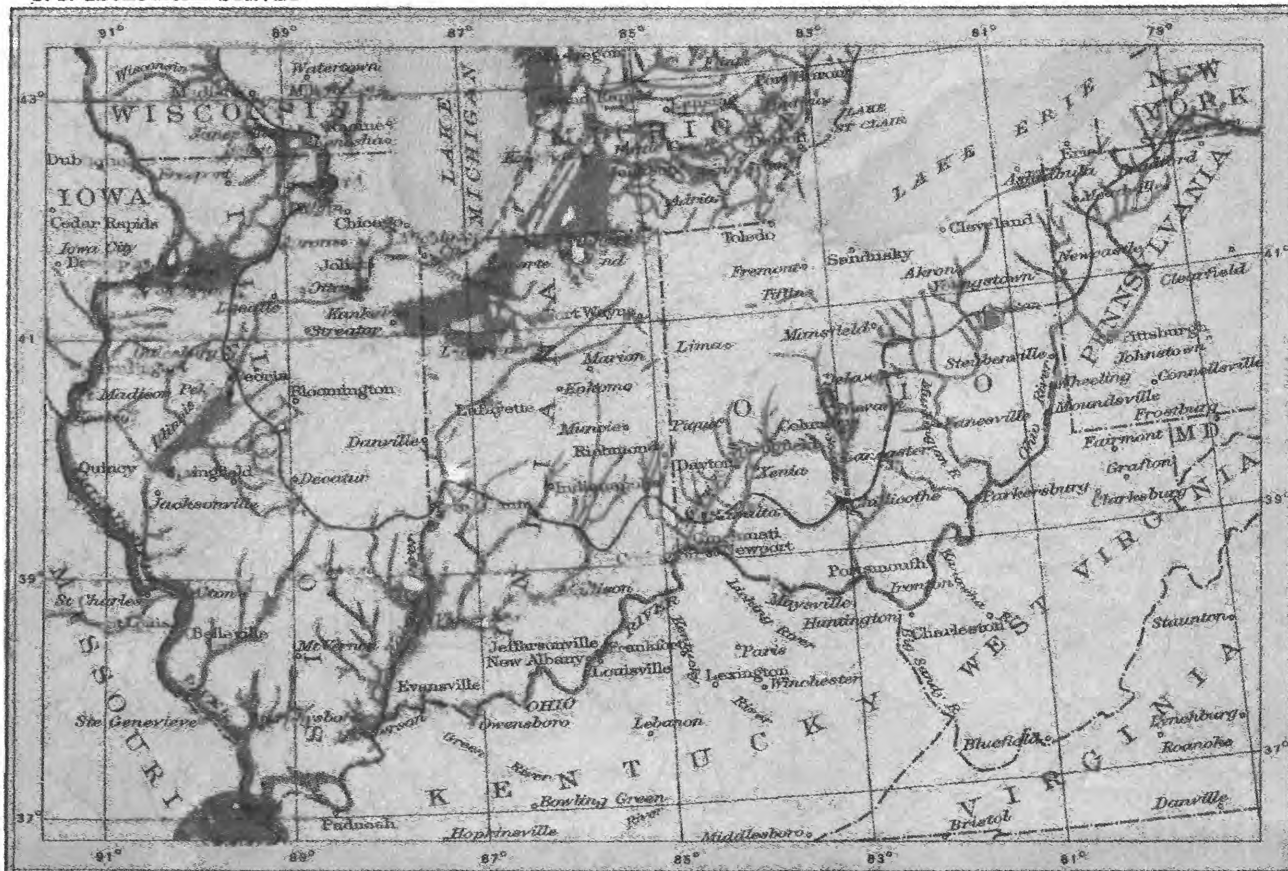
The north basin has an area of about 1,250 square miles. Like most other desert basins, it comprises two strongly contrasted types of topography, one in the mountains and the other in the valley. The mountains have a relief of several thousand feet, and their surface has been eroded or carved by streams; the valley has a relief of only a few hundred feet, and most of its surface is formed of deposits laid down by streams. The mountains are steep sided and almost infinitely varied in topographic detail; the valley consists of smooth, gentle slopes and nearly level plains. In general the relation of the mountains to the valley is that of cause and effect, and a study of the physiography of the basin therefore consists largely in correlating the land forms in the valley with the causal conditions in the mountains.

The greater part of the valley surface consists of coalescing alluvial fans, or slopes built of the rock waste discharged from the canyons. At their bases the slopes become very gentle and merge, in many places imperceptibly, into large playas, or alkali

[41] Brown, J. S., The Salton Sea region—a geographic, geologic, and hydrologic reconnaissance: U. S. Geol. Survey Water-Supply Paper 497 (in press).

[42] Mainly quoted from Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring valleys, Nev.: U. S. Geol. Survey Water-Supply Paper 423, 1917.

497781 O–59 (Face p. 298)



Compiled from maps by Frank Leverett, W. C. Alden, and M. L. Fuller

MAP OF REGION EXTENDING FROM PENNSYLVANIA TO IOWA

SHOWING GLACIAL OUTWASH (IN BLACK) CHIEFLY WATER-BEARING SAND AND GRAVEL

Heavy black line shows southern limit of the Wisconsin drift sheet

Scale $\frac{1}{7{,}000{,}000}$

100 50 25 0 50 100 200 MILES

1923

A. FAULT SCARP ON EAST SIDE OF TOYABE RANGE, NEV.

Stream erosion of this scarp has produced a rugged mountain front and has furnished rock waste that underlies Big Smoky Valley in the foreground. Some beds of rock waste yield water freely. Photograph by O. E. Meinzer.

B. INTERIOR OF TOYABE RANGE, NEV.

This area is less rugged than the mountain front because it has not yet been reached by the erosion cycle produced by the upfaulting of the range. Photograph by O. E. Meinzer.

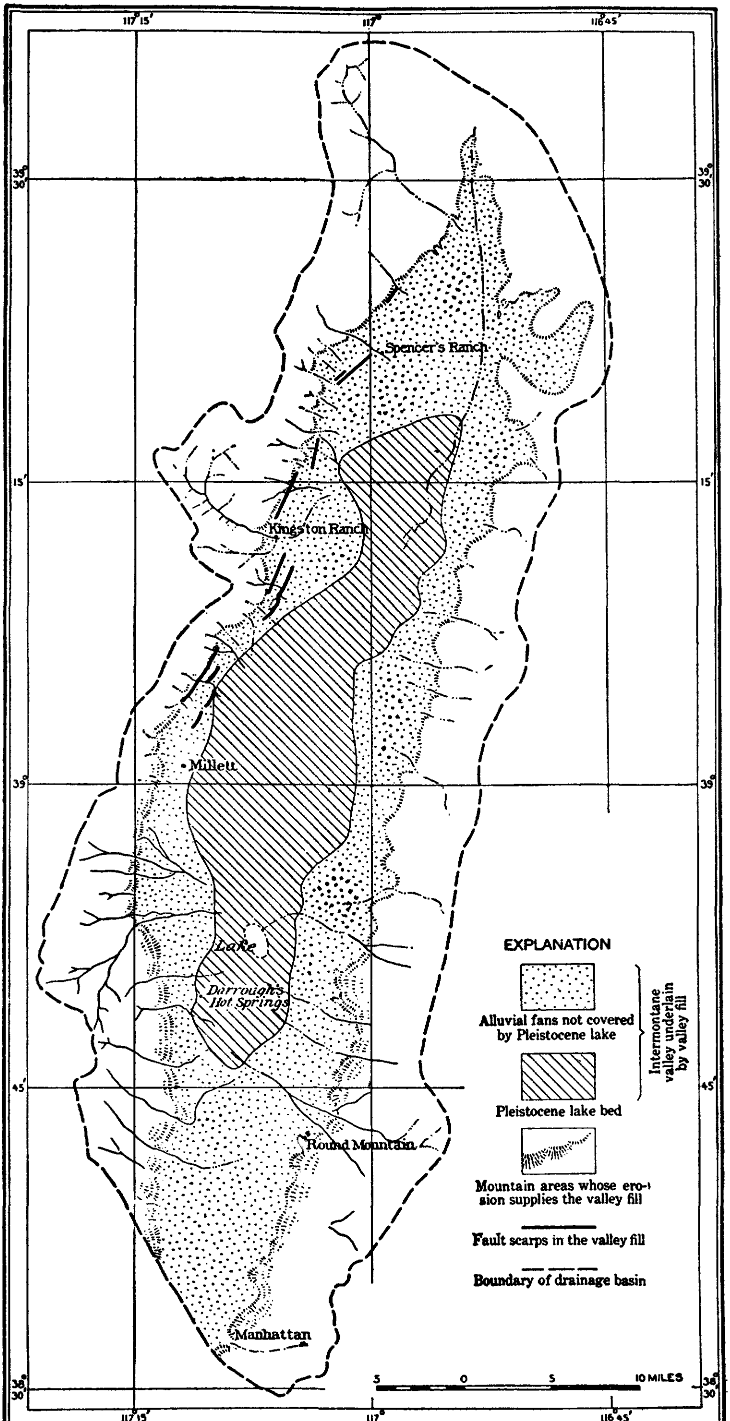


FIGURE 104.—Map of the northern drainage basin of Big Smoky Valley, Nev., showing distribution of Quaternary valley fill and its relation to the mountain areas that supplied this fill.

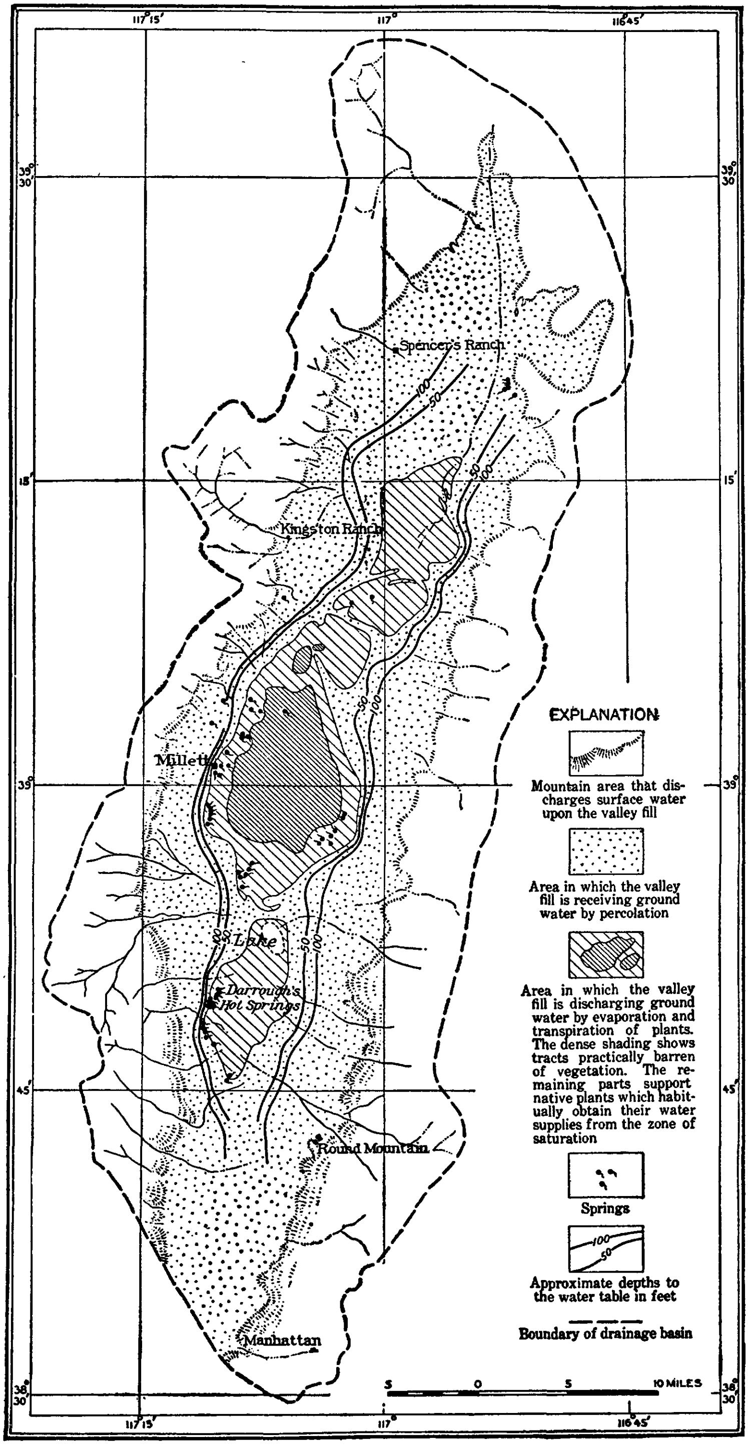


FIGURE 105.—Map of the northern drainage basin of Big Smoky Valley, Nev., showing the occurrence and circulation of water in the valley fill.

flats, that occupy the lowest parts of the valley. Superimposed on these main features are numerous scarps produced by recent faulting, large ridges built by ancient lakes, hills and ridges of sand heaped up by the wind, and in a few places mounds and terraces built by springs. The alluvial fans have also been modified by large, deep streamways carved into them.

The valley is nearly surrounded by a mountain wall in which are cut innumerable notches of various sizes. Each notch is the mouth of a canyon—the portal through which a certain part of the mountain area makes its contributions to the valley, not only of the water that falls upon it as rain or snow but of the very substance of the mountains themselves. The water that is discharged at the surface or as underflow is the vehicle by means of which the transportation of this rock material is effected, the soluble matter being carried in solution, the fine particles of sand and clay held in suspension, and the pebbles and boulders rolled over the surface by the impact of the water. Only from the larger canyons are these contributions made continuously, most of the canyons being dormant the greater part of the time and becoming active contributors only at long intervals, when freshets occur. The character and quantity of the contributions that the valley receives through these notches determine almost exclusively the shape of its surface, the distribution and capacity of its water-bearing beds, the quantity, quality, and level of its ground water, the character of its soil and native vegetation, and the agricultural possibilities of its lands.

At the mouth of each canyon is an alluvial fan, built of the materials contributed by the canyon. Each of these fans is or has been the greatly expanded streamway or flood plain of the stream that periodically flows from the canyon. The floor of a canyon and the surface of an undissected fan form parts of a single stream profile and are as closely adjusted to each other by the laws of stream gradation as the upper and lower courses of more ordinary streams. All the fans have the same general form because they are produced under the same general conditions. Each has an apex at the mouth of the canyon, from which it extends downward in all directions except as it is limited by other land forms. In each the grade diminishes with distance from the apex, thus giving the fan a concave profile along a line drawn from the apex in any direction in which the fan extends. In their size and in the shape of their concave profiles, however, the fans differ as widely as the canyons from which they are supplied. These differences are never haphazard but are determined by the sizes and gradients of the canyons, the volume and character of the floods which they discharge, and the quantity and nature of rock waste which the floods have to handle.

As the canyons are not far apart their fans are crowded together and modified by each other. Many small fans are superimposed on the larger ones, and fans of nearly equal size merge with each other in their middle and lower parts, forming a single smooth slope, a given point of which may receive sediments from two or more canyons.

As in most localities the contributing mountain areas on opposite sides of the valley differ in size, corresponding fans are likewise unequal, and the axis, or line of lowest depression, is not in the middle of the valley but relatively far from the side on which the mountains are large and near the side on which the mountains are small. The largest mountains are not, however, all on the same side, but are here on one side and there on the other. Consequently the line of lowest depression is a sinuous line that keeps far away from the large mountains.

The north basin once contained a lake whose surface fluctuated but never rose high enough to have an outlet. When at its highest level it was about 40 miles long, 9 miles in maximum width, and covered an area of approximately 225 square miles, or 18 per cent of the drainage basin in which it lay. Its maximum depth was about 170 feet. The shore features consist almost entirely of gravelly beaches and beach ridges, or embankments, many of which are very definite structures that can be followed for a number of miles, the largest attaining heights of nearly 50 feet.

At present the valley contains no perennial lake, but the flood waters that are not lost in their descent over the fans are impounded in the lowest parts of the valley, from which they are removed almost exclusively by evaporation. The impounded waters are always roily and on evaporation deposit fine sediments. This process of aggradation is as characteristic of the desert valleys as the aggradation on alluvial fans through deposition by running waters, and it produces as distinct a type of land surface. The running waters form surfaces with grades, whereas the impounded waters form surfaces that approximate horizontal planes.

The valley is arid. At one station the precipitation in 6 years averaged only 6.55 inches a year and in no year amounted to as much as 9 inches. In the higher mountains the precipitation is appreciably greater. About 50 of the canyons that drain into the upper valley contain small perennial streams.

The bedrocks of the drainage basin are relatively impervious and form a huge reservoir that is nearly water-tight. In this reservoir rests the great accumulation of porous rock waste called the valley fill, which is saturated with water up to a certain level known as the water table. The great body of water that is stored underground in this natural reservoir is derived from the rain and snow that fall upon the drainage basin. Contributions to the water in the valley fill are made by the perennial streams that flow out of the larger canyons; the floods discharged at long intervals from the canyons which are normally dry; the underflow of some of the canyons; the rain that falls in the valley; and water discharged underground from openings in the bedrocks.

It is roughly estimated that the perennial streams together contribute to the underground supply at an average rate of 15,000 to 30,000 acre-feet a year, most of which goes to the upper valley. The total annual recharge is considerably greater.

The contributions of water to the underground reservoir are balanced by losses from this reservoir. The losses occur chiefly through the return of the ground water to the surface but in smaller part through percolation out of the basin by way of underground passages. The return water reaches the surface by flowing from springs or by rising through the capillary pores of the soil or the roots and stems of plants where the water table is near the surface; it is all eventually evaporated. Ground water is returned to the surface over an area of about 160 square miles, or 100,000 acres, in the upper valley. The main west-side spring line extends, with a sinuous course, due to differences in the sizes of alluvial fans, a distance of more than 30 miles and includes innumerable springs that discharge a part of the copious underground supply received from the Toyabe Range. On the east side there is no spring line comparable to that on the west side, probably because the supply from the relatively low range on the east side is smaller than that from the higher mountains on the west. On the alluvial slope between the main west-side spring line and the mountains a few springs which flow from fault scarps are apparently produced by impounding caused by dislocation of the valley fill. The data seem to indicate that the quantity of water discharged from the main body of ground water in the upper valley is between 50,000 and 100,000 acre-feet a year, or between about 8 and 17 per cent of the precipitation on the north basin.

In the upper valley an area of about 100,000 acres has a depth of less than 10 feet to the water table, an area of about 170,000 acres has a depth of less than 50 feet, and an area of about 215,000 acres has a depth of less than 100 feet.

The coarse clean sand or grit derived from granite is porous and yields water freely. The arkosic grit derived from rhyolite and other igneous rocks of fine grain also generally yields water freely, but it contains more fine material and when it disintegrates it becomes quite compact. The pebbles derived from the angular fragments resulting from the weathering of slate and limestone may produce porous deposits but the pores are likely to be sealed to some extent by the cementation of calcium carbonate. The sediments derived from the tuffs are largely fine silt and form dense deposits that will yield little water. In the upper valley there are no wells that have been pumped at a rate of more than a few gallons a minute, but the evidence furnished by the character of the rocks in the adjacent mountains and the character of the sediments as shown at the surface and in well sections indicates that in most places between the 100-foot line and the flat, wells yielding moderately large supplies can be obtained. A well in the lower valley is pumped at the rate of 400 gallons a minute.

Several flowing wells have been sunk in the valley. These wells are all in or near the area which has more or less alkaline soil and a depth to water of 10 feet or less.

With few exceptions the waters of the upper valley contain only moderate amounts of mineral matter.

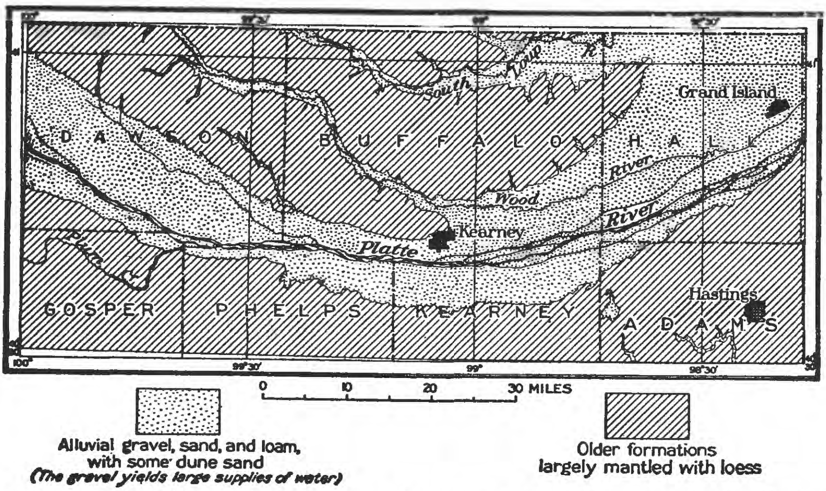


FIGURE 106.—Map of a part of Platte River valley, Nebr., showing great extent of water-bearing alluvium. (After N. H. Darton.)

ALLUVIUM OF THE GREAT PLAINS.[43]

The Great Plains also contain important Quaternary aquifers consisting of alluvial gravel and sand. These deposits were apparently laid down chiefly in the Pleistocene epoch. They are found mainly in the valleys which lead from the mountains and which trench the Tertiary and older formations that underlie the Great Plains. They

[43] The following publications (of the U. S. Geol. Survey, except as indicated) give information regarding water in Quaternary alluvial deposits on the Great Plains:

Colorado, Water-Supply Papers 9, 184.

Kansas, Water-Supply Papers 6, 140, 153, 258, 273, 345; Kansas Board Irr., Survey, and Exper. Rept. for 1895–1896; Kansas Univ. Geol. Survey Bull. 1.

Nebraska, Water-Supply Papers 12, 184, 215, 216, 425.

New Mexico, Twenty-first Ann. Rept., pt. 4, Twenty-second Ann. Rept., pt. 4.

Oklahoma, Water-Supply Papers 148, 345.

Texas, Water-Supply Papers 154, 191; Twenty-first Ann. Rept., pt. 4, Twenty-second Ann. Rept., pt. 4; Univ. of Texas Bull. 57.

Wyoming, Water-Supply Papers 70, 425

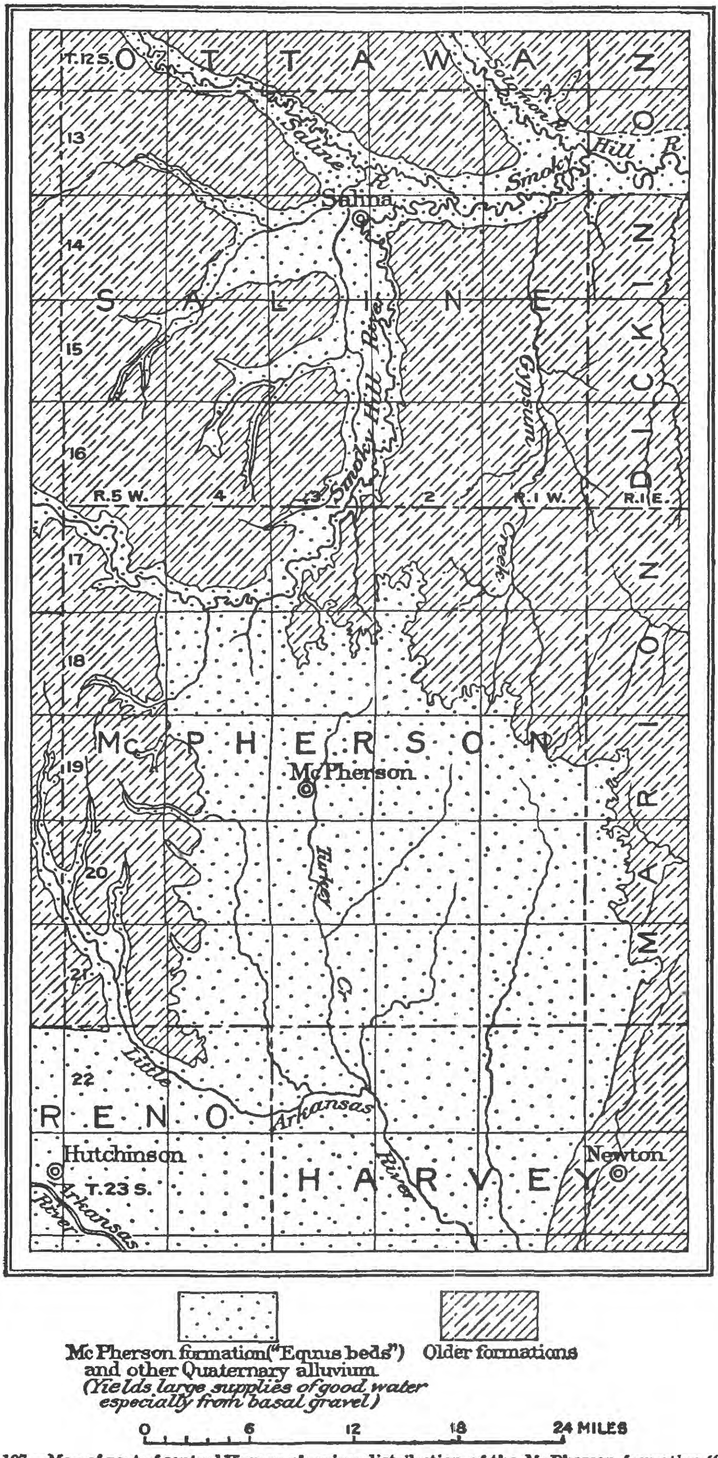


FIGURE 107.—Map of part of central Kansas, showing distribution of the McPherson formation ("*Equus* beds") and associated Quaternary alluvium of existing river valleys. (After C. S. Prosser and J. W. Beede.)

are extensively developed in the valleys of Arkansas and Platte rivers and many other streams and are also found in a few areas from which the streams that produced them have been diverted. These deposits extend for hundreds of miles from the mountains and in some places expand to considerable widths. In the part of the Platte River valley shown in figure 106 the belt of alluvium ranges from 5 to 20 miles in width. This alluvium contains large quantities of good water which it yields very freely to wells. It is heavily drawn upon for many purposes, including irrigation.

In central Kansas, between Smoky Hill and Arkansas rivers, there are Pleistocene alluvial deposits, known as the McPherson formation or "*Equus* beds," which apparently occupy an abandoned stream

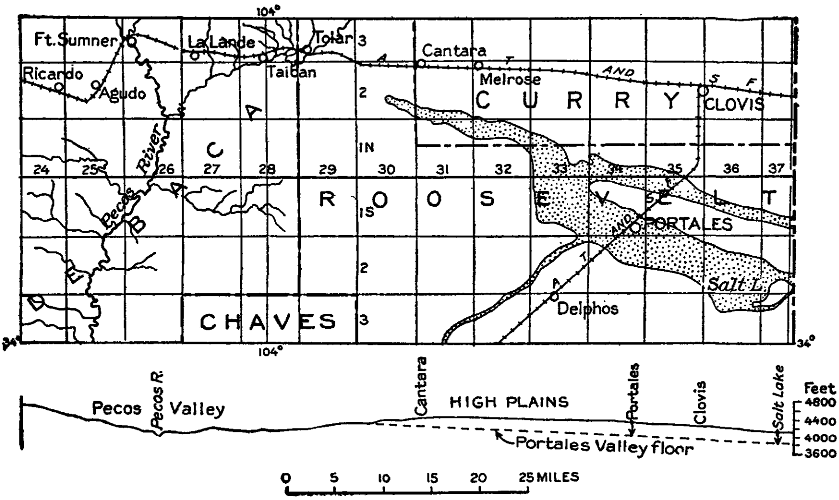


FIGURE 108.—Map and profile of Portales Valley and a part of Pecos River valley, N. Mex., showing shallow-water area in Portales Valley and topographic relations that suggest capture of the ancient stream of Portales Valley by Pecos River. Stippled pattern shows area in Portales Valley that has water table less than 25 feet below surface.

channel. They are about 200 feet in maximum thickness and cover fully 800 square miles (fig. 107). They consist chiefly of sand and clay but in some places include a thick bed of gravel at the bottom. They form an excellent aquifer, the basal gravels being especially productive.[44]

Portales Valley, a broad, shallow trench in the Tertiary beds of eastern New Mexico, contains no stream at present but was evidently excavated by a stream that headed far to the west and has since been captured by Pecos River[45] (fig. 108). This valley is underlain by

[44] Haworth, Erasmus, The geology of underground water in western Kansas: Kansas Board Irr., Survey, and Exper. Rept. for 1895–96, pp. 103–104, 1897.

[45] Underground water resources in Portales Valley, N. Mex. (O. E. Meinzer): U. S. Geol. Survey Press Bull. 406, October, 1909. Baker, C. L., Geology and underground waters of the northern Llano Estacado: Texas Univ. Bull. 57, pp. 52–54, 89–90, 1915.

porous deposits that yield very large supplies to rather shallow wells. It seems probable that these deposits were laid down by the ancient stream after it had excavated the valley, and that they are of Quaternary age. There are probably other valleys in this region with similar history and similar ground-water conditions.

DEPOSITS OF THE ATLANTIC COASTAL PLAIN.[46]

The Quaternary deposits in the Atlantic Coastal Plain are widespread and, on the whole, very important as sources of water (fig. 109). They include alluvial deposits, estuary and shore deposits, and limestone formed in shallow but clear parts of the sea.

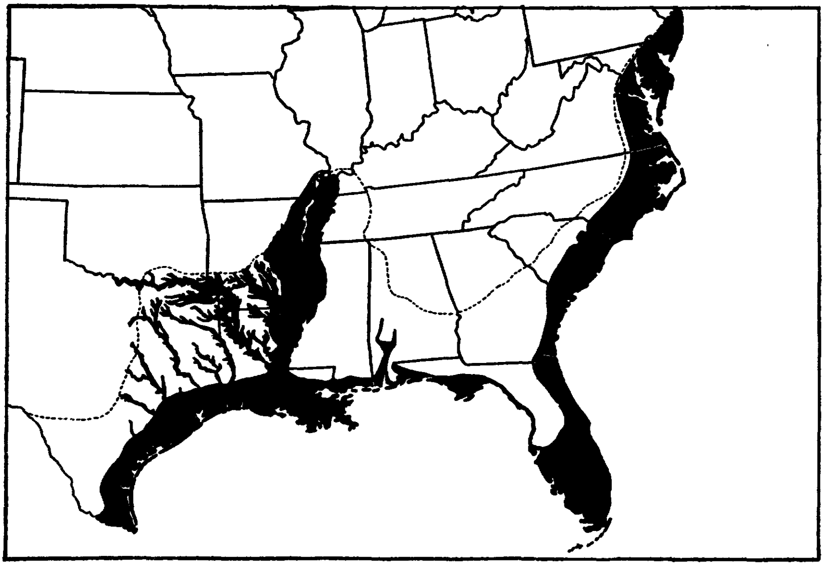


FIGURE 109.—Map of the Atlantic Coastal Plain showing distribution of principal Quaternary deposits. The alluvial gravel in the Mississippi lowland below the mouth of the Ohio and in Louisiana and Texas yields very large supplies of water. The boundary of the Coastal Plain is shown by the broken line.

Near the end of the Tertiary period the Atlantic Coastal Plain sank several hundred feet with reference to sea level and was therefore largely submerged beneath the sea. During the Quaternary period

[46] The following publications (of the U. S. Geol. Survey, except as indicated), give information relating to water in Quaternary deposits in the Atlantic Coastal Plain:

- Arkansas, Water-Supply Paper 399; Prof. Paper 46.
- Delaware, Geol. Folios 137, 211; Maryland Geol. Survey Special Pub., vol. 10, pt. 2 (cooperative report).
- Florida, Water-Supply Paper 319.
- Georgia, Water-Supply Paper 341; Georgia Geol. Survey Bull. 15 (cooperative report).
- Louisiana, Water-Supply Papers 101, 114; Prof. Paper 46.
- Maryland, Geol. Folios 137, 152, 182, 204, 211; Maryland Geol. Survey Special Pub., vol. 10, pt. 2 (cooperative report).
- Mississippi, Water-Supply Paper 159.
- Missouri, Water-Supply Paper 195.
- Texas, Water-Supply Papers 335, 375; Eighteenth Ann. Rept., pt. 2.

it emerged in successive stages, with minor submergences. Consequently, a series of terraces were formed at different levels, and these are generally underlain by alluvial or shore deposits, which in most places form only a thin mantle but in some places are very thick.

The highest terrace is generally considered to be of late Pliocene age. As shown in the section for Maryland and Delaware (pp. 253–254) the deposits at this level are now called the Brandywine formation (fig. 110), but the name "Lafayette formation" has been widely used for the high-level deposits of approximately the same age throughout the Atlantic Coastal Plain. The Quaternary terrace deposits are generally known as the Columbia group. In Maryland and Delaware (see pp. 253–254) Quaternary terrace deposits are known to occur at only three different levels (fig. 110), but in North Carolina[47] Quaternary terraces and terrace deposits have been recognized at five distinct levels. After the lowest of the present terraces was formed the region emerged, at least in large part, so that it stood higher with reference to sea level than at present, and the valleys

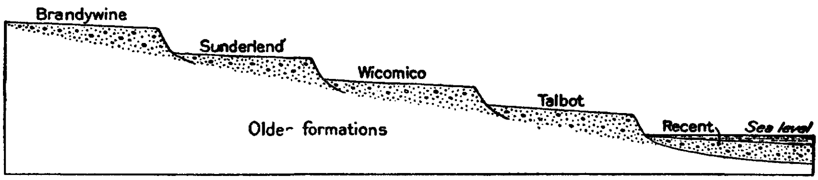


FIGURE 110.—Generalized section of Atlantic Coastal Plain in Maryland and Delaware, showing Pliocene and Quaternary terraces and terrace deposits. (After Clark, Mathews, and Berry.)

were eroded below the present sea level. Still more recently the region sank somewhat, and the lowest parts of the valleys have become submerged.

In the States bordering on the Atlantic Ocean these terraces are widely developed but the terrace deposits are not thick. They furnish small supplies to many shallow wells. As a rule the lowest terraces are more reliable for water supply than those at relatively high levels, but the water under the lowest terrace is likely to be salty.

Below the mouth of Ohio River the valley of the Mississippi becomes very wide, and in southeastern Missouri and northeastern Arkansas there is an abandoned valley of the Mississippi known as the Advance lowland, far west of the present river channel. The extensive lowlands formed by the present valley and the abandoned valley are underlain by Quaternary alluvium (fig. 109). In the Advance lowland and in the Mississippi lowland in Missouri, Arkansas, Kentucky, Tennessee, and Mississippi this alluvium is generally between 100 and 225 feet thick. It is composed of loam, clay, sand, and gravel. As

[47] Clark, W. B., and others, The Coastal Plain of North Carolina: North Carolina Geol. and Econ. Survey, vol. 3, 1912.

a rule there is a downward gradation from fine silt and loam at the surface through compact clay and fine sand to coarse sand and gravel at the bottom. The bulk of this material is of Pleistocene age. It is younger than the principal deposits of loess, and therefore was probably laid down largely during the latest glacial advance, when the Wisconsin drift sheet was deposited.[48] These alluvial deposits, especially the basal gravels, yield water in very large quantities and are drawn upon for various uses, including the irrigation of rice.[49]

In southern Louisiana the Quaternary deposits become much thicker and also yield water in large quantities (fig. 109). In some parts of the area the water is salty, but to a great extent it is of good quality. There are many flowing wells with large yields, and also many that are pumped very heavily for rice irrigation.

In Texas the Quaternary deposits of the Coastal Plain are also well developed (fig. 109) and of much importance as aquifers.[50] In the southeastern part of the State there are two principal Quaternary formations, the Lissie gravel and the Beaumont clay, which underlie a broad belt along the coast. The Lissie gravel is believed to represent the coalescing alluvial fans that were spread out at the mouths of the valleys of the streams which discharged into the sea during some parts of Pleistocene time, possibly the early and middle parts. It has a maximum thickness of about 900 feet but thins out in the direction away from the sea. It constitutes one of the most important water bearers of the Atlantic Coastal Plain. It yields large quantities of water which is in part salty but mostly potable. It gives rise to flowing wells over a large area adjacent to the sea, where it is covered by the Beaumont clay. The Beaumont formation consists of blue and reddish calcareous clay with lenses of sand and gravel. It is not a good water bearer but serves to confine the water of the Lissie gravel under artesian pressure.

In the valleys of the major streams of the Coastal Plain in Texas there is a series of Quaternary terraces with underlying alluvial deposits, like the terraces of the Columbia group farther east. Terraces at three distinct levels have been discriminated, the highest of which is the oldest. Each grades laterally into interstream phases, the Lissie gravel and Beaumont clay representing the interstream phases of the middle and lowest. The gravel beds in the stream valleys of this part of the Coastal Plain are largely the extensions of the deposits along the same streams on the Great Plains, just as the

[48] Stephenson, L. W., and Crider, A. F., Geology and ground waters of northeastern Arkansas, with a discussion of the chemical character of the waters by R. B. Dole: U. S. Geol. Survey Water-Supply Paper 399, pp. 120-121, 1916.

[49] Idem, p. 146.

[50] Deussen, Alexander, Geology and underground waters of the southeastern part of the Texas Coastal Plain: U. S. Geol. Survey Water-Supply Paper 335, pp. 78-84, 1914.

gravel deposits along Mississippi River and some of its tributaries are largely the extensions of their glacial outwash.

A large part of Florida, including nearly all of the southern part, is underlain by Quaternary deposits,[51] which consist chiefly of sediments laid down in the sea but also include alluvium and much wind-blown sand. They comprise sand, clay, marl, and limestone. The limestone is largely oolite and shell limestone and is soft and porous. The Quaternary system of Florida in general increases in thickness toward the southern part of the State, where, exclusive of sand hills, it probably has a maximum thickness of 125 feet. The Quaternary materials are as a rule very porous. In some places they are too thin to yield much water, but where they have considerable thickness they contain large supplies, which they yield freely to springs and wells. They absorb the surface water readily but also readily take in surface pollution. In some places the water is salty, but generally it is potable.

MARINE DEPOSITS OF THE NORTHEAST.

In the northeastern part of the United States, especially along the coast of Maine, there are marine strata of clay and silt with some interbedded and underlying sand and gravel.[52] These beds in Maine are chiefly within 10 or 20 miles of the coast although they extend much farther up the valleys of major streams. They are found up to elevations of 300 feet above sea level. They were formed during a submergence of the region that occurred at about the end of the Pleistocene epoch and are related to the glacial outwash of the Wisconsin drift. Considerable water can be recovered in some places by means of dug or driven wells ending in the interbedded or basal sand and gravel, but these supplies are local and not generally available.

GROUND-WATER PROVINCES IN THE UNITED STATES.

In order to summarize effectively the occurrence of ground water in the United States the country has been divided into 21 ground-water provinces, the approximate boundaries of which are shown in Plate XXXI. (See also Pl. XXVIII, p. 196.) Any such division is necessarily somewhat arbitrary, both as to the number of provinces and as to their boundaries, but it serves a very useful purpose for concise presentation of the conditions in the entire country.

In making the division consideration is given to the several important groups of aquifers in the country, namely, glacial drift, valley fill of the western basins, Tertiary lava, Miocene and Pliocene (upper

[51] Matson, G. C., and Sanford, Samuel, Geology and ground waters of Florida: U. S. Geol. Survey Water-Supply Paper 319, 1913.

[52] Stone, G. H., The glacial gravels of Maine and their associated deposits: U. S. Geol. Survey Mon. 34, pp. 41-58, 1899.

Tertiary) formations of the Great Plains, Eocene formations of the interior, Cretaceous formations, (chiefly the Upper Cretaceous of the interior, including the Dakota sandstone), Paleozoic sedimentary formations, and pre-Cambrian and other crystalline rocks. The general rules for classification are as follows:

1. A large area in which only one of these groups of aquifers exists or is important, constitutes a province. The provinces of this class are the Piedmont province (C), the South-central Paleozoic province (E), the Wisconsin Paleozoic province (G), the Black Hills Cretaceous province (J), the Trans-Pecos Paleozoic province (M), the Columbia Plateau Lava province (S), and the Southwestern Bolson province (U).

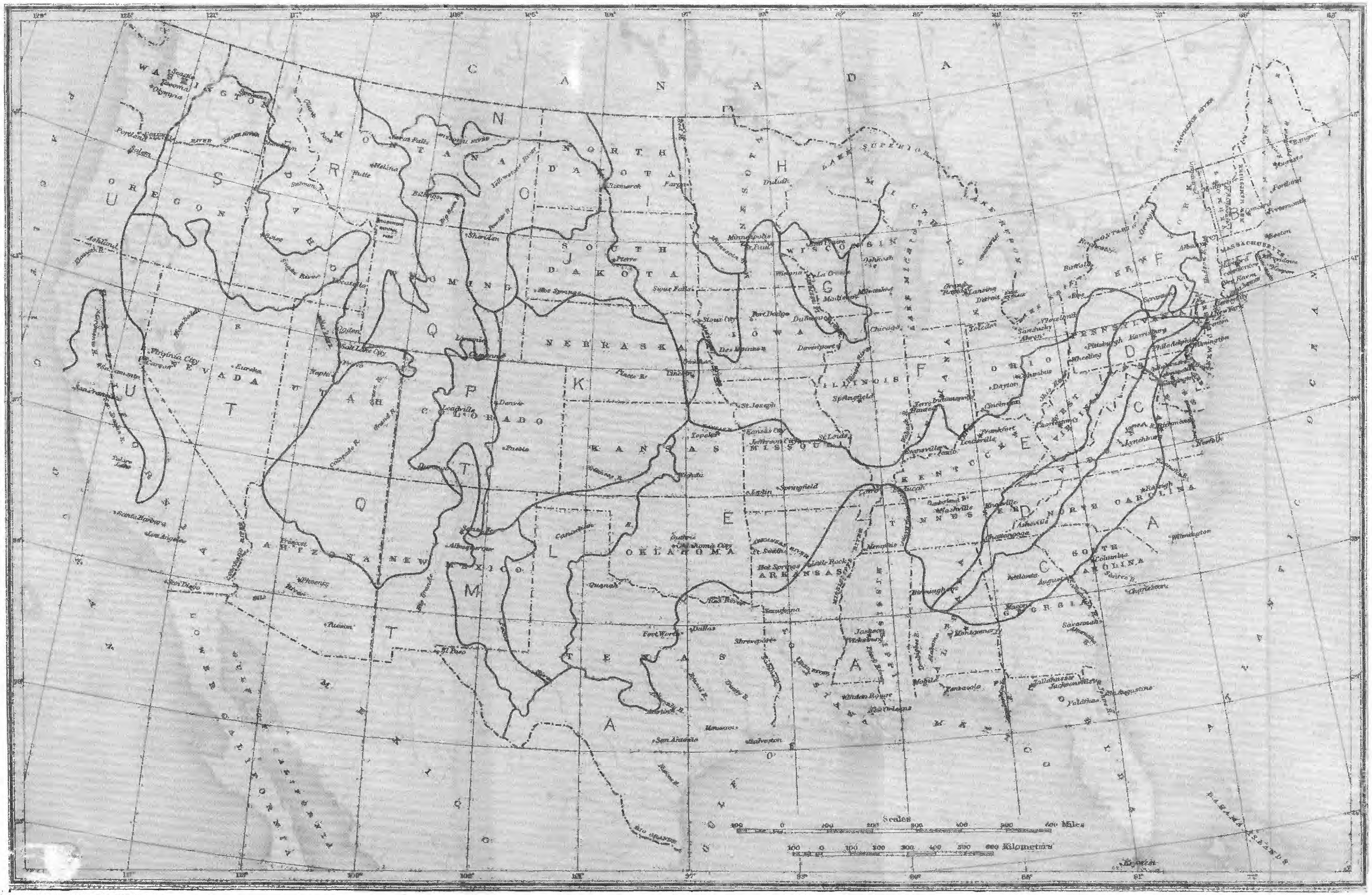
2. Where more than one of the principal groups of aquifers occurs the coextension of the two most important of these groups determines the limits of a province. The provinces of this class are the Northeastern Drift province (B), the North-central Drift-Paleozoic province (F), the Superior Drift-Crystalline province (H), the Dakota Drift-Cretaceous province (I), the Great Plains Pliocene-Cretaceous province (K), the Great Plains Pliocene-Paleozoic province (L), and the Montana Eocene-Cretaceous province (O). Modifications of this rule are represented by the Atlantic Coastal Plain province (A), the Northwestern Drift-Eocene-Cretaceous province (N), and the Montana-Arizona Plateau province (Q), in which at least three of the principal groups of aquifers are present and are so nearly equal in importance that they must all be taken into account.

3. In rugged and lofty mountainous regions the topography and, to some extent, the climate produce radical changes in ground-water conditions, which eclipse the differences due to the presence of different groups of aquifers. Such a mountainous region constitutes a ground-water province. The provinces of this class are the Blue Ridge-Appalachian Valley province (D), the Southern Rocky Mountain province (P), the Northern Rocky Mountain province (R), and and the Pacific Mountain province (T). The last-named province is not, however, a very satisfactory unit.

In this connection, it is interesting to call attention to an earlier division of the country into ground-water provinces that was made by Ries and Watson[53] in their excellent chapter on "Underground waters." They divided the country, very logically, into 10 provinces.

In a subsequent volume on ground water in the United States the writer intends to describe in some detail the conditions in each of the provinces which he has recognized. For the present volume the following very brief summary must suffice. Sources of further information regarding any of these provinces may be ascertained by con-

[53] Ries, Heinrich, and Watson, T. L., Engineering geology, pp. 330-337, New York, John Wiley & Sons, 1914.



GROUND-WATER PROVINCES

- A Atlantic Coastal Plain province
- B Northeastern Drift province
- C Piedmont province
- D Blue Ridge-Appalachian Valley province
- E South-Central Paleozoic province
- F North-Central Drift-Paleozoic province
- G Wisconsin Paleozoic province
- H Superior Drift-Crystalline province
- I Dakota Drift-Cretaceous province
- J Black Hills Cretaceous province
- K Great Plains Pliocene-Cretaceous province
- L Great Plains Pliocene-Paleozoic province
- M Trans-Pecos Paleozoic province
- N Northwestern Drift-Eocene-Cretaceous province
- O Montana Eocene-Cretaceous province
- P Southern Rocky Mountain province
- Q Montana-Arizona Plateau province
- R Northern Rocky Mountain province
- S Columbia Plateau lava province
- T Southwestern Bolson province
- U Pacific Mountain province

ENGRAVED AND PRINTED BY THE U.S.GEOLOGICAL SURVEY

MAP OF THE UNITED STATES SHOWING GROUND-WATER PROVINCES

1923

497781 O-59 (Face p. 310)

sulting Water-Supply Paper 427, Bibliography and index of the publications of the United States Geological Survey relating to ground water. This paper contains a detailed index of ground-water reports for every State and also includes a map of the United States that shows the area covered by each of the important reports.

A. *Atlantic Coastal Plain province.*—Water is derived in rather large quantities from Cretaceous, Tertiary, and Quaternary strata, chiefly sand and gravel interbedded with clayey beds. Very large supplies are obtained from alluvial gravels in Mississippi Valley and adjacent areas. The province includes extensive areas of artesian flow. The ground water ranges from low to high in mineral content.

B. *Northeastern Drift province.*—Principal ground-water supplies come from glacial drift. The till yields small supplies to many springs and shallow wells; the outwash gravels yield very large supplies, notably on Long Island. Many drilled rock wells receive small supplies, chiefly from joints in crystalline rocks or in Triassic sandstone. Ground water is generally soft and otherwise low in mineral matter.

C. *Piedmont province.*—Water that is generally low in mineral matter is supplied in small quantities by the crystalline rocks and locally by Triassic sandstone. Many shallow dug wells are supplied from surface deposits or from the upper decomposed part of the bedrock. Many drilled wells of moderate depth are supplied from joints in the crystalline rocks. Some wells in Triassic sandstone yield rather large supplies.

D. *Blue Ridge-Appalachian Valley province.*—This is a region of rugged topography with numerous springs which generally yield water of good quality from Paleozoic strata, pre-Cambrian crystalline rocks, or post-Cambrian intrusive rocks. The water supplies are derived chiefly from springs, spring-fed streams, and shallow wells.

E. *South-Central Paleozoic province.*—The ground-water conditions are in general rather unsatisfactory. The principal sources of supply are the Paleozoic sandstones and limestones. Throughout considerable parts of the province the Paleozoic supplies are meager or of poor quality. Deep Paleozoic water is highly mineralized. In many of the valleys large supplies are obtained from glacial outwash and other alluvial sands and gravels.

F. *North-Central Drift-Paleozoic province.*—Most water supplies are derived from the glacial drift. Numerous drilled wells obtain large supplies from glacial outwash or from gravel interbedded with till. The water from glacial drift in this province is generally hard but otherwise good. In many small areas the drift gives rise to flowing wells. Many drilled wells end also in Paleozoic sandstone or limestone and receive ample supplies of water. The deeper Paleozoic waters are generally highly mineralized and in many places are unfit for use; the shallower Paleozoic waters are commonly of satisfactory quality except that they are hard. In many valleys flowing wells can be obtained from Paleozoic aquifers.

G. *Wisconsin Paleozoic province.*—Most of the water supplies are obtained from wells of moderate depth drilled into Cambrian or Ordovician sandstone or limestone. These wells as a rule yield ample supplies of hard but otherwise good water. In many of the valleys artesian flows are obtained from the Paleozoic aquifers. The region is devoid of water-bearing drift except in the valleys, where there are water-bearing outwash gravels.

H. *Superior Drift-Crystalline province.*—In most parts of this province satisfactory water supplies are obtained from glacial drift. Where the drift is thin water supplies are generally scarce, because the pre-Cambrian crystalline rocks in most places yield only meager supplies, and as a rule there are no intervening Paleozoic, Mesozoic, or Tertiary formations that are thick enough to yield much water. The drift and rock waters range from soft waters of low mineralization, in Wisconsin, to highly mineralized waters—some of them unfit for use—in the western and especially the northwestern part of the province.

I. *Dakota Drift-Cretaceous province.*—The two important sources of ground water are the glacial drift and the Dakota sandstone. The drift supplies numerous wells with hard but otherwise fairly good water. It is available for water supply in nearly all parts of the province. The Dakota sandstone has extensive areas of artesian flow. It supplies many strong flowing wells, a considerable number of which are more than 1,000 feet deep. The Dakota sandstone waters are highly mineralized but are used for domestic supplies. The water from most parts of the formation is very hard, but the water from certain strata is soft, although rich in sodium sulphate and sodium chloride.

J. *Black Hills Cretaceous province.*—The conditions in this province are, on the whole, unfavorable with respect to shallow-water supplies because most of the province is underlain by the Pierre shale or by shales of the White River group (Oligocene). The principal aquifer is the Dakota sandstone, which underlies the entire region except most of the Black Hills. This sandstone will probably yield water wherever it occurs, and over considerable parts of the province it will give rise to flowing wells. Throughout much of the province it is, however, far below the surface. In some localities underlain by shale small supplies are obtained from shallow wells. In the Black Hills water is obtained from a variety of sources, ranging from pre-Cambrian crystalline rocks to Cretaceous or Tertiary sedimentary rocks.

K. *Great Plains Pliocene-Cretaceous province.*—The principal aquifers of this province are the late Tertiary sands and gravels (Ogalalla formation and related deposits) and the Dakota sandstone. The Tertiary deposits are exceptionally satisfactory for water supply over extensive areas where they underlie the smooth and almost uneroded plains. They yield large quantities of good water to relatively shallow wells. The Dakota sandstone underlies nearly the entire province and gives rise to various areas of artesian flow. Throughout much of the province, however, it lies too far below the surface to be a practical source of water. Where the Tertiary beds are absent or badly eroded and the Dakota sandstone is buried beneath thick beds of shale, as in parts of eastern Colorado, it may be very difficult to develop water supplies for even domestic and live-stock uses. Many of the valleys contain Quaternary gravels, which suppy large quantities of good water. Considerable Tertiary and Quaternary well water is used for irrigation.

L. *Great Plains Pliocene-Paleozoic province.*—The principal aquifers of this province are the late Tertiary and Quaternary sands and gravels, which give the same very favorable conditions as the Tertiary and Quaternary deposits in province K. The Tertiary deposits are underlain through practically the entire province by Permian or Triassic "Red Beds," which in most places do not yield much water or yield only highly mineralized water. In the localities where the Tertiary deposits are thin or absent or where they have been badly eroded the ground-water conditions are generally unfavorable.

M. *Trans-Pecos Paleozoic province.*—The bedrock consists of Carboniferous and Triassic strata, including limestone, gypsum, red beds of shale and shaly sandstone, and some less shaly sandstone. In most of the province these rocks yield only meager supplies of highly mineralized waters to deep wells. In the Pecos Valley, however, Carboniferous limestones and sandstones yield very large supplies to numerous flowing wells; the water is very hard but good enough for irrigation and for general domestic and live-stock uses. Locally the bedrock is overlain by Quaternary water-bearing gravels.

N. *Northwestern Drift-Eocene-Cretaceous province.*—Ground-water supplies are obtained from glacial drift and from underlying Eocene and Upper Cretaceous formations. Where the drift is absent or not water-bearing, wells are sunk into the underlying formations with variable success. The Eocene and latest Cretaceous, which underlie most of the eastern part of the province, generally include strata or lenses of sand, gravel, or coal that yield water. The Cretaceous formations that occur in the western part consist chiefly of alternating beds of shale and sandstone. The sandstones generally yield water, but the shales are unproductive, and where a thick shale formation immediately underlies the drift or is at the surface it may be very difficult to get successful wells. In certain localities upland gravels yield water to shallow wells.

O. *Montana Eocene-Cretaceous province.*—Fairly good water in quantities adequate for domestic and live-stock supplies and generally also adequate for small municipal supplies is obtained from strata and lenses of sand, gravel, and coal in the Fort Union (Eocene) and Lance (late Cretaceous or Eocene) formations which underlie most of the province. These formations in this province usually rest on the Pierre shale, a thick dense shale of Upper Cretaceous age that yields no water or only meager amounts of water, generally of poor quality. Hence, locally, where the Fort Union and Lance are absent or do not yield adequately, there is great difficulty in obtaining satisfactory water supplies. In the northern part of the province there is a little water-bearing glacial drift.

P. *Southern Rocky Mountain province.*—In this lofty mountain province, underlain for the most part by crystalline rocks, water supplies are obtained chiefly from springs, from streams fed by springs and melted snow, or from very shallow wells near the streams.

Q. *Montana-Arizona Plateau province.*—The question may properly be raised whether the large region included in this province is sufficiently homogeneous to be regarded as a unit with respect to ground water. It is, for the most part, an arid to semiarid plateau region underlain by sedimentary formations ranging in age from Paleozoic to Tertiary, not violently deformed but sufficiently warped and broken to produce a close relation between rock structure and the occurrence of ground water and to cause rather rapid variation in ground-water conditions from place to place. On the whole, water supplies are not plentiful and not of very satisfactory quality. Where thick formations of nearly impervious material, such as the Mancos shale, are at the surface, or where the plateau is greatly dissected, as in the Grand Canyon region, water supplies are very scarce. Locally, however, sandstone aquifers, such as the sandstones of the Kootenai formation, the Dakota sandstone, or the Mesaverde formation, are within reach of the drill and may yield very satisfactory supplies, in some places giving rise to flowing wells. Locally there are also water-bearing gravels of Quaternary age.

R. *Northern Rocky Mountain province.*—This is a relatively cold region, chiefly mountainous but with extensive intermontane valleys and plains. It is underlain by a great variety of rocks with complicated and diverse structure. As in other mountain regions, the water supplies are obtained largely from mountain springs and streams. Considerable water is in places available from valley fill, chiefly ordinary alluvial sand and gravel and the outwash deposits of mountain glaciers. A few supplies are also obtained from wells drilled into various rock formations—for example, the Belt series, of pre-Cambrian (Algonkian) age, and the sedimentary beds of Tertiary age.

S. *Columbia Plateau Lava province.*—The principal aquifers of this province are the widespread Tertiary and Quaternary lava beds and interbedded or associated Tertiary sand and gravel, such as those of the Ellensburg formation. In general, the lava yields abundant supplies of good water. It gives rise to many large springs, especially along Snake River in Idaho. Locally the lava or the interbedded sand and gravel give rise to flowing wells. However, much of the lava is so permeable and the relief of the region is so great that in many places the water table is too far below the surface to be reached except by deep wells. In certain parts of the province glacial outwash and ordinary valley fill are also important sources of water.

T. *Southwestern Bolson province.*—The principal source of water supply in this arid province is the alluvial sand and gravel of the valley fill underlying the numerous intermontane valleys that characterize the region. These water-bearing beds of sand and gravel not only provide numerous desert watering places and domestic, live-stock, mining, and municipal supplies, but in many places they also yield important irrigation supplies. In the elevated marginal parts of the valleys the water table may be very far below the surface or ground water may be absent; in the lowest parts, underlain by clayey and alkaline beds, ground water may be meager in quantity and poor in quality; at intermediate levels, however, large supplies of good water are generally found. The province includes the Valley of Southern California and the Great Valley of California, in both of which water from the valley fill is extensively used for irrigation. Most of the water in the valleys of this province is recovered by means of wells, but there are also many springs, some of which are large. There are numerous areas of artesian flow, but most of the water for irrigation as well as other purposes is pumped. In mountain areas of the province there are, in the aggregate, many springs, small streams, and shallow wells that furnish valuable supplies. As a rule, the most favorable areas in the mountains for springs and shallow wells are the areas underlain by granitic rocks.

U. *Pacific Mountain province.*—This is a somewhat heterogeneous province, characterized chiefly by lofty mountains with some intermontane valleys and by heavy precipitation. Water supplies are obtained largely from the numerous streams. Many shallow wells are supplied from crystalline rocks in the Sierra Nevada and other parts of the province. The lowland areas of the northern part of the province are underlain largely by glacial drift that yields water freely. Tertiary formations, which are well developed in Oregon and Washington, would doubtless also yield much water.

INDEX.

★ U. S. GOVERNMENT PRINTING OFFICE : 1959 O—497781