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THE CRYSTAL CAVITIES OF THE NEW JERSEY ZEOLITE REGION

BY

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ABSTRACT

The crystal cavities present in the mineral complex of the New Jersey trap-rock region have long excited the interest of mineralogists. In 1914 Fenner made the first detailed and comprehensive study of these cavities and suggested that babingtonite was the original mineral. Soon after this anhydrite was found occupying parts of some of the cavities at one of the quarries. At this time, too, Wherry concluded that glauberite was the original mineral of some of the cavities because of his studies of similar crystal cavities in Triassic shale at different places.

The cavities are found in an altered extrusive trap rock of Triassic age which, as lava, had flowed into preexisting lakes that occupied depressed areas in which glauberite and other saline minerals had accumulated. Where the lava poured over dry Triassic shale it contains no crystal cavities. Where it poured into lake water rich in glauberite certain minerals formed in it that were subsequently altered, dissolved, and removed; but their shapes are still retained by abundant empty crystal cavities in their matrices. The original minerals whose removal left the cavities crystallized before their present matrices were formed. The chemical composition of the river waters of the region is such as to allow the formation of glauberite.

The constituents of glauberite—calcium and sodium sulphate—entered into the chemical system that resulted from the interaction of the lava and the lake waters and produced quantities of anhydrite and of glauberite, two minerals not at all common to trap rock in general or to its secondary minerals. This is the unusual feature of the occurrence. The subsequent removal of these minerals formed most of the crystal cavities now present. Six stages in the development of the minerals have been recognized, a somewhat longer sequence than that previously identified by Fenner.

These crystal cavities have commonly been called "pseudomorphs," hence a brief classification of pseudomorphs is presented in this report.

Although it has been considered by many that only one mineral caused the formation of these crystal cavities, it is now believed that many minerals have been dissolved and removed and have left their regular cavities behind. The cavities observed are grouped into four classes, which are discussed in detail—rectangular cavities after anhydrite, lamellar cavities after anhydrite and possibly after calcite and babingtonite, rhombic cavities after glauberite, and miscellaneous cavities after apophyllite, quartz, calcite, natrolite, pectolite, and other minerals.

The rectangular cavities are shown by both indirect and direct evidence to represent anhydrite. Original anhydrite has been found in many of them. The alteration of anhydrite to gypsum and to thaumasite is described.

The lamellar cavities mostly represent anhydrite, but lamellar calcite and babingtonite are considered as possible original minerals. A comparison is made between the lamellar cavities in specimens from this locality and cavities known to represent lamellar calcite in specimens from localities outside of New Jersey.

The rhombic cavities are shown to represent glauberite, even though no glauberite has been found in this region. Some quartz cores, infiltration pseudomorphs in the rhombic cavities, afford crystallographic evidence of the identity of the original mineral. Many of these cores have been measured, and an extensive set of measurements is given, showing their identity with the forms of glauberite.

The question whether babingtonite was the original mineral of these cavities is discussed, and it is shown that neither the form nor the mineralogic sequence of babingtonite allows it to be considered as the original mineral of the cavities.

THE CRYSTAL CAVITIES OF THE NEW JERSEY ZEOLITE REGION

By Waldemar T. Schaller

INTRODUCTION

The zeolite region of New Jersey, as it is known to mineralogists, lies in the broad northeast-southwest belt (Piedmont province) of Triassic sedimentary rocks and trap ridges (Watchung Mountains) that crosses the north-central part of the State. (See fig. 1.) The beautiful specimens of zeolites and associated minerals that have been found in this belt have made famous such locality names as Paterson, Great Notch, and Bergen Hill. A remarkable feature of the zeolite region is the occurrence at certain places of peculiar cavities in some of the rocks. Many of these cavities are regular, bounded by plane surfaces, and have the shape of crystals. It is obvious that they represent spaces once occupied by minerals long since removed. Some of the cavities are perfectly preserved, but others are uneven or corroded and indistinct because of the mineral changes undergone by their matrices. These cavities have long excited interest among mineralogists, and many have speculated about the identity of the minerals that once occupied them. The writer, who has had access to much excellent material, feels that it is now possible in large measure to solve this problem.

HISTORICAL SKETCH

Some of the earlier ideas regarding the origin of the crystal cavities were rather fantastic. For example, Hunt[1] suggested that the cavities are siliceous casts of pectolite, which had been decomposed by heat aided by borax derived from decomposed datolite. Some of them had been refilled by later silica. According to one of his statements, "Casts of calcite crystals in quartz forming pseudomorphs by incrustation are not uncommon." Canfield[2] wrote of "that mysterious mineral which has disappeared, leaving the molds or casts

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[1] Hunt, J. H., The Paterson minerals: Minerals, vol. 1, No. 3, pp. 71–75, 1892.

[2] Canfield, F. A., Thomsonite in New Jersey: School of Mines Quart., vol. 32, p. 216, 1911.

FIGURE 1.—Map of New Jersey showing position of Triassic belt and Watchung Mountains (Piedmont province). The cross ruling indicates the position of the group of localities from which the specimens containing cavities were obtained

of its crystals to puzzle collectors of Paterson and Great Notch specimens." Some have assumed that pectolite was the original mineral, and many specimens have been labeled "pectolite pseudomorphs," but there is no relation between the crystal forms of pectolite and those of the cavities. Other minerals that have been suggested from time to time include barite, celestite, aragonite, and scolecite. In 1895 Moses[3] made some casts of the prismatic cavities in quartz from McDowell's quarry, Upper Montclair, N. J., and found that they showed four longitudinal prismatic planes with an angle of 61½° truncated by one plane parallel to the longer diagonal of the rhombic cross section. This plane was inclined 41° to the prism. He called attention to the angular similarity of his specimens to orthoclase but doubted if orthoclase was the original mineral. As shown later, the angles he obtained agree very closely with those of glauberite.

Some years later Fenner[4] published a very comprehensive paper on the paragenesis of the zeolites of the Watchung Mountains, N. J., and showed that in certain areas peculiar structures had developed in the trap rock when in the form of lava it had flowed into one or more lakes that then occupied shallow basins in the continental Triassic sediments. Still later he found the mineral babingtonite[5] in some of the crystal cavities and suggested that this might be the mineral which had caused these puzzling features.

In 1914 new blasting operations at McKiernan & Bergin's quarry, on McBride Avenue, Paterson, disclosed a number of prismatic quartz pseudomorphs, several of which showed terminal faces. These pseudomorphs filled rhombic holes identical in shape with many of the cavities earlier found. Although the writer carefully studied their crystallography he at first reached no conclusion about the identity of the original mineral. In November of that year, however, blasting at the West Paterson quarry revealed considerable anhydrite in the trap rock, and Allen[6] soon showed that some of the cavities of the region were due to this mineral. The anhydrite had altered first to gypsum, then to thaumasite, and finally had been almost dissolved away. The rectangular cavities left in the quartz had the shape of the original anhydrite crystals. The finding of anhydrite threw new light on the origin of these puzzling crystal cavities, for anhydrite is not a normal constituent of trap rock. Obviously some geologic factor, not sufficiently considered in previous investigations, was involved in the problem. This discovery at

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[3] Moses, A. J., Hollow pseudomorphs of quartz after an unknown mineral: School of Mines Quart., vol. 16, pp. 230–231, 1895.

[4] Fenner, C. N., The Watchung basalt and the paragenesis of its zeolites and other secondary minerals: New York Acad. Sci. Annals, vol. 20, pp. 93–187, 1910.

[5] Fenner, C. N., Babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, pp. 552–558, 1914.

[6] Allen, F. I., The origin of thaumasite: Am. Jour. Sci., 4th ser., vol. 39, p. 134, 1915. See also New York Times, Nov. 23, 1914, p. 7, cols. 3–4.

once suggested that some saline compound in the lake postulated by Fenner might have contributed calcium sulphate which had later recrystallized in the trap rock as anhydrite. If anhydrite could form in this way, why could not other saline minerals, especially those that contained calcium sulphate? In the light of this new evidence Fenner[7] concluded that other minerals besides babingtonite may have participated in the formation of the cavities.

In 1916 Wherry[8] published two papers on crystal cavities. He discussed other occurrences of similar cavities in the Triassic sedimentary rocks of eastern Pennsylvania, the original mineral in which he had determined to be glauberite. (See pl. 1.) Recognizing the similarity of the cavities in the Pennsylvania localities to those in the zeolite region of New Jersey, he concluded that the original mineral in the New Jersey localities was likewise glauberite. In the second paper cited he wrote:

> When the Triassic rivers spread over their flood plains, forming lakes, puddles, or swamps, from which the water rapidly evaporated, any saline constituents present in the water would, of course, crystallize out. The waters of many existing rivers are characterized by the presence of the ions of sulphuric acid, calcium, and sodium, and the same may well have been true of those of Triassic times; these constituents would crystallize together as glauberite. When a small body of water was formed evaporation would occur with especial rapidity, and numerous small crystals would result; when a large lake developed, so that crystallization could take place more gradually, the crystals would be fewer in number but larger in size. When mud surrounded the crystals and protected them from re-solution, their form would be accurately preserved; when partial solution could take place owing to dilution, cavernous faces would be produced. All of the features of the occurrences above described can thus be readily explained.

The writer's crystal measurements on quartz pseudomorphs from Paterson have since fully confirmed this conclusion.

Since Wherry's discoveries Stose[9] has observed and described glauberite crystal cavities near Gettysburg, Pa., and Hawkins[10] has described pseudomorphs of calcite and analcite after glauberite from a locality near Princeton, N. J. (See pl. 1.) The only other papers that contribute to the solution of the problem of the identity of the

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[7] Fenner, C. N., Additional notes on babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, pp. 598–605, 1914.

[8] Wherry, E. T., The lozenge-shaped cavities in the First Watchung Mountain zeolite deposits: Washington Acad. Sci. Jour., vol. 6, pp. 181–184, 1916; Glauberite crystal cavities in the Triassic rocks of eastern Pennsylvania: Am. Mineralogist, vol. 1, pp. 37–43, 1916.

[9] Stose, G. W., Glauberite crystal cavities in the Triassic rocks in the vicinity of Gettysburg, Pa.: Am. Mineralogist, vol. 4, pp. 1–4, 1919.

[10] Hawkins, A. C., Lockatong formation of the Triassic of New Jersey and Pennsylvania: New York Acad. Sci. Annals, vol. 23, pp. 163–164, 1914; Halite and glauberite cavities and included minerals from central New Jersey: Am. Mineralogist, vol. 13, pp. 238–239, 1928.

minerals now represented by the crystal cavities are those by Gordon,[11] Glenn,[12] and Shannon.[13]

SPECIMEN LOCALITIES

Zeolites and associated calcite, quartz, and other minerals, have been found at numerous places in the Triassic trap rocks of New Jersey, but the specimens containing the crystal cavities described in this report have all come from the northern part of First Watchung Mountain (fig. 1), specifically from Paterson, Great Notch, Cedar Grove, the reservoir of the Newark Water Department (about half a mile south of Great Notch station), and Upper Montclair. Some of the specimens have passed through many hands, and the correctness of many of the accompanying labels is questionable. Specimens from different localities look so much alike that they can not readily be distinguished from one another. In this paper an attempt has been made to give the exact locality of each specimen described, but some errors will doubtless be found. The exact locality, however, is not of great importance in this discussion, for the places mentioned are all near together. Crystal cavities have not been recorded from any of the zeolite localities around Jersey City, such as Bergen Hill and Weehawken; therefore it is evident that geologic conditions near Jersey City were somewhat different from those near Paterson when the original minerals that occupied crystal cavities were being formed. Similar crystal cavities probably occur over a somewhat more extended area, especially toward the south, but the extensive quarrying operations in the region between Paterson and Montclair have made this region the favorite collecting place for mineralogists. Possibly the outlines of the former Lake Paterson[14] might be considered the outside boundaries of the area in which these crystal cavities are likely to be found.

The localities furnishing the specimens described in this paper are listed below:

Hoxie's quarry, half a block south of Union Avenue and Marion Street, Paterson. Now built over. Some of the older specimens described as coming from Burger's quarry may have been collected at Hoxie's quarry. This applies particularly to some of the older specimens collected by W. S. Disbrow.

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[11] Gordon, S. G., A review of the genesis of the zeolite deposits of First Watchung Mountain, N. J.: Am. Mineralogist, vol. 1, pp. 73–80, 1916.

[12] Glenn, M. L., Pectolite pseudomorphs after quartz from West Paterson, N. J.: Am. Mineralogist, vol. 2, pp. 43–45, 1917.

[13] Shannon, E. V., The trap quarry at Meriden, Conn.: Am. Mineralogist, vol. 5, p. 34, 1920.

[14] Fenner, C. N., Features indicative of physiographic conditions prevailing at the time of the trap extrusions in New Jersey: Jour. Geology, vol. 16, pp. 312–323, 1908.

Burger's quarry. The quarries of the Paterson Crushed Stone Co. are located on both sides of New Street, Paterson, and are commonly referred to as in West Paterson. Local collectors distinguished the old or upper quarry from the new or lower quarry along the railroad track. The old or upper quarry is best known to collectors as Burger's quarry, and is so designated in this paper. It is here that the anhydrite was found in 1914.

McKiernan & Bergin's quarry, on McBride Avenue, Paterson, sometimes referred to as Hawkins quarry. Here the "cores" or quartz pseudomorphs after glauberite were found. The quartz pseudomorphs of the rhombic cavities found in this quarry form the best material for the determination of the crystal forms of the original mineral.

Francisco Bros.' quarry and Crushed Stone quarry, Great Notch, commonly referred to simply as Great Notch. Two adjacent quarries and the dump from a water-supply tunnel near by are three other localities usually included under the term Great Notch.

Cedar Grove, a quarry along the railroad, between Great Notch and Montclair.

Osborne & Marsellis's quarry, also known as McDowell's quarry, Upper Montclair, commonly referred to simply as Upper Montclair.

Paterson and Great Notch are in Passaic County; Cedar Grove and Upper Montclair in Essex County.

ACKNOWLEDGMENTS

The writer gratefully acknowledges his indebtedness to Mr. Frederick I. Allen, of New York, who gave him opportunity to study his private collection of anhydrite specimens and quartz pseudomorphs from the Hawkins quarry. Dr. W. S. Disbrow, of Newark, gave most liberally of his large collection of zeolites and associated minerals, most of which he had personally collected. Col. W. A. Roebling, of Trenton, N. J.; Mr. F. A. Canfield, of Dover, N. J.; Dr. H. P. Whitlock, of the American Museum of Natural History, New York; Mr. G. S. Stanton and Mr. J. G. Manchester, of New York; and Mr. G. O. Simmons, of Brooklyn, N. Y., were all very courteous in allowing free use of their specimens, many of which are illustrated in this report. Dr. E. T. Wherry, formerly of the United States National Museum, and Dr. W. F. Foshag, now a curator of the United States National Museum, have both kindly placed the museum specimens at the writer's disposal and in advice and suggestions have contributed much to this report. Mr. Robert Mercer, superintendent of the West Paterson quarry, has much appreciated the interest taken in the minerals found in the quarry and has made available to the student many valuable specimens that would otherwise have been lost. Mr. J. W. Hawkins, superintendent of McKiernan & Bergin's quarry, also contributed several specimens. Messrs. Adolph Knopf, F. C. Schrader, B. S. Butler, and E. L. Jones, former and present colleagues in the Geological Survey, furnished a number of specimens of crystal cavities after calcite from various localities in the West, some of which are here illustrated for comparative purposes.

GEOLOGY

GENERAL FEATURES

Although the problem of the origin of the crystal cavities is largely mineralogic, the geologic history of the region has had a most important bearing on it. The following geologic sketch has been compiled largely from papers by Fenner[15] and by Lewis and Kümmel.[16]

The rocks of New Jersey are mostly sedimentary and range in age from pre-Cambrian to Recent. Their general distribution is shown in Figure 1, which indicates that they lie in belts of northeasterly trend. The northwesternmost belt is underlain by Paleozoic rocks and is part of the Valley and Ridge province.

The next belt southeastward comprises the Highlands of New Jersey, which connect northeastward with those of New England, and is underlain by crystalline rocks, both metamorphic and igneous. The metamorphic rocks are chiefly pre-Cambrian gneisses and schists, with some crystalline limestones. Intimately associated with them in considerable proportion are igneous rocks, such as granite, gabbro, serpentine, syenite, and basic volcanic breccia. These two belts together occupy about one-fifth of the State.

Adjoining the Highlands on the southeast is a broad lowland which slopes gently southeastward and is interrupted by ridges and gently rolling hills, the more prominent of which are underlain by basalt or diabase (trap rocks). The Watchung Mountains, the highest ridges, rise nearly 900 feet above sea level. The other rocks of the belt are relatively soft sandstones and shales and, together with the trap rocks, are of Triassic age. Most of the material that formed the Triassic strata was derived from granitic rocks and consists of fragments of quartz, undecomposed feldspars mixed with iron oxides, and scattered pebbles of limestone. The resulting red sandstones and shales now dip rather uniformly toward the northwest at angles of 10° to 15°, and form a monocline which is locally gently flexed. This belt forms part of the Piedmont province which, like the other divisons named, is part of the Appalachian Highlands of the eastern United States. The New Jersey portion of this province lies in the Piedmont Lowlands, being a plain rather than a plateau. It, too, occupies about one-fifth of the State.

The remaining three-fifths of the State is part of the Atlantic Plain and is chiefly underlain by marine beds of sand, gravel, marl,

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[15] Fenner, C. N., Features indicative of physiographic conditions prevailing at the time of the trap extrusions in New Jersey: Jour. Geology, vol. 16, pp. 299–327, 1908; The Watchung basalt and the paragenesis of its zeolites and other secondary minerals: New York Acad. Sci. Annals, vol. 20, pp. 93–187, 1910.

[16] Lewis, J. V., and Kümmel, H. B., The geology of New Jersey: New Jersey Geol. Survey Bull. 14, 1915.

and clay of Cretaceous and Tertiary age. The Quaternary deposits of sand, gravel, morainic material, and mud are relatively insignificant.

BEARING OF TRIASSIC HISTORY

The principal events of the geologic history that bear upon the crystal cavities relate to the origin of the Triassic rocks, the Newark group. These were formed not long after the Appalachian revolution. The Paleozoic and pre-Cambrian rocks had been folded into mountain ranges with northeastward-trending axes, and there were broad intermontane depressions that gradually deepened and became filled with material washed from the neighboring mountains. Some of this material was in the form of coalescing fans laid down by streams, but some of it was deposited in lakes. Faulting occurred during the period of sedimentation and produced displacements ranging from a few inches to thousands of feet. Accompanying the faulting or perhaps in part preceding it great sheets of basalt were poured out at intervals on the sedimentary beds and were in turn buried by later accumulations of sediment. The great sill of Palisade diabase was also intruded during this epoch.

The climate was dry or semiarid while the rocks of the Newark group were being deposited, and because some of the lakes were without outlet the concentration of their waters produced salts, chiefly the carbonates, sulphates, and chlorides of calcium and sodium, which accumulated locally in considerable quantity.

The waters of the more or less ephemeral Triassic lakes played a most important part in the story of the crystal cavities. When lava flowed into these lakes the water chilled parts of it to basaltic glass instead of allowing it to crystallize as a dense, homogeneous mass. The sodium and calcium sulphates contained in the water were abundant enough in some of the lakes to form an unusual mixture with the lava, so that both anhydrite and glauberite later crystallized out, at some places singly and at others intermingled. Some of the crystals formed during the cooling of the lava in both its glassy and its more crystalline phases were several inches long.

In some of the lakes not entered by lava crystals of glauberite formed in the muds, as noted by Wherry (p. 4). The discovery of cavities formerly occupied by these crystals has furnished the clue for unraveling the more complicated part of the story, which concerns the changes experienced by the minerals formed in the lava that flowed into saline lakes—the changes that produced the zeolites and the crystal cavities.

The contrast in the behavior of the lava that entered lakes as compared with that which spread over ordinary sediments is illustrated in Plates 2 and 3.

Plate 2, *A*, illustrates the condition and appearance of a lava flow that came to rest quietly over dry sediments and crystallized to a normal compact basalt. Plate 2, *B*, shows the somewhat similar conditions to be seen at the base of a great sill. In Plate 3, however, the lava illustrated flowed into water and acquired a spheroidal or boulderlike structure. Excellent illustrations of the boulderlike structure are also shown by Lewis[17] and by Fenner.[18] The outside of each bouldery mass solidified to basaltic glass, but the inside crystallized to normal basalt. In some places the development of the spheroidal phase with much basaltic glass extended only part way upward in the lava. The higher parts there crystallized to dense uniform trap rock similar to that shown in Plate 2. The occurrence together of these two types of volcanic rock is shown in Plate 3, *B;* the crystal cavities appear only in the lower spheroidal phase.

PROCESSES OF ZEOLITIC MINERAL FORMATION

The processes that become operative immediately after the outpouring of lava on a lake bed have been admirably described by Fenner,[19] from whose paper the following notes have largely been taken. He has described in great detail the processes of zeolitic mineral formation and replacement at this locality.

A good deal of open space was formed in the rock by the shrinkage of the basaltic glass and by the cracking of the glass in its brecciation due to cooling. This open space gave access to heated vapors and water from the lake beds, impregnated with the saline minerals, and to very fine lake mud. The violent eruption of heated gases still further cracked the volcanic glass and opened some larger passages. This action induced the formation of additional minute cracks and closed some that had previously been formed. The lava above the lake bed became porous and permitted ready circulation of water. Steam from lake water may have introduced into the lava a little saline matter; more would be carried into it by the very hot lake waters or by heated meteoric waters that flowed into the lava from the sedimentary layer immediately beneath. The hot meteoric water would dissolve the saline minerals in the sediments and bring them into the porous lava.

In a lava flow most of the gases originally present in the molten rock usually escape into the atmosphere. Solidification by crystallization also excludes some of the gases. But the Watchung basalt soldified soon after its eruption, and gases escaped for only a short

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[17] Lewis, J. V., Petrography of the Newark igneous rocks of New Jersey: New Jersey Geol. Survey Ann. Rept. for 1907, pl. 43, 1907.

[18] Fenner, C. N., The Watchung basalt and the paragenesis of its zeolites and other secondary minerals: New York Acad. Sci. Annals, vol. 20, pl. 10, 1910.

[19] Idem, pp. 93–187, pl. 10.

time, so that the crust effectively retained some of the gases within the lava. Sublimates (B, S, Cu, and Fe compounds) whose sublimation temperatures were high therefore formed in cracks and crevices in the already solidified parts of the rock and became accessible to later circulating waters.

The heat of the lava probably vaporized much of the water in the shallow lake, together with some of the meteoric water that came in from below, but the temperature gradually fell, and soon the water level in the porous lava rose. Fenner has calculated that under the conditions described a maximum temperature of 180° C. may have been reached.

The circulating hot waters had several functions—they served as a medium in which chemical reactions took place; they carried in solution into the lava the constituents of the saline minerals from the lake and the underlying lake beds; they dissolved the volcanic glass and thus afforded wider channels for circulation; they added material for the formation of new minerals; and they dissolved and brought into the field of reaction the sublimates previously deposited in the cracks of the lava.

The aqueous solutions that moved through the lava were heated by it as the lava cooled. But after reaching a maximum temperature these solutions themselves cooled. There then ensued a continuous change of direction in the chemical and physical processes at work in the solutions. This change affected not only the temperature but also the concentration and character of the material deposited and of that left in solution. Conditions of chemical equilibrium were continuously changing. Minerals first deposited became unstable and were dissolved, and from this changed solution new minerals were separated.

The lava which has undergone extensive alteration into the present aggregate of calcite, quartz, and zeolites and which originally consisted in large part of basaltic glass is here called "zeolitic rock." As matrix to the well-developed minerals it includes portions of the fine-grained crystalline basalt as well as calcite, quartz, zeolites, and other associated minerals. Its boundaries are somewhat indefinite, but distinction is readily made between zeolitic rock and normal trap rock free or nearly free from zeolites.

Occurrences of zeolites in the more coarsely crystalline intrusive Palisade diabase are very different from those at Paterson and neighboring localities. In the Palisades, at Bergen Hill, Weehawken, and elsewhere, the zeolites and associated calcite, quartz, and other minerals occur in vertical fissures in the trap rock, which there has no spheroidal facies. Fissures similar to those of the Palisade diabase, in part filled with calcite and zeolites, are conspicuous at Francisco Bros.' quarry at Great Notch, above the spheroidal zeolitic rock. (See pl. 3, *B*.) There are no crystal cavities, however, in the material filling these vertical fissures, either at Great Notch or at any of the Palisade occurrences.

Crystal cavities might well have been formed occasionally in the compact lava above the spheroidal layers at this locality, for the heated waters might readily have carried upward into fissures in the compact trap some of the saline constituents of the lake. But, as a matter of fact, no such occurrences of the crystal cavities in the compact trap are known to the writer. For example, in Manchester's paper[20] on the zeolites and associated minerals from the Erie Railroad cut through Bergen Hill, Jersey City, no crystal cavities are described.

CHEMISTRY

In the preceding section it has been suggested that the constituents of the saline minerals of the lake beds, over which the lava of First Watchung Mountain flowed, were brought in solution by rivers flowing from the high surrounding mountains. What were these constituents? The following table presents four composite analyses of river water from New Jersey and the immediate vicinity and also shows, for comparison, the average composition of river and lake waters of the United States, all after Clarke.[21]

Analyses of river waters

[Per cent of anhydrous residue]

	1	2	3	4	5		1	2	3	4	5
CO_3	35.45	29.48	32.95	23.54	33.40	Mg	3.76	4.58	4.81	4.08	4.87
SO_4	15.84	14.08	17.49	27.53	15.31	K	1.78	1.76	1.46	1.33	1.77
Cl	3.96	5.52	4.23	7.19	7.44	SiO_2	10.90	18.77	13.12	7.72	8.60
NO_3	.79	2.23	1.60	3.02	1.15	Fe_2O_3	.20	.23	.15	.11	[a] .64
Ca	20.79	14.08	17.49	18.64	19.36						
Na	6.53	9.27	6.70	6.84	7.46		100.00	100.00	100.00	100.00	100.00

[a] Including Al_2O_3.

1. Hudson River at Hudson, N. Y. Mean of 36 composites.
2. Raritan River at Bound Brook, N. J. Mean of 35 composites.
3. Delaware River at Lambertville, N. J. Mean of 34 composites.
4. Susquehanna River at Danville, Pa. Mean of 36 composites.
5. Average composition of river and lake waters of the United States.

How closely these analyses represent the composition of Triassic river waters is unknown, though there is nothing to indicate that it was radically different from that of river waters to-day in the same

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[20] Manchester, J. G., The minerals of the Bergen Archways: Am. Mineralogist, vol. 4, pp. 107-116, 1919.

[21] Clarke, F. W., The data of geochemistry, 5th ed.: U. S. Geol. Survey Bull. 770, pp 76, 119, 1924.

area. Perhaps the very different climatic conditions of Triassic time may have affected the absolute concentration of the salts in these waters. However, it seems justifiable to assume that the character and quantity of the mineral contents in Triassic river waters are represented with reasonable accuracy by these analyses. The chlorine and sodium content of New Jersey river water is probably relatively greater now than in earlier times, because of human contamination and of present proximity to the sea.

The predominating acids in the analyses cited are those yielding carbonates, silicates, sulphates, and chlorides. The predominating bases are calcium, sodium, and magnesium. The concentration of the river waters in lake beds by evaporation, as described on pages 4 and 8, would tend to render the silica insoluble.

According to Clarke,[22] these lake-bed concentrates would contain

> ions capable of forming the chlorides, sulphates, and carbonates of sodium, calcium, and magnesium, which are the chief salts derivable from natural waters. Upon concentration, the difficultly soluble carbonates of calcium and magnesium will be precipitated first, to be followed by the slightly soluble gypsum. Next in order sodium sulphate and carbonate will form, and these salts are deposited by many saline or alkaline waters. Later, sodium chloride and magnesium sulphate may crystallize out, leaving at last a bittern containing the very soluble chlorides of calcium and magnesium. This is the observed order of concentration, but every step is not necessarily taken in every instance. All of the calcium may be eliminated as carbonate, leaving none for the formation of other salts. All of the sulphuric ions may be taken to produce gypsum, and then no sodium sulphate can form. In short, the actual changes which take place during the concentration of a specified water depend on the proportions of its constituents and vary from case to case. The proposed order of deposition is simply the general order, which conforms to the facts of observation and to the known solubilities of the several salts. The least soluble possible salt will form first; the most soluble will remain longest in solution.

The sulphates and carbonates of calcium and sodium would thus tend to accumulate as solids in the lake beds, but the very soluble chlorides of calcium and magnesium might be washed away by floods, rains, or other means, though if the lake had no outlet they, too, would accumulate in the same way. A further source of loss of the chlorides and possibly also of some of the less soluble salts lies in their tendency to effloresce by capillarity and then be blown away by wind.

The finding of numerous glauberite cavities in the Triassic shale in many places clearly shows that in some areas the sulphates of calcium and sodium were concentrated enough to form large quantities of glauberite. According to Stose,[23]

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[22] Clarke, F. W., The data of geochemistry, 5th ed.: U. S. Geol. Survey Bull. 770, p. 180, 1924.

[23] Stose, G. W., op. cit., p. 4.

It is probable that glauberite crystallized out of ponded waters at various times during the Triassic epoch; and the crystals were inclosed at many horizons throughout the Triassic section, although thus far clearly defined molds of the mineral have been found in this area only in beds which have been somewhat hardened by the metamorphic action of the intrusive diabase.

Many evidences of the formation of saline minerals in the Triassic muds and shales of this region may have been obliterated through geologic processes. More extended search may show them to be far more abundant than is now known.

The chemical elements contributed by the lake waters to the zeolitic rock are as follows:

Calcium was doubtless present in large quantity. Calcium salts are commonly found in the salines produced by the evaporation of river waters, and the abundance of glauberite (calcium-sodium sulphate) in the Triassic shales and sandstones is further evidence of plentiful calcium. The calcium content of the waters circulating through the basalts must have been high, and as a result many minerals containing calcium were formed—for example, anhydrite, glauberite, calcite, and prehnite.

Sodium is indicated by the same evidence as calcium, and the list of sodium minerals is long, including glauberite, albite, pectolite, stilbite, natrolite, analcite, and others. The greater solubility of sodium compounds as compared with those of calcium explains the greater abundance of calcium minerals among those first formed.

Very little, if any, of the iron abstracted from the lake muds entered directly into any of the chemical reactions that took place in the zeolitic rock, but iron-stained mud was carried mechanically upward by steam and water and deposited around some of the earliest formed minerals. When these in turn were surrounded by deposits of silica, this mud impregnated portions of the silica and helped to form the narrow bands that now surround the cavities.

Carbon, as carbonate, may have been one of the chief acid-forming elements contributed by the lake beds. Calcite is very abundant in the zeolite rock now, and its carbonic acid has been attributed by Fenner to an atmospheric source. Some of it, however, may have come from carbonates in the lake beds. The calcium carbonate dissolved by hot waters and carried in solution into the basalt may have yielded a slight precipitate of lamellar calcite in the early stages of mineral formation, but most of the earlier carbonate remained in solution until the last stages of mineral formation.

Sulphur, as sulphate, was the other acid-forming element present in abundance in the lake beds, in the form of glauberite and possibly gypsum and other rarer sulphates.

Silicon, as silica, may have been added to a considerable extent by the quartz of the Triassic sandstones and shales, over which the lava flowed.

Chlorine is present to-day in the river waters, as shown in the analyses on page 11, in quantities ranging from 3 to 8 per cent. These proportions are doubtless higher than they were in Triassic time. Much of the chloride in the salines may have been lost from the lake beds by flooding or efflorescence. Crystal cavities after sodium chloride are practically absent in the Triassic sedimentary formations of this region. Hawkins [24] describes two " excellent casts of halite crystals " in Triassic red shales near New Brunswick, N. J., and notes that " there is no record of such halite crystal cavities having been found previously in this formation at any point south of Massachusetts."

Other elements not mentioned in the river analyses, but found to-day in the zeolitic rock, have been attributed to the sublimation products of the basaltic rock, but their derivation from the lake beds is not excluded.

Sulphur occurs sparingly as sulphides in the zeolitic rock. These may have been formed in part by the reduction of sulphates derived from the lake beds. Organic matter in the lake beds may have acted as a reducing agent.

Copper is most simply explained as from the basaltic rock, but the presence of copper in sedimentary beds elsewhere (the Triassic " Red Beds " of the Southwest, especially in New Mexico, and the Triassic of western Europe) suggests the possibility that at least part of the copper in the zeolitic rock of New Jersey may have come from the lake beds.

The chemical elements contributed by the basalt, especially in its glassy phase, are shown by the following analyses:

Analyses of basalt from First Watchung Mountain

	1	2	3		1	2	3
SiO_2	51.36	51.82	50.19	Na_2O	1.54	2.79	2.64
Al_2O_3	16.25	14.18	14.65	K_2O	1.06	1.26	.75
Fe_2O_3	2.14	.57	3.41	TiO_2		1.17	1.13
FeO	8.24	9.07	6.96	P_2O_5		.17	.18
MnO	.09	.13	.07	H_2O	1.33	1.70	3.04
MgO	7.97	8.39	7.95				
CaO	10.27	8.60	9.33		100.25	99.85	100.30

1. Watchung Mountain, N. J. L. G. Eakins, analyst; U. S. Geol. Survey Bull. 150, p. 255, 1898.
2. Scotch Plains, N. J. R. B. Gage, analyst; New Jersey Geol. Survey Ann. Rept. for 1907, p. 159, 1907.
3. Near Springfield, N. J. Idem.

Silicon, as silica, forms about half of the basalt, and the minerals derived from its alteration are rich in silica, as shown by the fact that silicates (zeolites), with quartz, are the dominant minerals of the zeolitic rock.

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[24] Hawkins, A. C., Halite and glauberite cavities and included minerals from central New Jersey: Am. Mineralogist, vol. 13, p. 238, 1928.

Aluminum is derived from pyroxene and feldspar. The abundance of aluminum silicates (the zeolites) testifies to the large amount of aluminum originally present.

Iron is derived from pyroxene, olivine (or its altered forms, chlorite and serpentine), the iron ores, magnetite and ilmenite, and possibly from hematite that may have been among the sublimation products of the basalt.

Magnesium is derived from olivine and secondary chlorite and serpentine.

Calcium is a constituent of pyroxene and feldspar. The calcium content of the basalt was considerably augmented by calcium from the salines in the lake beds.

Sodium was present in the basalt, chiefly in the feldspar. Its proportion, less than 3 per cent, is rather small to account for the large amount of sodium silicates now present. The glauberite of the lake beds no doubt contributed considerably to the total sodium present in the zeolitic rock.

Potassium was relatively sparse and as practically none was contributed by the lake beds its effect in the production of zeolitic minerals is small. The only potassium mineral in this association is apophyllite.

Manganese, titanium, and phosphorus occurred in relatively small quantities in the basalt. They received no increase from the lake beds and took little part in the subsequent mineral development.

The elements listed below are not reported in the analyses of the Watchung basalt but may have been originally present in this basalt. Fenner considered them to be among the sublimation products of the lava.

Boron, as boracic acid, is a well-known product of volcanic activity, and borates are common among volcanic sublimates. The presence of much datolite in the intrusive volcanic rock of the Bergen Hill region, where no lake beds were present, shows that the boric acid in the datolite was contributed by the lava.

Sulphur, as sulphides, is now found in chalcopyrite and other sulphides, which have derived their sulphur from the sublimates of the lava.

Copper may well have been among the sublimates of the basalt. Sublimates of copper minerals are well known to occur at Vesuvius and other localities of volcanic rocks. Some of the trap rocks of New Jersey contain chalcopyrite, and some of the pyroxene contains traces of copper.

Fluorine has likewise been referred to the basaltic sublimates.

The following table summarizes the derivation of the chemical elements now found in the zeolitic rock:

Source and relative quantities of chemical elements now found in the zeolitic rock

Chemical element	Basalt	Lake beds	Chemical element	Basalt	Lake beds
Oxygen	Much	Much.	Potassium	All	None.
Hydrogen	Little	Most.	Carbon	None [a]	Little.[a]
Silicon	Most	Little.	Sulphur	Little	Most.
Aluminum	All	None.	Boron	All	None.
Iron	Most	Little.	Copper	Much	Much?
Magnesium	All	None.	Fluorine	All	None.
Calcium	Much	Much.	Chlorine	None?	Little.
Sodium	do	Do.			

[a] Much of the carbon, as carbonate, was derived from the atmosphere and meteoric waters.

The chief contributions of basalt were silica, alumina, lime, iron oxide, magnesia, soda, and boric acid; of the lake beds, carbonates, sulphates, lime, and soda.

It should be emphasized that the saline minerals of the lake waters and muds were not carried into the lava as solids by the ascending waters. These salts were in solution in waters hot enough to increase markedly their solvent power. The mineral identity of the salts thus carried into the lava was therefore completely lost, and it can only be said that the lake beds furnished material capable of forming carbonates and sulphates of sodium and calcium. Anhydrite probably did not exist in the lake beds. Calcium sulphate, however, did exist there as a constituent of glauberite. The albitization described by Fenner as one of the first mineral changes that took place may have been accelerated by the increase in the percentage of sodium in the waters when the calcium crystallized out as anhydrite.

The waters that formed the zeolitic rock thus contained a complex mixture of various elements. The order of succession of the minerals formed was dependent mostly on the solubility of certain compounds in the solution at any particular stage. The recognition of this order has therefore permitted the subdivision of the whole process of zeolitic mineral formation into two well-defined but overlapping epochs.

In the beginning of the first epoch sulphates were the least soluble compounds in the solution, and consequently large quantities of glauberite and anhydrite were formed. Later on quartz was formed, followed by the crystallization of prehnite, pectolite, and datolite. The first epoch was constructive; it formed minerals in large quantities directly from a solution of their ions. The later part of the first epoch overlapped the second epoch, which was both destructive and constructive. The new minerals formed in the second epoch derived their constituents largely from minerals of the first epoch. The lower temperature, the lower silica content, and the lower concentration of most of the chemical elements in the solutions gave rise to conditions very different from those of the first epoch. The sulphates had become soluble, and the minerals formed were mostly hydrous. The processes of alteration are still active.

The continuous addition of meteoric water diluted the solutions that had first been active, so that as time went on they dissolved some of the earlier-precipitated sulphates.

MINERALOGY

MINERALOGIC PROCESSES

The following list includes most of the minerals found in the trap rock of New Jersey. A few of the rare ones may be omitted, but for the present purpose greatest interest attaches to the abundant minerals. The minerals are grouped according to genetic relationships as primary, hydrothermal metamorphic, and weathering, as in Gordon's classification,[25] though several of the minerals that he ascribes to weathering (gypsum, thaumasite, and aragonite) are here classified as hydrothermal metamorphic minerals.

Primary minerals: Olivine, labradorite, diopside, magnetite (and the glassy phase of the basalt). Lewis[26] adds biotite, quartz, orthoclase, pyrite, apatite, chalcopyrite, and rutile.

Hydrothermal metamorphic minerals (essentially the list given by Lewis): Albite, amphiboles (several varieties), analcite, anhydrite, apatite, apophyllite, aragonite, babingtonite, barite, biotite, brookite, calcite, chabazite, chalcedony, chalcocite, chalcopyrite, chlorite, copper, cuprite, datolite, dolomite, epidote, fluorite, galena, garnet, glauberite (only as cavities and quartz pseudomorphs), gmelinite, gypsum, hayesine (from the Bergen Hill region), hematite, ilmenite, laumontite, marcasite, mesolite, natrolite, opal, orthoclase, pectolite, prehnite, psilomelane, pyrite (?), pyrolusite, pyrrhotite, quartz (several varieties), rhodochrosite, scolecite, serpentine, sphalerite, siderite, silver, stilbite, talc, thaumasite, thomsonite, and tourmaline.

Weathering: Azurite, chrysocolla, limonite, malachite, manganese oxide (?), opal (?), and stevensite.

The paragenesis of these minerals has been so well described by Fenner[27] that his lists of mineral succession or sequences are adopted, though with slight modification and with the addition of later discoveries. The question of mineral succession or sequence is of great importance for this paper, because the identity of the minerals that originally occupied the crystal cavities depends on it to a large extent.

All close students of the occurrence of these crystal cavities have noted that the rhombic cavities are found almost wholly in quartz,

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[25] Gordon, S. G., A review of the genesis of the zeolite deposits of First Watchung Mountain, N. J.: Am. Mineralogist, vol. 1, pp. 73–80, 1916.

[26] Lewis, J., Origin of the secondary minerals of the Triassic trap rocks: New Jersey Geol. Survey Bull. 16, pp. 45–49, 1915.

[27] Fenner, C. N., The Watchung basalt and the paragenesis of the zeolites and other secondary minerals: New York Acad. Sci. Annals, vol. 20, pp. 120–180, 1910.

whereas the rectangular and lamellar cavities occur not only in quartz but in prehnite, datolite, pectolite, and several of the zeolites. This naturally implies, as noted by Fenner,[28] a difference in conditions of deposition. It would also seem to imply a decided time difference in stability of the original minerals; the original mineral of the rhombic cavities was no longer stable and could not exist when prehnite, datolite, pectolite, and certain zeolites were forming unless it was protected by its matrix from the attack of circulating solutions.

Fenner [29] has divided the process of mineral alteration into three periods, as follows:

Period I. Boric acid period:
  Stage 1. Albite, quartz, garnet, amphibole, specularite, sulphides.
  Stage 2, Datolite, prehnite, pectolite, amphiboles, specularite, sulphides.
Period II. Zeolite period: Zeolites, amphiboles, chlorite, specularite, sulphides.
Period III. Calcite period: Thaumasite, calcite, gypsum, amphiboles, chlorite, specularite, sulphides.

These three periods of mineral alteration may be extended to six by raising the two stages of period I to period rank and by assigning to additional periods the original solidification of the trap rock and basaltic glass and the formation of the saline minerals derived from the lake waters. The raising of Fenner's two stages to period rank seems fully justifiable from genetic considerations and also for simplicity of classification.

The six periods of mineral formation thus recognized in the zeolitic rock are as follows:

1. Trap rock and basaltic glass period: Olivine, labradorite, diopside, magnetite, basaltic glass.
2. Saline period: Saline minerals, derived from the lake waters—the original minerals of most of the crystal cavities. Anhydrite and glauberite. Possibly lamellar calcite.
3. Quartz period (stage 1 of Fenner's period I): Quartz, largely of the massive variety (some of the euhedral crystals may belong to a later period), albite, babingtonite (?), amphiboles, garnets, specularite, sulphides.
4. Prehnite period (stage 2 of Fenner's period I): Prehnite, pectolite, datolite, amphiboles, specularite, sulphides.
5. Zeolite period (Fenner's period II): Zeolites, chlorite, specularite, sulphides.
6. Calcite period (Fenner's period III): Calcite, babingtonite, gypsum, thaumasite, amphiboles, chlorite, specularite, sulphides.

Although parts of the trap-rock formation were the first of these to form, it is probable that at some places minerals of the saline period began and ended their formation before all the lava had completely solidified. Periods 1 and 2 thus overlapped in time of formation to a considerable extent. Period 3, the quartz period, followed closely, and its minerals surrounded the crystals of the saline

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[28] Fenner, C. N., Additional notes on babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, p. 604, 1914.

[29] Fenner, C. N., op. cit. (1910), p. 121.

group, firmly preserving their shape for posterity. This was accomplished, in general, by a quartz replacement of the basaltic glass and trap rock surrounding the saline minerals, which were not themselves affected by the quartz-forming solutions. Could the early formation of considerable quartz be due in part to the assimilation of the abundant quartz of the Triassic sediments by the lava? Fenner's descriptions suggest that a small quantity of babingtonite may have formed during this period, immediately after the anhydrite and before the quartz. It was thus emplaced between anhydrite and quartz, where it is found to-day in a few of those rectangular cavities from which the anhydrite was later removed.

The entire mass of trap rock and glass, attacked and altered by hot solutions, was not a single, connected, open chemical system in which the same conditions of stability would occur throughout at the same time. Thus at some places one mineral would form and be stable, and at other places other minerals would form. If the saline lake into which the lava poured was rich in glauberite, as is believed, and if the lake water carried into the lava rock abundant sodium and calcium sulphate in solution, then anhydrite would form at one place and glauberite at another. At still other places both sulphates would form at once, although it is far more common for a single specimen to show predominantly the crystal cavities of one or the other than both the rectangular and the rhombic cavities intermingled in about equal number.

The time of formation of glauberite and its period of stability were much shorter than those of anhydrite. After the quartz period (No. 3) had passed and the prehnite period (No. 4) had begun, very little if any glauberite formed or remained. Consequently, glauberite cavities are practically absent from the minerals of the prehnite period—prehnite, pectolite and datolite—and are found dominantly only in the quartz of the preceding period (No. 3). Anhydrite, on the other hand, remained during the prehnite period, and rectangular cavities are very abundant in prehnite.

At some places glauberite apparently formed after anhydrite had been dissolved away. For example, in the two specimens shown in Plate 25, glauberite pseudomorphs occur inside of anhydrite cavities but do not project through the walls of the cavities.

At many places in the trap rock one or more of the periods of mineral alteration were omitted. Thus Fenner has clearly shown that albite (period 3) may have changed directly to one of the zeolites of period 5—for example, natrolite, apophyllite, or stilbite—without first passing through one of the minerals of period 4, such as prehnite.

Periods 1 and 2 were constructive, because minerals were being formed then. Period 3 was essentially constructive, though in part also destructive. The labradorite of the trap rock was being albitized during this period, and large quantities of quartz were being formed, whereas not many earlier minerals were being replaced by others of essentially different composition. Periods 4 to 6 were largely destructive, the minerals of these periods being produced to a large extent by the destruction of the minerals of periods 1 to 3 and by the rearrangement of their chemical components into new compounds.

In period 3 considerable quartz was produced, and some of it was formed around the saline minerals that were developed in period 2. It was not until period 4, when prehnite, pectolite, and their associates began to form, that the saline minerals became unstable and were largely removed by solution. This instability of the saline minerals was due to many causes, of which one of the most effective was the relatively large addition of chemically active hot water to the whole system. This increased the destructive action of these waters by increasing their solvent power. This increase of chemically active hot water, however, was due to a lowering of temperature which caused a greater condensation of water vapor. These hot waters also contained less dissolved material, because a considerable quantity which they had previously held in solution had been precipitated out as anhydrite, glauberite, and quartz.

The dissolving of the saline minerals during period 4 changed these conditions. By their solution large quantities of sodium and calcium, as well as sulphates, were added to the waters. Accordingly, calcium compounds crystallized out before the sodium compounds. In period 4, therefore, the minerals that were formed—prehnite, pectolite, and datolite—are very high in calcium (from 27 to 35 per cent CaO). Though none of the minerals of period 4 are anhydrous, they all have a very low water content (3 to 6 per cent). Two of the three minerals of period 4 do not contain alumina, but all the zeolites of period 5 (except apophyllite, which may belong to period 4) are high in alumina. In the minerals of period 5, the zeolite period, the calcium content is relatively much lower than in the minerals of period 4, whereas the sodium content is higher.

The differences in chemical composition of the minerals of periods 3, 4, and 5 may be expressed as follows if quartz is considered as representative of period 3, prehnite, pectolite, and datolite of period 4, and the zeolites of period 5.

	Period 3	Period 4	Period 5
Boric oxide (B_2O_3)	None.	Present.	None.
Alumina (Al_2O_3)	None.	Absent in two out of three minerals.	Present in all except apophyllite, which may belong to period 4.
Lime (CaO)	None.	High.	Moderate.
Soda (Na_2O)	None.	Low.	Moderate.
Water (H_2O)	None.	Low.	High.

Alumina, as an essential constituent, increased from zero to a maximum in passing from period 3 to period 5.

Lime reached a maximum in period 4, during which the greatest solution of the saline minerals (anhydrite and glauberite) was taking place.

Soda, alumina, and water increased as essential constituents of the minerals in passing through the three periods.

The high lime content of the three minerals of period 4 demonstrates the precipitating effect of the introduction of much lime into the solutions when anhydrite and glauberite dissolved near the beginning of the period. Obviously, too, under the conditions of equilibrium then existent both soda and alumina tended to remain in solution until the later stages of the process, when they came out together in the zeolites.

The mineral history of the six periods, as related to the crystal cavities of rectangular and rhombic cross section, may be summarized as follows:

Period 1. Solidification of basaltic glass and trap rock.

Period 2. Saline period. Anhydrite and glauberite begin to form. Both crystallize out and replace the already formed lava rock. Considerable overlapping of periods 1 and 2. Additional water has come in from outside sources, and silica now becomes stable as an individual compound and comes out as quartz.

Period 3. Quartz period. Much quartz forms, replacing the lava but not the anhydrite or the glauberite, because the solutions, having partly attacked the lava, are supersaturated with silica and are about saturated with anhydrite and glauberite and therefore are neutral in their reaction to the already formed sulphates. Glauberite stops forming and begins to dissolve.

Period 4. Prehnite period. Additional water again comes in, and the solutions are no longer saturated with glauberite and begin to dissolve it, but they are nearly saturated with calcium sulphate and therefore still remain neutral to anhydrite. Glauberite is mostly dissolved away. Rhombic cavities are formed. Anhydrite stops forming. The excess of lime and soda added to the solutions throws out the minerals of period 4, all high in lime. Thus prehnite, for example, forms before the anhydrite is attacked and dissolved and coats and preserves it. Anhydrite begins to be dissolved when the solutions are impoverished in lime by the precipitation of prehnite, datolite, and pectolite and by additional water coming in. The solutions are now no longer saturated or neutral with reference to anhydrite. Rectangular cavities are formed. Anhydrite is dissolved except that which is protected by lava or quartz from the action of solutions.

Period 5. Zeolite period. The abundance of zeolites is partly due to the increased content of lime and soda, supplied by the saline minerals, anhydrite and glauberite.

Period 6. Calcite period. Any remaining anhydrite may be changed to gypsum and to thaumasite.

The mineral changes are expressed graphically in the accompanying table. The value of the tabulation is obvious, for the mineral whose solution and removal formed a cavity must have existed prior to the time or period of the formation of the matrix or host mineral of the cavity. Thus, if such a cavity is present in prehnite (period 4), then the mineral originally forming the cavity must have existed either in a stage of period 4 earlier than the formation of prehnite or in one of the earlier periods. Again, a crystal cavity of apophyllite, for example, should not occur in quartz, because apophyllite followed quartz. On the other hand, a crystal cavity of quartz in apophyllite would be perfectly natural.

Conclusions regarding age relations of cavity and matrix based solely on the use of such a tabulation are valid only if the tabulation is complete and correct. Knowledge of sequence relations is incomplete, and consequently the tabulation must be used with caution. Much still remains to be done in solving the problems of mineral sequences in this most interesting and fruitful locality, and the fine piece of work accomplished by Fenner has done much to blaze the way. Further details, especially among the minerals of a given period, remain to be deciphered. Moreover, it is not certain just how far the formation of a single mineral is restricted to a single period. Quartz, for example, has probably formed in periods later than period 3, especially in its development of euhedral crystals, though the quartz of period 3 is essentially the compact, massive variety. Local conditions, too, may readily change the stability of minerals and the direction of chemical reaction and thereby cause a local reversal of the sequence of formation.

PSEUDOMORPHS

The word "pseudomorph" has at times been applied to any mineral that has undergone a change, and the expression "pseudomorphic texture" has been used to denote the texture produced by a mineralogic change of almost any kind. With such a loose meaning the crystal cavities of the New Jersey zeolite region might be termed pseudomorphs. A more precise use of technical terms is to be preferred, however, and although these cavities are better known as pseudomorphs, this word does not properly apply. A pseudomorph is in reality a mineral whose present crystal form does not correspond to the form naturally associated with its chemical composition. A pseudomorph may also be defined as a mineral which has replaced another of different composition but which has retained the crystal form of the original mineral. A pseudomorph is therefore a solid; it can not be a cavity.

True pseudomorphs are found in the zeolite region in association with the cavities, but they are not abundant. Quartz pseudomorphs after glauberite, the original mineral of the rhombic cavities, have afforded the best evidence of the identity of that glauberite. These pseudomorphs are formed, at least in part, by infiltration of quartz into the cavity left by the removal of the glauberite. Pseudomorphs

Mineral changes in formation of zeolitic rock

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Lava minerals	Labradorite →	→	Albite→Quartz →	Prehnite →	Zeolites →	Calcite.
	Diopside →	→	Albite→Quartz → Amphiboles.	Prehnite →	Zeolites →	Calcite.
			Albite →	→	Zeolites →	Calcite.
	Olivine →	→	Garnet. Chlorite →	→	Serpentine.	
	Magnetite →	→	Hematite.			
Saline minerals	Lava →	Anhydrite →	Quartz.			
		→	→Rectangular and lamellar cavities.			
		→	→	→Rectangular cavities.		
		→	→	→	→	Gypsum Rectangular cavities. Thaumasite.
	Lava →	Glauberite →	Quartz.			
		→	→Rhombic cavities.			
	Lava →	Calcite (lamellar) (?) →	→	→Lamellar cavities (?).		
Zeolitic rock minerals			Albite →	Prehnite Datolite Pectolite →	Apophyllite. Chabazite. Natrolite. Stilbite.	
			Quartz →	Prehnite Datolite Pectolite →	Apophyllite Chabazite Heulandite →	Calcite.
			Garnet →	Prehnite. Green amphibole.		
			Babingtonite (?).			
			Green amphibole→ garnet.			
				Prehnite→Datolite Pectolite →	Apophyllite Chabazite Natrolite Stilbite →	Calcite.
				Datolite →	Chabazite Heulandite Natrolite Stilbite →	Calcite.
				Pectolite →	Apophyllite. Chabazite. Natrolite.	
					Analcite Chabazite Heulandite Natrolite Stilbite →	Calcite.
					Apophyllite →	Calcite.
					Chabazite Heulandite Laumontite Natrolite Stilbite	Calcite.
					Heulandite Laumontite Natrolite Stilbite	Calcite.
					Laumontite→Natrolite→	Calcite.
					Natrolite →	Calcite.
					Scolecite→Natrolite.	
					Stilbite→Natrolite→	Calcite.
					Chalcopyrite →	Azurite. Chrysocolla. Malachite.
					Pyrite (?) →	Limonite.
					Babingtonite →	Fibrous amphibole(?).
						Gypsum→Thaumasite.

of gypsum and of thaumasite after anhydrite have been found, and many other pseudomorphs of the silicate minerals are probably present,[30] for the entire process of mineral formation in this zeolite region has just been shown to be one of long-continued chemical reaction and replacement.

According to Dana,[31] pseudomorphs may be classified into three groups, as follows:

1. Pseudomorphs by substitution or replacement. Example, quartz after fluorite, copper after aragonite, quartz after anhydrite and glauberite. [See pl. 4, *B*.]
2. Pseudomorphs by deposition:
   (*a*) Incrustation (epimorph). The removal of the original mineral may have taken place simultaneously with the deposition of the second mineral, or perhaps later, in both examples leaving a hollow shell. Example, quartz over fluorite, quartz over anhydrite. [See pl. 4, *D*.]
   (*b*) Infiltration. The original mineral has disappeared, leaving a regular crystal cavity which later has been filled partly or completely by a second mineral. Example, quartz after glauberite. [See pl. 4, *C*.]
3. Pseudomorphs by alteration:
   (*a*) Without a change of composition (paramorph). Example, calcite after aragonite, rutile after brookite.
   (*b*) By the loss of an ingredient. Example, copper after cuprite.
   (*c*) By the addition of an ingredient. Example, malachite after cuprite, anglesite after galena, gypsum and thaumasite after anhydrite. [See pl. 12.]
   (*d*) By a partial exchange of constituents. Example, limonite after pyrite, chlorite after garnet.

Crystal cavities, such as are commonly but erroneously called pseudomorphs, are illustrated in Plate 4, *A*. The specimen shows one large crystal cavity, many smaller ones, and groups of still smaller ones. This specimen is typical of a large number of such occurrences in the zeolite region of New Jersey. The remaining three illustrations in Plate 4 show examples of several of Dana's types of pseudomorphism. In *B* the matrix, originally lava or trap rock, has also been replaced by quartz; in *D* the anhydrite around which the quartz was deposited has been removed. (See also pls. 26, 27, 28, and 29.)

The many empty crystal cavities found in the zeolite region do not properly fall into any of Dana's categories of pseudomorphs and therefore should not be given such names as negative pseudomorphs or negative crystals. They have also been termed casts and molds. A mold is the regular cavity formed in a substance by the removal of a different substance formerly inclosed in it. This term may there-

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[30] The United States National Museum possesses an excellent fan-shaped pseudomorph of natrolite after anhydrite (catalog No. 95860), measuring about 3 by 5 inches, that came from this region.

[31] Dana, E. S., Textbook of minerals, 3d ed., revised by W. E. Ford, pp. 326–327, 1922.

fore be correctly applied. But the term "crystal cavity" is here preferred because it is more definitely applicable to the features to be discussed and is not ambiguous. A cast is properly the filling of a mold, and the "quartz pseudomorphs" from McKiernan & Bergin's quarry may properly be termed "casts or cores" (term used by Wherry)

CRYSTAL CAVITIES

OCCURRENCE

At many places in the trap rock of First Watchung Mountain, from Paterson southward to Montclair, quarrying operations have exposed zeolitic minerals together with crystal cavities. The cavities are so numerous that by implication the original minerals that once filled them must have been present in considerable quantity. These features, at first regarded as abnormal, have been shown by the previous discussion to be in accord with recognized chemical and mineralogical processes under given conditions and hence are perfectly normal, even if unusual. Many of them are described in later pages of this report. The localities from which this material has come are stated on pages 5–6.

VARIETIES

It was formerly supposed that one mineral was the progenitor of all the types of crystal cavities found in the zeolite region of New Jersey, and more than one attempt was made to identify that mineral. Now it is known that several minerals have been involved in making these cavities, but interest has centered on the rectangular and rhombic types, especially the rhombic, because its original mineral has not yet been found in an unaltered state.

Four groups of crystal cavities are discussed in this paper—rectangular, after anhydrite; lamellar, after anhydrite and possibly also after calcite and babingtonite; rhombic, after glauberite; and miscellaneous, after apophyllite, quartz, calcite, natrolite, and pectolite.

Not many of the miscellaneous cavities have been found or collected, and few of them are exhibited in museum collections. It must be said, however, that no great attention has been paid to them. They are not very attractive in appearance, and collectors in general would have little incentive for preserving them. They may therefore be more abundant than is indicated by the material now preserved in collections.

RECTANGULAR CAVITIES

SUMMARY OF CONCLUSIONS

The original mineral of the rectangular crystal cavities was anhydrite. In 1914 sufficient unaltered anhydrite was found in place at West Paterson to settle this question definitely. Specimens illustrating all stages of the formation of the rectangular cavities were obtained, and some of them are figured in this report. The forms of the anhydrite correspond to the forms of the cavities in size, shape, and structure. The method of removal of the anhydrite may be readily followed. Some of the anhydrite is partly altered. Alteration begins with the development of fine-grained, compact gypsum. This may be recrystallized as selenite, altered to thaumasite, or dissolved and removed so that rectangular crystal cavities are left.

ABUNDANCE

Rectangular and rhombic crystal cavities comprise the greater number of those found in the region. Almost every hand specimen of zeolitic rock, about 3 by 4 inches, contains more than a single cavity. Commonly half a dozen are present, and many single specimens will show from half a dozen to a hundred or more distinct cavities. (See pls. 4, *A*, 5, 6, *A*, 17, *C*, 18, *A*, 21, 22, 24, and 25.) The total number of crystal cavities in the specimens collected must be measured at least in the thousands. The total proportion of the cavities of the zeolitic rock to the lava affected by the lake waters is probably about 5 per cent.

SIZE

The cavities are not uniform in size; even in the same specimen and in the same group the individual cavities show great variations. (See pl. 4, *A*.) Cavities small as pin pricks are directly associated with others whose length may be expressed in fractions of a foot. The rectangular cavities are characteristically elongated in one direction (compare pls. 4, *A*, 6, *B*, 7, 8, and 10, *B*), and the two cross dimensions are seldom equal (pl. 5). Some of the largest of the rectangular cavities seen measure as much as 5 by 3½ inches. Fenner[32] states that a length of 3 or 4 inches is not uncommon, and in one specimen he observed impressions of a group of fanlike crystals "which measured 8½ inches (21.5 centimeters) in length and 7½ inches (19 centimeters) in greatest breadth. Apparently a considerable portion of the center of the group has been broken away, so that the original length was probably 3 or 4 inches greater."

SHAPE

Most of the rectangular crystal cavities are bounded by three planes at right angles to one another. Many of the cavities show only two

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[32] Fenner, C. N., Babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, p. 553, 1914.

planes that can be demonstrated to be at right angles; but where the third plane is also present it is perpendicular to each of the other two. Examples are shown in Plates 4, *A*, 5, 6, *A*, 7, 8, *B*, and 10, *B*. Each of these planes represents a direction in the original mineral which was a direction of well-developed cleavage. Thin walls of minerals of later sequence (mostly quartz and prehnite, in part altered still later to zeolites) have in many specimens entered the cleavages of the original mineral or else have replaced the obsidian or trap rock between parallel tabular crystals of the original mineral and have remained after the original mineral was dissolved and removed. Consequently, many of the rectangular cavities contain numerous thin walls parallel to one, two, or all three of the planes that now bound them. Two such specimens are shown in Plate 7.

Measurements of the angles between the bounding planes have shown no greater deviations from 90° than the errors of measurement. The angles of some of the smaller cavities, measured under the microscope, ranged from 89½° to 90½°, and many of the angles were exactly 90°. That the angle is exactly 90° can readily be seen under the microscope by means of the right-angled cross hairs. If the cavity is accurately centered and one side is brought parallel to one of the cross hairs, then the other side will be exactly parallel to the other cross hair. In many of these cavities the angle between the bounding planes is considerably different from 90°. The variation is not constant and is a result of the disturbing effects produced by the considerable mineral changes that have taken place in the matrix.

Similarly the thin walls of quartz or of prehnite inside the cavities (pl. 7) are also at right angles to each other.

HABIT

The individual cavities show several distinct habits, which so grade into one another that it would be difficult to classify many of them accurately unless a large number of habits were named. The extreme cases are, however, rather well defined and may be given as types of habit. Then all the occurrences may be listed either as belonging to one or the other type or as intermediate between them. The rectangular cavities are either isolated holes resulting from the removal of a single crystal or are aggregated in a regular way, showing that the material originally occupying the cavities was not a single crystal but a large number grouped together in a regular fashion and commonly in actual or very close contact with one another.

Most of the individual rectangular cavities resulting from the removal of a single crystal may be grouped under one of three habits whose relative dimensions may be stated as follows: (1) Very thin tabular, 1 by 250 by 50; (2) thick tabular, 1 by 5 by 10; (3) elongated prismatic, 1 by 1 by 10.

Many of the very thin tabular cavities (pls. 17 and 18, *A*) are lamellar in habit and are described under the heading "Lamellar cavities." They usually occur in irregular aggregates, abutting against each other and in some specimens showing very little tendency toward parallel arrangement. Such aggregates do not show a definite rectangular outline. Some of the thick tabular cavities (pl. 17, *A*) show a definite rectangular outline and are due to anhydrite; others are less certain. With increasing thickness the lateral extent of the thin tabular cavities is relatively shortened, and tabular gashes, with a distinct rectangular outline, 1 millimeter thick, have lateral dimensions of about twenty to thirty times as much. Single cavities of a thick tabular habit with a cross-section ratio of about 1:2 are not very common. The thick tabular cavities show a marked tendency to aggregate in parallel or slightly radiating position as soon as the thickness of the plates reaches about 1 or 2 millimeters. Such aggregates are shown in Plate 5.

A few thick tabular cavities were seen that gave no indication that more than one crystal had been present. The individual elongated rectangular cavities with a square cross section (pl. 10, *B*) are more abundant, but they also occur more commonly in groups than as single cavities.

Both the thick tabular and the prismatic cavities are generally elongated. As the original mineral of the very thin tabular cavities has not yet been found in place (in the zeolite region of New Jersey [33]), the relationship of development of the different crystal forms in the different habits is not known. The three abundant groups of rectangular cavities are rarely represented on the same specimen.

Radial groups of the rectangular cavities, especially those of thick tabular and elongated prismatic habit, are more abundant than single cavities of either habit. Several groups of such radial rectangular cavities are shown by the specimen reproduced in Plate 5, which gives a cross section of most of the groups. A specimen showing radial grouping parallel to the elongation of the cavities is illustrated in Plate 6, *B*; the group is fan-shaped and in a single plane.

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[33] Thin plates of anhydrite similar in size and shape to the thin tabular cavities of the New Jersey field have been found in the trap rock of Massachusetts and Connecticut. (See pp. 41, 46.)

Such crystal cavities may be compared with the similar radial groups of anhydrite shown in Plates 11 and 12, *A*.

On many specimens the rectangular cavities are isolated or grouped into fan-shaped aggregates consisting of only two, three, or four cavities in parallel position, as in the specimen shown in Plate 6, *A*.

Some of the groups of thin tabular cavities are almost in parallel position, though others are slightly radial, as if the group were connected on one side only. Where the individual cavities are separated from one another, it seems as if a group of distinct and separate platy crystals, in parallel position, were originally present.

In numerous specimens these thin tabular cavities, apparently separated, represent a single connected compound crystal with many narrow extensions, as shown in Figure 2, *A*. These extensions may have been a noncontinuous group of parallel crystals whose separating walls (of trap rock or of quartz) have been dissolved away, but the sides of the thin tabular cavities are so nearly rectangular and so sharply angular, not rounded, that no solution of the matrix can have taken place when the anhydrite was dissolved. The original crystal that formed the cavity was more probably a single crystal with outstretching overlying plates. Crystals of anhydrite with such outstretching or overlying plates are not rare and have been described in the literature. Such crystals have been illustrated by drawings, which have been collected and reproduced by Goldschmidt.[34] Very similar forms to that shown in Figure 2, *A*, have been repeatedly observed in the drill cores from the potash fields of New Mexico and Texas and seem to be a rather common form of anhydrite.[35]

Some of the cavities, however, may represent a group of platy crystals aggregated together in parallel position. The individual plates may have been in contact, without any material between them, as shown in Figure 2, *A*, or they may have been slightly separated by interstitial trap rock, as shown in Figure 3. If in such a parallel aggregation as illustrated in Figure 2, *A*, the plates were not of equal size and were not centered but projected considerably and unequally over one another, they could form a cavity similar to that shown in Figure 2, *B*. On the other hand, if the individual plates were not in contact but separated by thin layers of trap rock (fig. 3), then the anhydrite crystals could have been removed after the trap rock had been replaced by quartz. Thus a rectangular cavity would be left, divided by plates of quartz that were formed by the replacement of the thin layers of the trap rock. This would yield cavities similar to those shown in Plate 7, *A*.

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[34] Goldschmidt, V., Atlas der Krystallformen, vol. 1, pl. 66, figs. 55, 56, 1913.

[35] Schaller, W. T., and Henderson, E. P., Mineralogy of the drill cores from the potash field of New Mexico and Texas: U. S. Geol. Survey Bull. 833, fig. 2, 1931.

Two explanations can be offered for the formation of the thin plates and ridges of later minerals (mostly quartz) in rectangular cavities (pl. 7, *A*), in which the plates and ridges of quartz are parallel to the walls of the cavity and to the cleavages of the original anhydrite. First, crystals of anhydrite growing in the trap rock may have been subjected during and after their growth to strains, caused by pressure generated by the contraction of the basaltic glass on cooling or possibly by its partial devitrification or crystallization.

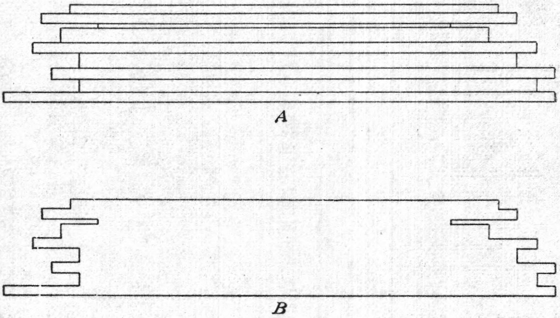

FIGURE 2.—*A*, Aggregate of parallel tabular crystals of anhydrite, in close contact, in which the thin tabular plates projected considerably and unequally over the main part of the aggregate, whose removal would form a cavity similar to that shown in *B*. *B*, Rectangular cavity produced by the removal of the parallel tabular crystals of anhydrite shown in *A*

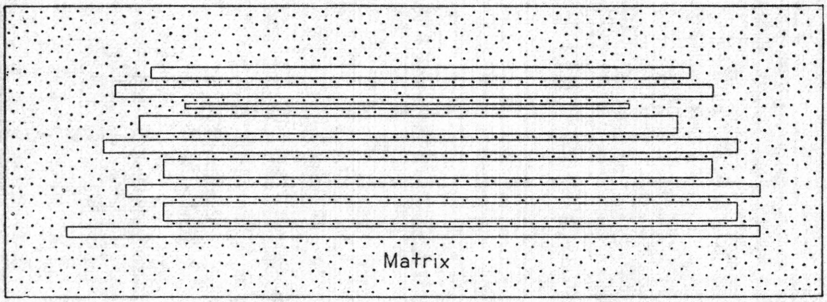

FIGURE 3.—Aggregate of parallel tabular crystals of anhydrite, separated by thin layers of trap rock. If the trap rock were replaced by quartz, the solution and removal of the anhydrite would yield a cavity similar to that shown in Figure 2, *B*, but with parallel thin walls, as illustrated in Plate 7, *A*

This pressure could have caused the cleavage planes of the anhydrite to separate sufficiently for solutions to enter and precipitate quartz. Thus the condition illustrated in Plate 7 could easily have been derived from that illustrated in Plate 10, *A*, if silica were deposited in the cleavage cracks of the crystal there shown and the anhydrite were later dissolved. Again, if the cavity does not represent a single crystal, but an aggregate of tabular plates in parallel position, separated by thin layers of basaltic glass or trap rock, then the silicification of the glass or trap rock and subsequent removal of the anhydrite would yield an end product similar to that of Plate 7, *A*. A single crystal of anhydrite, not opened up by pressure in the way just described, would yield a cavity, without any walls of quartz, as shown in Plate 10, *B*.

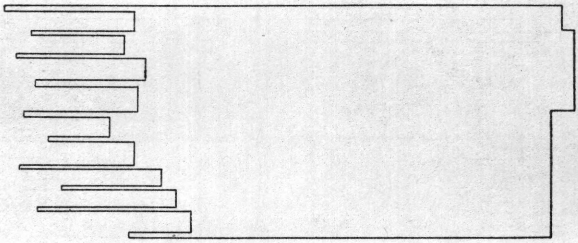

Figure 4.—A single cavity after an anhydrite crystal that continued its growth at one end only as an aggregate of parallel plates. Many of the cavities show a form corresponding to such a crystal

The structure of some of the cavities suggests that in some aggregations of tabular plates their unequal projection over one another was confined largely to one side, as shown in Figure 4. Such an aggregate suggests that the anhydrite started to grow as a single rectangular unit, but after its growth had reached a certain stage some change in the conditions caused the single crystal to continue its growth as a group of parallel plates instead of a single crystal. Many of the crystal cavities show such a structure.

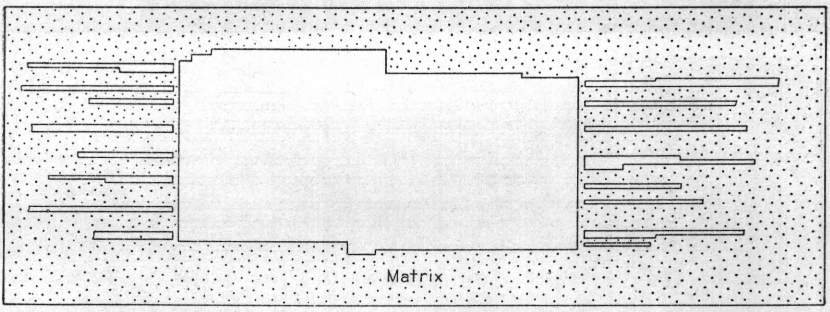

Figure 5.—A cavity after a crystal of anhydrite that continued its growth at both ends as an aggregate of parallel plates. Usually there is a thin wall of matrix between the larger single cavity and the aggregate of parallel tabular cavities

Other anhydrite crystals continued their growth as a group of parallel plates at both ends, as shown in Figure 5, the change from a single solid crystal to an aggregate of parallel plates being very sudden. Apparently a definite change of conditions very quickly changed the growth of anhydrite from a single crystal into a group of parallel platy crystals. The increasing viscosity of the cooling basaltic glass may have been a dominant influence. On most cavities of this type, though not on all, there is a thin wall of silica separating the larger single cavity from the aggregate of parallel tabular cavities.

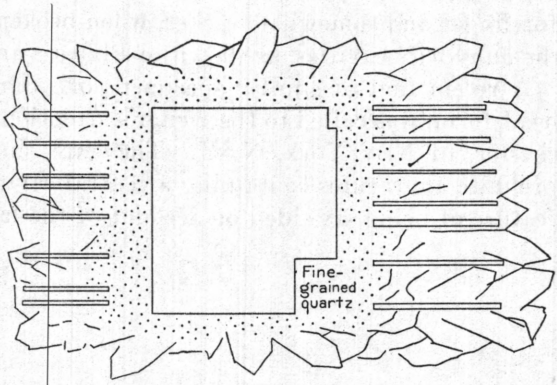

FIGURE 6.—Compound group of cavities

A common type of these cavities is sketched in Figure 6. The central large cavity is typically rectangular and is surrounded by fine-grained massive quartz, which in turn is surrounded by coarse-grained quartz that has an incipient tendency to develop euhedral crystals. Numerous narrow gashes parallel to one side of the large central cavity but not connected with it appear in the euhedral quartz mass. If the main central cavity is surrounded by the coarse-grained, incipiently euhedral quartz, or by prehnite, then the narrow gashes on each side extend out from the borders of the main cavity, as shown in Figure 2, *B*.

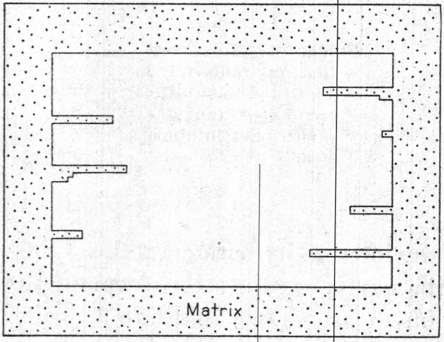

FIGURE 7.—Rectangular cavity with inward-projecting walls of the matrix

In some cavities thin walls of the matrix project inward, as shown in Figure 7, as if the individual projecting tabular plates of anhydrite were much thicker than those shown in Figure 2, *A*. The alinement of the two extreme sides suggests, however, that such a cavity has been formed by partial replacement, by the matrix, of the anhydrite along its cleavage before its removal.

Numerous specimens of prehnite (pl. 8, *A*) and less frequently of quartz (pl. 8, *B*) showing a pseudostalactitic structure owe their structure to the former presence of original crystals of anhydrite. These were either single prismatic crystals or more commonly groups of thin tabular plates, in parallel position but not accurately centered, so that many of the plates projected irregularly over the sides. The structure of such compound crystals was like that shown in Figure 2. These crystals became covered with a thick deposit of prehnite or quartz and were later removed by solution. The present projecting masses of prehnite or quartz, usually not quite as long as a man's forefinger and somewhat thicker, when broken open, invariably show the anhydrite cavities, as shown in Plates 8 and 9.

A recent find of similar specimens of prehnite, but with a spearhead form, was called to the writer's attention by Mr. James G. Manchester, of New York, N. Y. They are similar to other flattened prehnite aggregates containing a central cavity but have the unusual feature of being six-sided on account of the large development of the orthodome $r(101)$ on the original inclosed anhydrite crystal. When they are cut open, the shape of the cavity outlines the form of the original mineral. Two such specimens are shown in Plate 9, which also gives the crystallographic interpretation of the form of the original anhydrite.

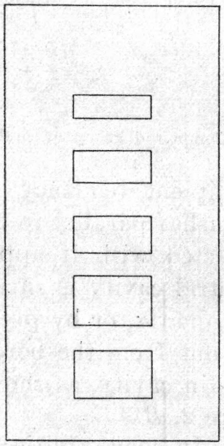

FIGURE 8.—Cross section of radial group of rectangular cavities in alinement, the original group of radiating crystals of anhydrite having been in a plane

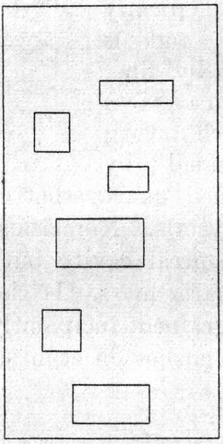

FIGURE 9.—Cross section of radial and partly spherulitic group of rectangular cavities not in alinement

These crystals were flattened parallel to the side pinacoid $b(010)$ and were bounded by faces of $c(001)$ and $r(101)$, with no faces of the front pinacoid $a(100)$. The angle of the corner to the right measured 99°, half of which, or 49½°, corresponds closely to the angle $c(001) \wedge r(101)$ of anhydrite—namely, 48° 15′. These crystals were also unusual in being scepter crystals, with a long combination of only *c*(001) and *b*(101), the dome faces (*r*) being developed only at the end.

Many of the rectangular cavities consist of radial groups, such as are shown in Plates 5 and 6, *B*. Such cavities may be united at one end and separated at the other, as if the original group of radial anhydrite crystals had its distal terminations developed as free non-attached crystals, grouped in a manner similar to that shown in Figure 2, except that the individual crystals were radial instead of parallel. The individual free crystals of anhydrite (and their consequent cavities) may have formed a fan-shaped aggregate in a single plane, so that a cross section of the resultant cavities would be in alinement, as shown in Figure 8 and Plates 5 and 6, *B*, or they may have formed a partly spherulitic aggregate, not in a single plane, so that the cross section of the resultant cavities would not be in alinement, as shown in Figure 9 and Plate 6, *A*.

MARKINGS AND INCLOSED WALLS

The rectangular cavities have characteristic markings on most of the surfaces. The commonest are a series of numerous very fine parallel lines or striations which extend the entire length of the cavity or only part way. They are parallel to one of the sides and represent either the striations present on the original anhydrite crystal or else the edges of original platy crystals in parallel position. In some of the cavities after prismatic crystals the markings indicate an alinement of a few very differently sized rectangular crystals in parallel position, yielding a sort of steplike structure, as shown in Plate 10, *B*. Rectangular markings caused by the parallel groupings of a number of crystals of different sizes have also been observed. (See pls. 4, *A*, and 10, *B*.)

As many of the seemingly simple crystals were in reality compound and built up of many platy crystals in parallel positions, the parallel walls of quartz now observed in many of the rectangular cavities are not due to the cleavage of the mineral but to the fact that the individual plates were slightly separated from one another. The interstitial lava was later easily attacked by circulating waters, which replaced the lava by quartz and possibly also slightly dissolved the anhydrite and widened the spaces. The walls that trend dominantly in one direction (pl. 7, *A*) were probably formed largely in this way. The walls that not only trend dominantly in one direction but are radial instead of parallel, as shown in Plate 6, *B*, are not due to cleavage alone but to solutions entering and replacing the interstitial lava. Some groups of anhydrite crystals may have grown as radiating crystals in open spaces among the rounded boulderlike masses of lava, the spaces between the crystals being later filled with quartz.

The walls that are well developed in all three directions, as shown in Plate 7, *B*, are to be referred to the cleavages of the original anhydrite. But several processes have operated—namely, the replacement of the interstitial lava by quartz, the filling of incipient cleavage cracks by quartz, and the filling of open spaces between the crystals by quartz. The resultant cavity, with these walls, may thus show the result of several different processes.

MATRIX

The most abundant matrix of the rectangular cavities is either quartz or prehnite. Rectangular cavities have also been found in datolite, pectolite, albite, analcite, stilbite, thomsonite, and calcite. There is a marked difference between the matrix of the rectangular cavities, found abundantly in minerals other than quartz, and the matrix of the rhombic cavities, found almost exclusively in quartz. This feature is not in conformity with the suggestion that only one mineral was the original mineral of all these cavities.

MINERALS IN CAVITIES

The following minerals have been found in the rectangular cavities:

Anhydrite, residual from original crystal.
Gypsum, alteration product of anhydrite (pseudomorphs).
Thaumasite, alteration product of gypsum (pseudomorphs).
Quartz, as walls of fine-grained, compact quartz.
Prehnite, as walls and euhedral crystals.
Datolite.
Apophyllite.
Stilbite.
Laumontite.
Chabazite.
Heulandite and the other zeolites.
Calcite.
Babingtonite.
Hematite.
Chlorite and various secondary alteration products.

ASSOCIATED CAVITIES

Crystal cavities after some mineral other than the one which formed the rectangular cavities are frequently associated with the rectangular type. As described on pages 19 and 54 and illustrated in Plate 25, rhombic cavities (after glauberite) are found inclosed in rectangular cavities. Some of the rhombic infiltration pseudomorphs likewise contain rectangular cavities, as illustrated in Plate 4, *C*. Cavities after other minerals are also occasionally found in the rectangular cavities, as shown in the upper left corner of the cavity shown in Plate 7, *B*.

ORIGINAL MINERAL

SUMMARY OF CHARACTER OF CAVITIES

The following facts in themselves afford sufficient evidence that anhydrite was the original mineral of the rectangular cavities.

1. The rectangular shape of the cavities, with angles of 90°, and the presence in them of thin walls of quartz and other minerals, parallel to the bounding walls of the cavities and consequently in three directions, normal to one another, agreeing in angular position with the cleavages of anhydrite, and in position with any interstitial matter of a group of parallel or radiating tabular crystals of anhydrite.

2. The markings in the cavities, striations, and cleavage walls are in complete accord with structural features of anhydrite, as for example, the unequal quantity of walls in the three directions (pls. 7, *A*, and 8, *A*, right side), corresponding to the unequal development of the three cleavages of anhydrite.

3. The cleanness and whiteness of most of the cavities show that the mineral contained no strong coloring element.

4. The smoothness and sharpness of the walls show that the mineral was easily dissolved and removed without an attack on the walls of the matrix.

The presence of calcium sulphate is accounted for by the saline mineral glauberite in the lake waters into which the lava flowed and in the lake beds beneath. The high temperature of the solutions at the early stage of mineralization rendered the calcium sulphate insoluble, and it was therefore precipitated, to be dissolved later, at lower temperature, when additional water had entered the chemical system.

The specimens obtained during the last 15 years show considerable anhydrite still in the trap rock and in its altered phase, the zeolitic rock. Several such specimens are illustrated in Plates 10, *A*, 11, 12, *A*, and 13, and the alteration of anhydrite to gypsum with its further alteration to thaumasite in Plates 12, 13, 14, 15, and 16.

Several specimens of anhydrite, some of which has been altered to gypsum, show the "laminae of quartz projecting from the walls into the anhydrite,"[36] as described on pages 37–39, so that this former argument of Fenner's against anhydrite no longer holds.

OCCURRENCE

The occurrence of anhydrite in the trap rock in Burger's quarry at West Paterson was announced in the New York Times for November 23, 1914, by Frederick I. Allen, of New York, and a little later was

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[36] Fenner, C. N., Additional notes on babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, p. 600, 1914.

described in more detail. The genetic relation between anhydrite and thaumasite was recognized by Allen, the thaumasite being an alteration product of gypsum. He writes:[37]

> The thaumasite has in many cases disappeared from the places of its formation, leaving cavities in the quartz in the form of the original anhydrite crystals. Specimens showing these rectangular cavities have been collected in large numbers, but it has not been known heretofore what minerals these pseudomorphs represented.

Later study by Allen[38] has convinced him that gypsum is always an intermediate product and that the direction of alteration is anhydrite→gypsum→thaumasite→rectangular cavities. A study of the available specimens has fully confirmed the general trend of Allen's idea, but the development of thaumasite as an intermediate product in the formation of a rectangular cavity from anhydrite is not always necessary, as many cavities probably resulted directly from the solution and removal of gypsum.

At many places there has been considerable migration of the hydration and alteration products of anhydrite, forming large masses of gypsum and of thaumasite, which in their present position give no clue to their origin. Specimens of unaltered anhydrite were also obtained in 1916 from McKiernan & Bergin's quarry, Paterson.

PROPERTIES

The anhydrite from Paterson is transparent to translucent in small pieces, but the larger crystals are opaque. The crystals are mostly light blue, but some are pale pink, white, or colorless. The quantity of anhydrite found is not large; probably several dozen specimens would include all. An estimate of the known amount of anhydrite taken from the quarry has shown that at least several pounds of the unaltered anhydrite is distributed in various collections. Individual crystal groups are several inches long, and their sizes are comparable to those of the rectangular cavities. One of the largest groups of radiating crystals is shown in Plate 12, *A*.

The matrix of the anhydrite is trap rock, quartz, or typical zeolitic rock. In some of the specimens the quartz immediately surrounding the anhydrite has an amethystine hue, which, with the pale blue of the anhydrite, makes a charming color combination.

The individual crystals are square prisms showing the three pinacoids, *a*(100), *b*(010), and *c*(001), mutually normal. Such a specimen is shown in Plate 10, *A*. The exposed faces are probably all cleavages, developed during the blasting, but the outlines of the crys-

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[37] Allen, F. I., The origin of thaumasite: Am. Jour. Sci., 4th ser., vol. 39, p. 134, 1915.

[38] Personal communication.

tal against the matrix show clearly that it is bounded by the pinacoidal faces. All three directions of pinacoidal cleavage are well shown. In Plate 10, *B*, is shown a specimen of the common and abundant form of rectangular crystal cavities. The deviation of such a cavity from an anhydrite crystal can readily be followed by a comparison of the two views in Plate 10. The removal of the anhydrite in *A* (enlarged view) would yield a cavity of very nearly the same size as the lower one of the two large cavities shown in *B*. Many of the supposed individual crystals, however, are composed of flattened or lath-shaped individuals much compressed parallel to *c*(001) and greatly extended parallel to *b*(010). These flattened crystals are so aggregated on some specimens that the group resembles a single crystal. In other groups the plates, though in parallel position, overlap slightly and irregularly, so that an apparent single crystal has an appearance similar to that of the cavities described on page 28 and illustrated in Figure 2. The simple square cavities may have been due to a single square anhydrite crystal, or to a group of platy crystals in parallel position and of equal length. (See p. 30.) If each of these plates were exactly centered on the others, then a square crystal with plane surfaces would result. The fact that much of the original anhydrite occurred in platy crystals suggests that the very thin, lamellar cavities (pls. 17 and 18, *A*) were also formed after anhydrite and that where these did not combine in parallel position they formed an irregular aggregate of lamellar crystals in the positions of the cavities shown in Plates 17, *B*, and 18, *A*. The tendency of some of these lamellar cavities to approach parallelism is shown in parts of Plate 18, *A*, and supports the idea that most, if not all, of the lamellar cavities were caused by anhydrite.

A similar tendency to aggregate in parallel or nearly parallel groups is shown by many platy or lamellar minerals, such as the platy babingtonite (pl. 32, *A*), and platy hematite (specularite) from this locality.

The three pinacoids are the chief forms of the anhydrite from West Paterson, but a few crystals show the presence of an inclined dome, such as has been described for the spearhead specimens of prehnite originally coating flattened anhydrite crystals on which faces of the orthodome *r*(101) were prominently developed.

In several specimens the anhydrite forms radiating groups, the individual crystals being thin tabular. Two such specimens, with the anhydrite partly removed, are shown in Plate 11. In *B* several of the walls of quartz can be seen penetrating some of the remaining anhydrite. These quartz walls are usually buff and likewise penetrate a zeolitic mineral, which appears very dark in the view, and are also present in the massive white quartz in the center, which has probably replaced anhydrite. The complete removal of all the anhydrite would yield a radiating group of rectangular cavities, such as are shown in Plate 6, *B*. A similar group of radiating anhydrite is shown in Plate 12, *A*.

ALTERATION

The alteration of anhydrite begins by the formation of compact white gypsum, as illustrated in Plates 12, *A*, and 13, at some places with no change in volume. It is not known whether at any stage of the changes in the zeolitic rock the solutions were able to dissolve the anhydrite directly or whether, as seems more probable, the anhydrite was always first changed to gypsum. It might be contended that such a change of anhydrite to gypsum would, by the increase in volume, crush the thin quartz walls, such as those shown in Plate 7. The alteration, however, has proceeded without any noticeable change in volume. (See pls. 12, 13, 15, and 16.) Part of the crystal illustrated in Plate 13, *A*, has changed completely to gypsum and except for a slight swelling at the extreme upper end has not increased appreciably in volume. To the left is a nearly vertical layer of altered anhydrite changed to compact white gypsum with no change in volume. Plate 13, *B*, likewise shows that the change of anhydrite to gypsum can take place with no increase in volume. In Plate 16, *B*, is shown an anhydrite crystal which has been altered to thaumasite, through the gypsum stage, with no change in volume. Even the change of gypsum to thaumasite has often proceeded without appreciable change in volume, as shown by the specimens illustrated in Plates 12, *B*, and 16. Where the secondary gypsum has been recrystallized into the selenite variety there is generally a decided change in volume, probably caused by the accretion of additional material from passing solutions during the recrystallization, as shown in Plate 14, *B*.

The gypsum resulting directly from the alteration of anhydrite is fine granular, white, and opaque. (See pls. 12, *A*, 13, *A* and *B*, and 15.) In a number of the specimens the gypsum has recrystallized into transparent selenite and no longer retains the shape of the anhydrite crystals and groups but assumes the characteristic shape and form of selenite. (See pl. 14, *B*, upper right.) Many large pieces of such water-clear selenite have been found in the zeolitic rock. One side of a specimen exhibiting both phases of the gypsum (pl. 14, *A*) shows the opaque white gypsum retaining the shape of the radiating anhydrite group; the other side of the same specimen (pl. 14, *B*) shows similar opaque white gypsum in its lower portion, but on its upper side there is a mass of the clear, colorless, uniformly oriented recrystallized selenite. Several quartz walls are embedded in this gypsum. One such wall can be seen in the lower left corner of Plate 14, *B*, and about a dozen similar walls are present in the left side of the specimen.

Similar changes of anhydrite to gypsum and to thaumasite, with no appreciable change in volume, are shown in Plate 15.

The alteration of the anhydrite to gypsum, as revealed by thin sections, does not everywhere follow the cleavages of the anhydrite but replaces masses of the anhydrite in irregular-shaped bodies, the contact between the two minerals having no reference to any crystallographic direction of the anhydrite. At some places, however, the alteration has proceeded along the cleavages of the anhydrite for considerable distances.

The further alteration of the granular white opaque gypsum to thaumasite with retention of the crystal form of the original anhydrite, as shown in Plate 16, yields pseudomorphs of thaumasite after anhydrite. In *A* there has been a slight increase in volume, so that the rectangular pseudomorphic crystal in the center of the specimen has lost its sharp outlines. In *B* there has been very little change in volume during the change.

The formation of such pseudomorphs without passing through the gypsum stage seems not to have occurred. There is also no evidence that the anhydrite has been dissolved away and the resultant cavity later filled with thaumasite. In other words, it seems that the granular white opaque gypsum must form before any of the further changes can take place. The specimen shown in Plate 15 contains several areas of thaumasite, as well as of anhydrite and gypsum, but the areas of thaumsite are all in the white granular gypsum and not in the anhydrite. The specimen shown in Plate 11, *A*, also has small masses of gypsum and thaumasite in the anhydrite.

The genetic history of the thaumasite, as first given by Allen,[39] showing its derivation from anhydrite, has led Wherry [40] to regard thaumasite, systematically, as a sulphate rather than a silicate. However, the occurrence of thaumasite in veins cutting contact-altered limestone in the Old Hickory mine, Beaver County, Utah, as described by Butler,[41] raises doubts as to whether it should be so considered. Similar doubts are raised by the occurrence of thaumasite in Cresmore, Riverside County, Calif., where it was derived from spurrite, a carbonate silicate of calcium, as described by Foshag,[42]

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[39] Allen, F. I., The origin of thaumasite: Am. Jour. Sci., 4th ser., vol. 39, p. 134, 1915.

[40] Wherry, E. T., Notes on mimetite, thaumasite, and wavellite: U. S. Nat. Mus. Proc., vol. 54, pp. 378–379, 1918.

[41] Butler, B. S., Geology and ore deposits of the San Francisco and adjacent districts, Utah: U. S. Geol. Survey Prof. Paper 80, p. 103, 1913; The ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, p. 188, 1920.

[42] Foshag, W. F., Thaumasite (and spurrite) from Crestmore, Calif.: Am. Mineralogist, vol. 5, pp. 80–81, 1920.

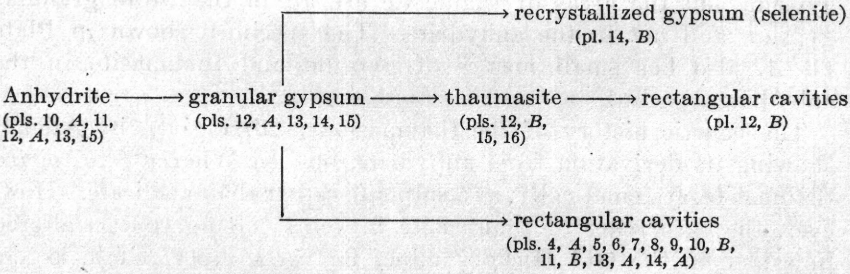
and is associated with foshagite, a hydrous calcium silicate, as described by Eakle.[43]

The character of the solutions acting on the granular gypsum must have varied considerably at different places and at different times, for three different reactions seem to have occurred. The first reaction was a recrystallization more or less in place of granular white opaque gypsum, pseudomorphic after anhydrite without increase in volume, to a well-crystallized colorless transparent selenite, which no longer showed the form of the original anhydrite but expressed its own crystallographic identity in new crystal faces. (See pl. 14, *B*.)

In the second reaction the solutions added calcium silicate and calcium carbonate to the granular white opaque gypsum and changed it to a granular mass of well-crystallized thaumasite, in some places with no increase of volume (pls. 15 and 16), but in others with a marked increase. This increase, however, is masked by the additional material afforded by the replacement by thaumasite of minerals other than gypsum and produces large masses, a foot or more thick, of practically pure thaumasite.

In the third reaction the solution merely dissolved the gypsum and carried it away, leaving the empty rectangular cavities. In two of the rectangular cavities were found small residual (?) masses of thaumasite; but cavities formed by the solution and removal of thaumasite seem to be very much rarer than those formed by the solution and removal of gypsum.

The reactions that took place in the alteration of the anhydrite may be summarized as follows:



The cycle of the changes from anhydrite through gypsum to rectangular cavity is well shown in Plate 13, *A*.

SIMILAR OCCURRENCES OF ANHYDRITE

Pinkish-purple anhydrite of composite structure, formed as an aggregate of prismatic crystals, was reported by Koenig[44] as having

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[43] Eakle, A. S., Note on the crystallization of thaumasite: Am. Mineralogist, vol. 10, p. 66, 1925.

[44] Koenig, G. A., On anhydrite: Acad. Nat. Sci. Philadelphia Proc. for 1889, pp. 11–12, 1890.

been found on diabase among the ballast of the Baltimore & Ohio Railroad track south of the tunnel at Darby, Delaware County, Pa. As stated by Gordon,[45] this ballast probably represented trap rock from New Jersey.

A few years later the occurrence of anhydrite in trap rock from Massachusetts was described by Emerson.[46] It was found in the trap rock of Larrabee's quarry,[47] beside the Connecticut River, on the town line between Holyoke and Northampton. The tabular masses of bluish anhydrite, as much as 3 inches in length, are generally slightly radiated. As stated by Emerson, "The surface of the overflowing trap sheet was covered with mud while still plastic, and trap and shale are confusedly mingled."

Anhydrite is also reported from the trap rock at Meriden, Conn., by Shannon,[48] who says:

> Anhydrite occurs in large pearly masses showing cleavage surfaces often 10 centimeters [4 inches] or more broad. There is abundant evidence that anhydrite has been present in almost universal distribution, but it now remains undissolved only in the centers of the less pervious blocks of rock. Molds of anhydrite crystals varying from stout prisms to exceedingly thin sheets are abundant everywhere. Anyone who entertains a doubt as to the origin of the rectangular molds in the New Jersey zeolite specimens would surely have that doubt dispelled by visiting Meriden.

Lindgren[49] describes the occurrence of copper ore at the Cactus mine, in Beaver County, Utah, as a stockwork within which the igneous rock (monzonite, a granitic plutonic rock) is crushed and shattered. The ore (chalcopyrite) is the cement of the monzonite breccia and is also disseminated throughout the rock. The gangue minerals accompanying the sulphide ore are tourmaline, quartz (?), siderite, specularite, anhydrite, and gypsum. Intergrowths of chalcopyrite with large transparent flakes of gypsum are abundant. The anhydrite, when fresh, forms crystalline masses, the individuals of which may be several centimeters in length; the rough crystals may have a cubical or, more commonly, a flat tabular form. The color is a characteristic pale violet or purple. The three planes of cleavage are perpendicular to one another but are of differing degrees of perfection. Polished pieces show very clearly the incipient develop-

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[45] Gordon, S. G., The mineralogy of Pennsylvania: Acad. Nat. Sci. Philadelphia Special Pub. 1, p. 187 (footnote), 1922.

[46] Emerson, B. K., A mineralogical lexicon of Franklin, Hampshire, and Hampden Counties, Mass.: U. S. Geol. Survey Bull. 126, p. 26, 1895.

[47] Same as Delaney's quarry (?). See Emerson, B. K., op. cit., p. 90; also U. S. Geol. Survey Mon. 29, pp. 471–472, 1898.

[48] Shannon, E. V., The trap quarry at Meriden, Conn.: Am. Mineralogist, vol. 5, p. 34, 1920.

[49] Lindgren, Waldemar, Anhydrite as gangue mineral: Econ. Geology, vol. 5, p. 522, 1910.

ment of gypsum in seams, parallel to the cleavage, or traversing the mineral irregularly. Lindgren says further:

> More abundantly, however, it (chalcopyrite) is intergrown with anhydrite, quartz, and siderite, but it is mainly later than these minerals; in some places it fills the interstices between well-developed crystals of anhydrite of rectangular cross section. A frequent mode of occurrence of the chalcopyrite is also as thin lamellae between the cleavage planes of the anhydrite.

If in the last sentence of the above quotation the word quartz were substituted for chalcopyrite, the relations to anhydrite would be exactly those found at Paterson.

The monzonite at the Cactus mine was intrusive into Paleozoic sediments. Could these sediments have contained sulphate salines which were dissolved in the heated waters and crystallized therefrom as anhydrite? Otherwise the intrusive magma must have supplied "an unusually large amount of sulphuric acid," as stated by Lindgren. He also quotes the results of some experiments on the solubility of calcium sulphate at high temperatures. Above 100° C. the solubility of anhydrite decreases very rapidly, so that at 218° C. the mineral is almost insoluble. Its solubility at 100° C. is about 13 times as great as at 218°.

LAMELLAR CAVITIES

SUMMARY OF CONCLUSIONS

The lamellar crystal cavities are less abundant than either the rectangular or rhombic cavities but are nevertheless, at some places and in some specimens, very abundant. In shape they grade more or less into the tabular rectangular forms, but they are all characterized by extreme thinness.

The original mineral of these lamellar cavities is not known. Some of the cavities doubtless represent very thin plates of anhydrite, such as those described by Emerson as occurring near Northampton, Mass., and by Shannon at Meriden, Conn. Other cavities do not present definite structural evidence on which the identification of the original mineral can be based. Many of them bear so close a resemblance to similar cavities from localities outside New Jersey, which are known to be due to lamellar calcite, that this mineral is suggested as a possibility. Several illustrations of lamellar calcite and the crystal cavities resulting from its removal are therefore presented for purposes of comparison.

ABUNDANCE

The lamellar cavities are probably less abundant than either the rectangular or the rhombic cavities, but they are much more plentiful than those caused by the removal of quartz, calcite, pectolite, and the zeolites. Many of them are found at Cedar Grove, between Paterson and Great Notch, but they also occur in considerable number at these two localities. In some specimens (pls. 17, *B*, *C*; 18, *A*) they are very numerous; in others (pl. 17, *A*) only a few isolated lamellar cavities are to be noticed. They are so thin that their actual volume is small, and it is probably true that the lamellar cavities form the smallest proportion of the total volume of all the cavities. Yet their actual number is large, as is shown by the specimens illustrated in Plates 17, *B* and *C*, and 18, *A*.

In many of the specimens it is difficult to tell whether to classify these cavities as lamellar or as thin tabular rectangular. Some of them (see pl. 17, *A*) could possibly be classed as thin rectangular. There seem to be all gradations between lamellar and rectangular cavities, but those here classified as lamellar do not distinctly show a rectangular outline.

SIZE

Lamellar cavities, like those that are rectangular, may be very minute, almost lost in the change of volume of the matrix due to successive mineral changes, or several inches in length. The largest ones seen were 3 inches long but only about one-fiftieth of an inch thick.

SHAPE AND HABIT

Lamellar cavities resemble gashes cut by a razor blade. Much of their matrix has been so transformed mineralogically that any definite shape or outline the ends of the gashes may have had originally has been largely obliterated. On some of the gashes a rectangular ending, either simple or steplike, is imperfectly preserved. Such cavities are probably due to anhydrite. On others a sloping or tapering ending makes very problematical their reference to anhydrite or calcite or any other mineral.

The habit is fairly constant. Lamellar cavities less than a sixteenth of an inch thick have about equal lateral extent in the other two directions. No cavities in which unequal lateral extent in two directions was in greater ratio than 3 to 1 were noticed. As a rule these lamellar cavities are straight, but rarely they seem to be slightly curved.

The thin lamellar cavities that are probably due to anhydrite have a thickness of less than a millimeter and a lateral extension in both directions of at least several hundred times as much. Many of the smooth areas on prehnite, each representing a surface of one of these cavities, are several centimeters across.

Very thin tabular cavities, if isolated, more commonly come together than remain single, but they rarely cross one another. Some groups of the original isolated thin tabular crystals, each not over a millimeter thick, became coated with a layer of prehnite many times as thick as one of the inclosed crystals. Such groups, roughly rectangular in shape, now measuring from a quarter to half an inch in thickness, extend laterally for 2 inches. Specimens of this type, in which the original mineral was anhydrite, are illustrated in Plate 8, *A*. When broken open, the thin tabular cavity, usually not over a millimeter in thickness, is found in the center, as shown in Figure 10.

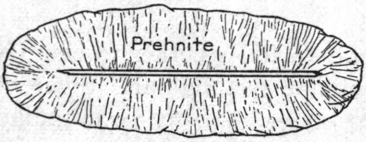

FIGURE 10.—Lamellar cavity in a flattened mass of prehnite. Compare with Plate 8, *A*, especially on the left side

Plate 17 shows three very typical examples of these lamellar cavities. In *A* the cavities could as well be described as thin rectangular, though evidence of their rectangularity is not clearly present. From the character of the wall markings, however, it is considered probable that they were once occupied by anhydrite. In *B* no clear, definite evidence was seen from which the character of the original mineral could be deduced. In *C* the abundant lamellar cavities likewise afford no definite clue to the original mineral.

Another typical specimen of the lamellar cavities is shown in Plate 18, *A*. Here again no definite clue to the identity of the original mineral was observed.

MARKINGS

Definite markings are seldom seen on the walls of the lamellar cavities. Their present matrix is commonly one of the softer minerals (pectolite, prehnite), and the very fine markings or striations that may have been presented on the original mineral have become obliterated by the mineral changes to which they have been subjected. The extreme thinness of the original crystals was also not conducive to the preservation of thin markings or striations. On a few of the prehnite specimens (pl. 17, *B*), are seen ridges, as illustrated in Figure 11, which suggest strongly the rectangular cleavages of anhydrite.

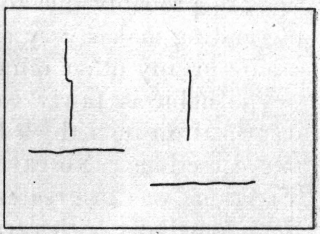

FIGURE 11.—Rectangular ridges on the sides of some lamellar cavities

The markings observed in the tabular rectangular cavities indicate anhydrite as their original mineral. The continuity of the series ranging from rectangular cavities through tabular or thick lamellar cavities (pl. 17, *A*) to thin lamellar cavities (pls. 17, *B* and *C*) strongly suggests that anhydrite was also the original mineral of all the lamellar cavities. No evidence has been encountered to disprove this suggestion, yet another mineral—calcite—is a possibility to be considered in regard to some of the lamellar cavities. The three directional markings at angles of 120° to one another, commonly present on the base, *c*(0001), of tabular calcite crystals, as illustrated in Figure 31, have however, not been observed on the walls of any of these lamellar cavities.

MATRIX

The lamellar cavities have been found in quartz, prehnite, pectolite, datolite, and some of the zeolites. The original mineral, like that of the rectangular cavities, persisted in some places until after the zeolite period had begun. The absence of quartz pseudomorphs (like those after glauberite; see p. 22) suggests that the original mineral persisted until the period of quartz formation had passed.

ASSOCIATED CAVITIES

Though lamellar cavities are occasionally found on the same specimen as the much larger rectangular and rhombic cavities, characteristically they occur much more abundantly without the other types.

MINERALS IN CAVITIES

The thinness of the lamellar cavities does not furnish much space for the development in them of minerals of the later periods. In a few specimens, however, the lamellar cavities contain a considerable quantity of a dark-green mineral looking like chlorite. The significance of this feature is discussed on page 51. Thin platy masses of prehnite occurring here and there in the zeolitic rock suggest replacement pseudomorphs of prehnite after the original lamellar mineral.

ORIGINAL MINERALS

The lamellar cavities are very thin gashes, few of which show any definite shape in their outline and most of which show no markings on their walls that would serve to identify the original mineral. Some of them, especially the thicker ones, seem to have a rectangular ending and show poorly developed rectangular markings on their walls; they are probably due to anhydrite. For most of them, however, no characteristic features, except their tabular shape, have been noted which would be of value in identifying the original mineral.

ANHYDRITE

No specimen has been seen by the writer in which the original lamellar mineral has persisted. The following characteristics, however, strongly suggest that anhydrite was probably the original mineral of many of them, the lamellar type being simply an extreme development of the thin tabular cavities whose rectangular outlines can still be observed. The evidence on which the reference of many of these cavities to anhydrite is based is as follows:

1. Tabular habit, similar to that of the thin tabular rectangular cavities from the same locality. Emerson,[50] in describing the anhydrite from Northampton, Mass., in the trap rock above the Triassic sediments, says of the anhydrite:

> The plates vary in width from an eighth of an inch down to extreme fineness, are bounded by nearly parallel planes, but taper slowly to an edge, and are replaced by the thickening of their neighbors.

Such a description fits perfectly many of the specimens from New Jersey.

2. Occasional rectangular ridges on walls of cavities. (See fig. 11.)
3. Cleanliness of cavities and absence of secondary decomposition products and of coloring effects, showing that the original mineral was readily soluble and free from coloring matter.
4. The mineral character of the matrix, identical with that of the rectangular cavities.

CALCITE

From purely circumstantial evidence, it is suggested that lamellar calcite may have been the original mineral of some of the lamellar cavities. The presence of the carbonate radicle in the solutions is in accord with the geologic conditions outlined on page 8, if the lake beds and waters contained a carbonate mineral as well as a sulphate mineral. The abundance of calcite in the zeolite rock is suggestive of a supply of the carbonate radicle independent of carbonic-acid gas derived from the atmosphere.

For purposes of comparison, Plate 19 shows crystal cavities after calcite from localities outside of New Jersey, the original calcite crystals of which were similar in habit to the lamellar calcite crystals shown in Plates 18, *B*, and 20. A comparison of the specimens shown in Plates 17 and 18 *A* (from New Jersey) with those shown in Plate 19 (from localities outside of New Jersey) suggests that some of the lamellar cavities of New Jersey (pl. 17) were formerly occupied by calcite. These cavities show no markings by which a definite conclusion can be reached, and the other evidence—cleanliness of molds, freedom from coloring alteration products, and ready solubility of original mineral—would apply as well to calcite as to anhydrite.

All the calcite now present in the zeolitic area belongs to the sixth period of the mineral sequence (see insert, p. 22), being later than the

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[50] Emerson, B. K., A mineralogical lexicon of Franklin, Hampshire, and Hampden Counties, Mass.: U. S. Geol. Survey Bull. 126, p. 26, 1895.

zeolite period and much later than the saline period during which the anhydrite and the glauberite were formed.

Each of the different habits of calcite—the lamellar (variety argentine) parallel to the base, the rhombohedral, pyramidal, and scalenohedral—has a different time history and represents crystallization under different conditions and especially at different temperatures. Where several of these habits of calcite occur on the same specimen there is a definite sequence in time formation, according to the habit. In 1912 Wilhelm Maucher, a mineral dealer in Munich, Germany, told the writer that he had concluded, from an examination of a large number of mineral specimens, that the lamellar calcite was always the oldest, forming first at the higher temperature, and that the rhombohedral and scalenohedral types of calcite were of later origin. Kalb [51] has recently expressed the same conclusion, stating that the tabular habit parallel to the base was that habit of calcite which formed at the higher temperature. Koenigsberger [52] states the same relation: "As the oldest mineral at the highest temperature calcite is tabular after the base, in the later generation rhombohedral, and as the youngest mineral it is acute scalenohedral." In a later paper Kalb [53] discusses the crystal form that bounds the tabular crystals and states that either $(10\bar{1}1)$ or $(21\bar{3}1)$ may be the most abundant form. If either of these two forms bounds the tabular crystals they will be inclined to the large tabular face, as $c(0001) \wedge r\ (10\bar{1}1) = 44° 37'$ and $c\ (0001) \wedge v\ (21\bar{3}1) = 66° 29'$. Crystal cavities after tabular calcite, of the combination *cr* or *cv*, could then be readily distinguished from tabular cavities after anhydrite, of the combination *abc* in which the angles are 90°. On the other hand, anhydrite crystals with the combination $b(010)$, $c(001)$, $r(101)$ would have a side inclination of 48° 15′ $(=c(001) \wedge r(101))$ that would be difficult to distinguish from the calcite angle $c(0001) \wedge r(10\bar{1}1)$, except that if for calcite, the rhombohedron $r(10\bar{1}1)$ were the only inclined form, then the two side bounding faces would be parallel, as sketched in Figure 12, *c*, whereas in anhydrite they would not be parallel as shown in Figure 12, *d*. On some tabular crystals of calcite the only form present besides the base $c(0001)$ is the prism $m(10\bar{1}0)$, and such crystals would yield a rectangular outline, not distinguishable in shape from a pinacoidal anhydrite crystal.

The outlines presented by these crystals, when viewed with the faces normal, are shown in Figure 12.

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[51] Kalb, Georg, Die Kristalltracht des Kalkspates in minerogenetischer Betrachtung: Centralbl. Mineralogie, 1928, Abt. A, p. 339.

[52] Koenigsberger, J., Konstanz und Variabilität in Kristallhabitus und Trach erläutert an Hand zentralalpiner Vorkommen: Fortschr. Mineralogie, vol. 11, p. 13, 1927.

[53] Kalb, Georg, Bemerkung zu den minerogenetischen Kristalltracht-typen des Kalkspates: Centralbl. Mineralogie, 1929, Abt. A, p. 137.

Obviously, from the outlines alone, which would represent the outlines of the crystal cavities resulting from the removal of the mineral, it would be impossible to distinguish between *a* (calcite) and *b* (anhydrite) and probably difficult, on the very thin cavities, to distinguish between *c* (calcite), *d* (anhydrite), and *e* (calcite).

The base, *c*(0001), of these tabular calcites, is generally striated in three directions, at angles of 120° to one another, as shown in Figure 31. On many of the specimens from localities outside of the New Jersey field showing lamellar cavities after such tabular calcite, as illustrated in Plate 19, these sets of striations in three directions, 120° apart, are shown on the walls of the cavities and serve as the best indication of the previous presence of calcite. But no such markings have been seen on any of the lamellar cavities from the New Jersey region.

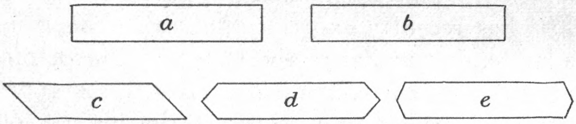

Figure 12.—Outlines presented by crystals of calcite and of anhydrite, viewed normal to the crystal faces. *a*, Calcite, *c*(0001) and *m*(1010); *b*, anhydrite, any two of the three pinacoids *a*(100), *b*(010), *c*(001); *c*, calcite, *c*(0001) and $r(10\bar{1}1)$; *d*, anhydrite, *c*(001) and *r*(101); *e*, calcite, *c*(0001) and $v(21\bar{3}1)$

Tabular calcites have been found to a minor extent in the zeolite region of New Jersey, but no specimen of them has been found in which a definite sequence can be determined. A specimen of tabular calcite from Moore's station, N. J., is shown in Plate 18, *B*. Such an aggregate of tabular calcite crystals, if covered with a later mineral, such as quartz or prehnite, would give, when removed, the same type of lamellar cavities as shown by the specimens in Plates 17 and 18, A.

The specimen shown in Plate 19, *A*, from Silver City, Idaho, has lamellar cavities after calcite very similar to those shown in Plates 17 and 18, *A*. A few of the cavities in this specimen have oblique terminations, like Figure 12, *c*, *d*, *e*, and small groups of parallel cavities are like those shown in Plate 18, *A*. The specimen shown in Plate 19, *B*, from the same locality as *A*, has a number of cavities with similar oblique terminations at the ends, and on a few walls are indistinct sets of parallel striations in three directions at 120° to one another, like those shown in Figure 31. A comparison of Plate 19, *B*, with Plate 17, *C*, shows the similarity in the character of the cavities. The specimen of Plate 19, *C*, from Wonder, Nev., shows the three sets of striations very well developed on the walls of the cavities. The cavities are very similar to those from New Jersey (pls. 17, *B*, *C;* 18, *A*), especially in the grouping of sets of parallel cavities.

In Plate 20, *A*, is shown a group of lamellar calcite crystals from Andreasberg, Germany, which, in shape, closely resemble the lamellar cavities from the New Jersey zeolite region shown in Plates 17 and 18, *A*. The grouping of several of the lamellar crystals in parallel position is particularly worthy of note, and this specimen should be compared with the sets of parallel lamellar cavities shown in Plates 17, *B* and *C*, and 18, *A*.

A specimen of very similar lamellar calcite from the Banner mine, Florida Mountain, Silver City district, Idaho, is illustrated by Piper and Laney.[54]

Lamellar calcite and quartz pseudomorphs after it, associated with ore deposits, have been described several times, the genetic relation of the calcite to the other minerals being indicated. Where the lamellar calcite was first inclosed in quartz and later removed lamellar cavities have been found. These cavities are, at some places, filled by later deposition of quartz, yielding what has been termed "pseudomorphic quartz." Thus Lindgren [55] writes:

> Practically all of the quartz gangue from that vicinity (De Lamar) is pseudomorphic after other minerals, probably calcite and barite. * * *
>
> The De Lamar, Webfoot, Garfield, Chautauqua, and other veins in the same vicinity are all distinguished by the universal presence of a laminated quartz,[56] which is clearly of pseudomorphic origin. * * * This laminated quartz forms a cellular network of thin and straight intersecting laminae of quartz. * * *
>
> It seems most probable that calcite was the original mineral of these pseudomorphs, though barite may also have been present. The thin plates of quartz may originally have been deposited between the calcite grains. When the latter were dissolved the quartz remained and the cells were filled or coated with secondary quartz.

The specimen of " pseudomorphic quartz " shown by Lindgren in his Plate XXX, *A*, would yield a group of cavities like those shown in Plates 17 and 18, *A*, of this report, if the original lamellar calcite had been dissolved and the resulting cavities had remained empty.

Similar descriptions have been given by Knopf [57] for the ore deposits of the Helena region, in Montana. He writes:

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[54] Piper, A. M., and Laney, F. B., Geology and metalliferous resources of the region about Silver City, Idaho: Idaho Bur. Mines and Geology Bull. 11, pl. 5, *A*, 1926.

[55] Lindgren, Waldemar, The gold and silver veins of Silver City, De Lamar, and other mining districts in Idaho: U. S. Geol. Survey Twentieth Ann. Rept., pt. 3, pp. 169, 170, 1900.

[56] This sometimes appears as if it had been cut or chopped by a sharp instrument while soft. Hence the German name of " Zerhackter Quarz," or chopped quartz, which is often given to occurrences similar to these.

[57] Knopf, Adolph, Ore deposits of the Helena mining region, Montana: U. S. Geol. Survey Bull. 527, pp. 55, 64, 65, 1913.

> In some deposits * * * the quartz is pseudomorphic after a thinly lamellar calcite. This has given rise to a gangue of characteristic appearance. * * *
>
> The pseudomorphic lamellar quartz is developed in extraordinary perfection in the veins of Marysville, where in fact considerable quantities of unreplaced lamellar calcite still remain. Plates III [here reproduced as pl. 20, *B*] and IV are photomicrographs of a thin section of calcite ore from the second level of the Belmont mine, Marysville. The lamellar habit of the calcite and the extreme thinness which the plates attain—some under 0.001 of an inch—are well displayed. * * *
>
> The gangue material is of highly characteristic composition and structure. It consists of quartz, commonly of lamellar habit, and calcite in broad, thin lamellae. * * * In many of the typical ores of Marysville the calcite lamellae attain great breadth and extraordinary thinness—at the Empire mine, for example, the extreme diameter being 6 inches and the thickness only one-fiftieth of an inch.

Very similar ore material is described by Schrader:[58]

> A striking feature of the Jarbidge gangue is its characteristically laminated or platy and bladed structure, in which innumerable contiguous or connecting laminae or plates are variously arranged. * * * Much of the pseudomorphic platy and cellular structure seems to be due to silicification and replacement of calcite. This replacement begins along the cleavage planes of the primary calcite. The plates range from minute size up to nearly an inch in diameter and from the thickness of a knife blade to that of ordinary pasteboard. They are mostly triangular in outline and form tetrahedral or polyhedral cavities (Pl. VIII).

The specimen illustrated by Schrader in the lower part of his Plate VIII would, like the specimen from Idaho illustrated by Lindgren to which reference has just been made, yield lamellar cavities like those from New Jersey (pls. 17 and 18, *A*), if the calcite had been simply dissolved and the resulting cavities remained empty.

Similar specimens of "pseudomorphic quartz," in many of which the original lamellar calcite is still present, have been collected from other localities than those mentioned, notably in California and Arizona—in fact, ore rock of this type is rather characteristic of many of the western Tertiary gold veins.

These examples have been cited to show that the formation of lamellar calcite and its inclosure by later quartz and subsequent solution and removal is by no means a rare occurrence but seems to be typical of deposits where the temperature was high enough to cause the calcite to crystallize in lamellar plates tabular after *c* (0001). In many of the western localities cited lamellar cavities after calcite, similar to those from New Jersey, have been found, and at all places the calcite has preceded the formation of quartz, a genetic relation

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[85] Schrader, F. C., A reconnaissance of the Jarbidge, Contact, and Elk Mountain mining districts, Elko County, Nev.: U. S. Geol. Survey Bull. 497, p. 54, 1912.

entirely in accord with the mineral history in the New Jersey field. This suggests that some of the New Jersey lamellar cavities may represent lamellar calcite, but, as cited on page 18, all the calcite thus far observed in the zeolite region is of the sixth period. Definite evidence in support of this suggestion has not been found. In fact, for many of these cavities no diagnostic feature has been observed which would point to any one of several minerals that might have assumed a thinly tabular habit.

BABINGTONITE

Babingtonite may have been the original mineral of a few of the lamellar cavities. Fenner's sketch of shreds of babingtonite (then referred to as an abnormal amphibole, probably arfvedsonite) in calcite[59] is very suggestive of a conformity of the shape of the lamellar cavities with the crystals of babingtonite. As stated on page 37, babingtonite crystals from the New Jersey area are tabular rather than equidimensional. Although most of the babingtonite from this area belongs to a late period of the mineral sequence, it is very probable, as stated by Fenner, that some of it crystallized out much earlier and may have formed during the prehnite stage (period 4). Several specimens have been found in which the lamellar cavities are filled with a dark-green mineral that looks like chlorite. This product may have been formed in place from the original babingtonite, although the presence of a similar mineral in other cavities, particularly in the rectangular cavities after anhydrite, shows that it can not be considered a necessary result of the alteration of previously existing babingtonite.

This dark-green mineral, looking like a fine-grained chlorite to the unaided eye, has commonly been referred to diabantite. Though a chloritic mineral is present in the zeolitic rock, some of the material so called is not a chlorite but a fibrous prismatic mineral closely related to aegirite. This is true of the compact substance found in several of the cavities as well as of the very small tufts of acicular crystals perched on the zeolites and associated minerals. The prismatic crystals are strongly pleochroic—parallel to the elongation deep green with strong absorption, normal to the elongation a pale olive-green almost colorless. The extinction is nearly parallel, the highest measured being less than 4°. Anomalous interference colors are common, in indigo-blue and deep burgundy-red. The axial plane is parallel to the elongation, with a large positive axial angle normal to the prism zone. If this axial angle is the obtuse one,

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[59] Fenner, C. N., The Watchung basalt and the paragenesis of its zeolites and other secondary minerals: New York Acad. Sci. Annals, vol. 20, fig. 14, 1910.

then the mineral is negative. α is about 1.76 and the birefringence is strong. Fenner[60] gives γ as 1.81 and states:

> I think that on the whole the data indicate a slightly abnormal aegirite. * * * The data given above apply to the mineral in its most common and characteristic form. There seem to be transitions, however, to a less common, nearly colorless, variety.

These are the varieties earlier referred to by Fenner as amphibole, varieties 2 and 3.

RHOMBIC CAVITIES

ABUNDANCE

Rhombic crystal cavities are very abundant in the zeolitic rock and the numerical estimates given for the rectangular cavities would apply equally well to the rhombic variety. They are commonly grouped together in bunches of smaller radiating groups (pl. 21, *A*) and also as single radiating masses (pls. 23, *B*, and 24), which reach a considerable size. The rhombic cavities have been found at all the quarries where crystal cavities have been obtained, and although they occur with the rectangular cavities on many specimens, they usually form independent groups.

SIZE

The size of these cavities varies considerably. Some are minute, but others, such as the one shown in Plate 23, *A*, are relatively large. This cavity measured diagonally is nearly 3½ inches across. In the Disbrow collection at Newark there is a remnant of another large rhombic cavity. This is imperfect and has walls less than an inch high, but it measures 3 inches along one side. Apparently this cavity if entire would be larger than the cavity illustrated in Plate 23, *A*.

John Obert,[60] of Ridgewood, N. J., reports a rhombic cavity measuring 4 inches along its longest diagonal and 2 inches along its shortest diagonal.

James F. Morton, of the Paterson Museum, has a similar specimen with a rhombic cavity whose longest diagonal is 2½ inches and whose two sides measure 1¾ and 1¼ inches. The cavity was probably originally somewhat longer.

Minute rhombic cavities are few in comparison with the number of such cavities among the rectangular type. There also seems to be a greater tendency toward uniformity in size both on any one specimen and on all the specimens seen. A cross section extending from a quarter of an inch to 1 inch would include many of them.

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[60] Personal communication.

SHAPE AND HABIT

The rhombic crystal cavities are very uniform in shape. In cross section they all show the same appearance, and in depth they considerably exceed their width.

The habit of the rhombic cavities is very constant, all being prismatic. The original crystals seldom grew in isolation but were commonly united in radiating groups.

Some of the cavities were later filled by infiltrating silica, which formed casts that are easily removable and consequently show the crystal habit and combination of the original mineral. Such natural silica casts as shown in Plates 26, 27, and 28, are all prismatic. Some of the rhombic cavities were completely filled with silica, yielding solid pseudomorphs whose concentric structure, as shown in Plate 29, indicates that they are infiltration pseudomorphs and not replacement pseudomorphs. A few specimens, like the one shown on the right in Plate 4, *B*, appear to be true replacement pseudomorphs.

A very typical group, composed of aggregates of radiating prisms, is shown in Plate 21, *A*. Another typical occurrence, in massive quartz, is shown in Plate 21, *B*.

The development of the McKiernan & Bergin quarry, Paterson, exposed a set of these rhombic cavities, in many of which were quartz casts or cores, whose crystallographic character, described in detail, permitted the identification of their form with that of glauberite. The matrix of these casts or cores is shown in Plate 22, *A* and *B*, representing the front and back of the same specimen. This specimen is an aggregate of quartz, which includes the cavities and in type of structure resembles the similar forms described for the rectangular cavities illustrated in Plate 8, *B*. Each of the elongated masses of quartz shown in Plate 22, *A*, contains a rhombic cavity, as is revealed by the reverse side of the specimen. (See pl. 22, *B*.) A typical occurrence is the presence of one larger cavity (or two or three but rarely more), which generally contains a well-defined quartz cast or core. (See pls. 27 and 28.)

MARKINGS

The walls of the rhombic cavities are usually free from any markings that would help identify the original mineral. Some of the cavities, however, show oriented markings, which are reproduced in casts or cores and are described on page 73. The only observed markings in these cavities are poorly preserved sets of parallel striations that lie at an angle to the elongation of the prismatic cavities and suggest an oscillatory combination of two or more crystal forms on the original mineral. Striations parallel to the elongation of the cavities, such as are common for the rectangular cavities, are entirely lacking.

MATRIX

The matrix of the rhombic cavities is strikingly and almost exclusively quartz. Specimens formerly in the collection of F. A. Canfield, of Dover, N. J., and now in the United States National Museum show these cavities in prehnite and in datolite, but such specimens are rare, and it is at least probable that the original matrix was quartz which had been changed to prehnite or to datolite. The presence of a quartz matrix in so many specimens shows that the original mineral (glauberite) dissolved away near the end of the quartz period (p. 21), and when prehnite, pectolite, and the zeolites crystallized out almost none of the glauberite was left for these later minerals to inclose. The solutions that deposited later silica entered some of the cavities left by the glauberite and partly or completely filled them with quartz, thus forming the solid or hollow quartz pseudomorphs. Many specimens are coated with a layer of quartz crystals, which themselves are now covered by such later minerals as the zeolites. In some specimens it seems as if the silica-depositing solutions surrounded the original glauberite crystals in such a way that they all became well covered with a layer of compact quartz except the larger indviduals, which projected farther out. These later become covered like the others but with crystalline rather than compact quartz, which did not make so impervious a coating. Still later solutions dissolved away the glauberite in those cavities to which they had access and then deposited compact silica, thus forming infiltration pseudomorphs only in the larger cavities. Anhydrite had a longer range of existence than glauberite, for many anhydrite crystals that are now gone existed during the prehnite period.

ASSOCIATED CAVITIES

The rectangular and lamellar cavities are very rarely associated with the rhombic cavities. Where two varieties are found on the same specimen they usually occur in separate groups, not intermingled. (See pl. 4, *B*.)

In a few specimens rhombic and rectangular cavities occur together in an association that shows a definite sequence. (See pl. 25.) In both the specimens illustrated the rhombic cavities form radiating groups within a single much larger rectangular cavity. As the rhombic aggregates do not project through the walls of the large rectangular cavity but are confined to it, they were probably formed after the anhydrite had been dissolved. This would indicate that the formation of anhydrite began before that of glauberite.

MINERALS IN CAVITIES

None of the original glauberite of these rhombic cavities has yet been found in the zeolitic rock. The ease with which glauberite is attacked by water, which dissolves out the sodium sulphate and leaves most of the calcium sulphate (as gypsum), renders it very improbable that any considerable quantity of glauberite will ever be found there. If found, it will probably be in a very dense, compact, and unfractured phase of the trap rock, which has escaped the changes caused by the later development of the zeolitic rock. The later zeolites and other minerals of this field are occasionally found in the rhombic cavities.

ORIGINAL MINERAL

GLAUBERITE

The rhombic crystal cavities have a uniform shape and habit. Some have been found to contain solid or hollow casts or cores of quartz, easily removed, which preserved the outlines of the original mineral. From their crystallography data could be obtained on the crystallography of the original mineral. Crystallographic measurements (pp. 61–72) have shown the complete identity of the casts with the crystal form of glauberite not only in habit but in mode of occurrence and in angular relations. The casts or cores on which the identification of the original mineral as glauberite is based were found in McKiernan & Bergin's quarry, Paterson. The orientation of glauberite has been changed from the normal position into two other positions, bringing out better the crystallography of the cores.

CRYSTALLOGRAPHY OF QUARTZ PSEUDOMORPHS

The cores are all prismatic in habit and range in thickness from one-eighth of an inch (pl. 26, *A*) to nearly 2 inches (pl. 26, *B*) and in length from 1¼ to 3¼ inches. Their size and shape can be well seen in Plates 26, 27, and 28. Three very slender casts (the middle one broken off) are shown in Plate 26, *A*, and one of the largest found is shown in *B*. A cross section of the cast shown in Plate 26, *B*, is reproduced in Plate 29, *A*, showing its solid character.

Groups of these cores are shown in the middle and lower rows of Plate 27 and in Plate 28. The upper row (Nos. 1, 2, 3, and 4) of Plate 27 represents glauberite crystals from other localities, which are included for comparison. (See p. 58.) The cores in the middle row of Plate 27 are relatively simple in their crystallographic development, but those in the upper row of Plate 28 show several different crystal forms.

The five cores in the middle row of Plate 27 (Nos. 5, 6, 7, 8, and 9) are shown in orientation III (see p. 60), with the base *c*(001) in the position of the positive unit orthodome (101). When so oriented, the base *c*(001) is almost the only terminal face showing. (Compare figs. 13, 16, 17, and 18.) The form *y*(223), as illustrated in Figure 18, may have been present as narrow faces on some of the original crystals of glauberite, but the subsequent corrosion has so rounded the edges $c \wedge s$ that its presence can only rarely be detected.

Nos. 10 and 11 (pl. 27) show the quartz capping over the terminated end and Nos. 12 and 13 show additional smaller cores attached to the large core—in No. 13 in apparent parallel position.

The top row of Plate 28 (Nos. 1, 2, 3, 4, and 5) shows the cores in orientation II, with the base *c*(001) in the rear and the orthopinacoid *a*(100) in the position of the positive unit dome (101). This side of the terminated cores is much richer in crystal faces than the other side and shows faces of *a*(100), *m*(110), $e(\bar{3}11)$ and $x(\bar{3}31)$. (Compare figs. 22, 23, and 24.)

The second row of Plate 28 (Nos. 6, 7, 8, 9, and 10) shows the tapering character of the other end of the cores, which come almost to a point in Nos. 6, 7, and 9 and to a short, almost prismatic handle in Nos. 8 and 10.

Nos. 11 and 13 show the serrated character of one pair of the intersection edges of *s*(111), Nos. 12 and 13 again show the quartz capping, and No. 14 shows an additional smaller core projecting almost at right angles from the large core.

The specimens illustrated were found in place in a matrix of incrusted pseudomorphs of quartz and were nearly all sufficiently loose to be pulled out and replaced at will. Not a single one has been observed that is complete in its crystallographic development at both ends. Many of them, however, show a complete termination at the thicker end. The other end, if not broken, tapers almost to a point. So striking in appearance is this tapering that some observers have considered the pseudomorphs to be truly hemimorphic. But, as presently shown, this effect is due to the mutual interference of several crystals in a radiating group, united at their tapering ends. The other ends of many of the crystals show complete development of crystal faces, front and back. On several of these pseudomorphs the positions of the original faces have been sufficiently well preserved to permit measurement of their angles with a contact goniometer. The results show that these angles agree very well with those of glauberite and confirm the opinion that these faces represent monoclinic symmetry. The front and back faces and combinations are very different, but both sets of faces are symmetrical to a vertical plane passing through the center of the pseudomorph. The following description of the crystallography is therefore based on that of glauberite.

Glauberite is monoclinic and shows in its crystal development two very different habits. One, perhaps the more common, is a tabular habit parallel to the base. A thicker crystal of this habit is shown as Figure 1 in Dana's "System of Mineralogy," page 898. Similar tabular crystals have been described and illustrated by Koechlin.[61] In these crystals the base is by far the largest face and determines the tabular habit. The forms *s*(111), *m*(110), and *a*(100) are next in size. Somewhat similar crystals, but more simple in their combination, have been described and illustrated by Gale.[62] These crystals have the simple combination *c*(001), *s*(111), *m*(110), with *c* and *s* in about equal development, giving them a rhomboid shape, the faces of *m*(110) being long, narrow faces, truncating the edges formed by *c* and *s*.

The other distinct habit of glauberite is prismatic and is formed by the elongation of the faces of the pyramid *s*(111). Zepharovitch[63] described prismatic crystals with the faces of *s*(111) dominating. The illustration he gives shows the glauberite to be short prismatic in habit, owing to the extension of the pyramid faces. Similar rhomboid forms of casts made from the cavities in the Triassic shale 1 mile south of Steinsburg, Bucks County, Pa., are described and illustrated by Wherry,[64] who showed conclusively that these cavities were due to the former presence of glauberite. Similar conclusions were reached by Lewis.[65] In Wherry's paper attention is also called to long pyramidal types of crystal cavities that are occasionally found.

This habit is also mentioned by Dana as "prismatic by extension of *s*(111)," but is not illustrated by him. Crystals of glauberite of this habit from Peru were described by Senarmont[66] and are illustrated by Goldschmidt.[67]

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[61] Koechlin, R., Ueber Simonyit- und Glauberitkrystalle von Hallstatt: K. k. naturhist. Hofmuseums, Wien, Annalen, vol. 15, Heft 1, pp. 103–110, figs. 4, 5, 1900; Ueber Glauberit vom Dürnberge bei Hallein: Idem, Heft 2, pp. 149–152, 1900.

[62] Gale, H. S. Salines in the Owens, Searles, and Panamint Basins, southeastern California; U. S. Geol. Survey Bull. 580, p. 303, fig. 83, 1914.

[63] Zepharovitch, V. R., Mineralogische Mitteilungen, V; 1, Die Glauberit-krystalle und Steinsalz-Pseudomorphosen von Westeregeln bei Stassfurt: K. Akad. Wiss., Math.-naturw. Cl., Sitzungsber., vol. 69, Abt. 1, p. 16, 1874.

[64] Wherry, E. T., Glauberite crystal cavities in the Triassic rocks of eastern Pennsylvania: Am. Mineralogist, vol. 1, pp. 37–43, 1916.

[65] Wherry, E. T., op. cit. (1916), p. 39, footnote 5. See also Stose, G. W., Glauberite crystal cavities in the Triassic rocks in the vicinity of Gettysburg, Pa.: Am. Mineralogist, vol. 4, p. 1, 1919.

[66] Senarmont, H., Note sur les formes de la glaubérite de Iquique (Pérou): Annales chimie et phys., vol. 36, pp. 157–158, 1852.

[67] Goldschmidt, Victor, Atlas der Krystallformen, vol. 4, pl. 29, figs. 11–13, 1918.

Senarmont states that the crystals were remarkable for their extreme elongation of the striated faces of *s*(111) and that they reached an elongation of 4 to 5 centimeters (nearly 2 inches). Wherry also calls attention to Groth's description of crystals from the same locality (Iquique, Peru).[68] The reddish glauberite there occurs in very long, slender prisms after *s*(111).

Four such prismatic crystals of glauberite are shown natural size in the top row of Plate 27. As can readily be seen, all four of the crystals are decidedly prismatic in habit, the elongation being formed by the extension of the faces of the pyramid *s*(111). A group of similar elongated glauberite crystals from Westerergelen, near Magdeburg, Prussia, are also in the American Museum of Natural History (catalog No. 16328).

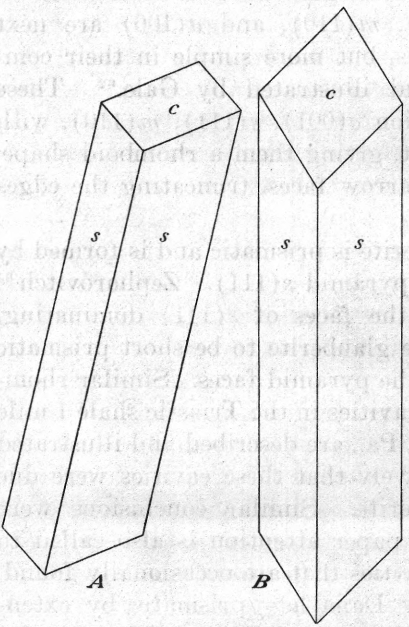

FIGURE 13.—Crystallographic interpretation of glauberite crystals shown in top row of Plate 27. Forms: *c*(001), *s*(111). In *A* the crystal is drawn in the normal orientation (I) of glauberite; in *B* the crystal is drawn in a different orientation (III), so chosen as to make the unit pyramid *s*(111) the unit prism form (110)

The crystallographic interpretation of the four crystals illustrated is given in Figure 13. These drawings and the top row of Plate 27 are to be compared with the pseudomorphs from Paterson shown in the second row of Plate 27. The faces of *s*(111) of the glauberite crystals are striated parallel to the edge of *c*(001) ∧ *s*(111), and as *c*(001) has a good cleavage, the traces of any incipient cleavage planes (after *c*) will appear on the faces of *s* parallel to the striations. Similar prismatic crystal cavities after glauberite were found by Wherry[69] in shale near Steinsburg, Pa., and illustrated by him in the center of the bottom row of his Figure 1, which shows a cast two and one-third times as long as wide. According to the illustration this cast is very similar in crystal development to the glauberite crystals shown in the top row of Plate 27 and the pseudomorphs shown in the second row of the same plate.

There are thus several occurrences of glauberite where the crystals have a long prismatic habit due to the extension of the faces of the

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[68] Groth, Paul, Die Mineralien-Sammlung der Kaiser-Wilhelms-Universität, Strassburg, p. 155, 1878.

[69] Wherry, E. T., Glauberite crystal cavities in the Triassic rocks of eastern Pennsylvania: Am. Mineralogist, vol. 1, pp. 37–43, 1916.

pyramid *s*(111), and this habit can not by any means be considered to be rare or unusual. It ranks about next to the commonest habit of glauberite crystals.

The pseudomorphs from Paterson shown in the second row of Plate 27 can readily be seen to be similar to the glauberite crystals shown in the first row. Measurements of the angles of the faces on these pseudomorphs show practical identity with the angles for the similar forms of glauberite. On the first three glauberite crystals the faces of *a*(100) (in the upper rear) are not present, and consequently the top terminal of the *c* face comes to a point, whereas in the pseudomorphs the *a* face is usually present and in the orientation here chosen (III) would appear in the upper rear as the rear dome ($\bar{1}$01), truncating the top apex of the faces of *c* as a horizontal line. The glauberite crystal shown as No. 4, Plate 27, suggests the presence of such a small *a* face.

The angles of the faces of the pseudomorphs being essentially the same as those of glauberite, the axial ratios of glauberite are taken as the fundamental elements of the crystallography of the pseudomorphs. The normal orientation of glauberite, as consistently given in the literature, does not allow the crystallographic portrayal of the faces on the pseudomorphs so well as an orientation in which the elongated faces of the pyramid *s*(111) are taken as faces of the unit prism (110). Consequently, the crystal drawings and the photographic reproductions (pls. 27 and 28) are shown in orientations different from the normal one of glauberite. Two such different orientations have been chosen in order to show adequately the terminal faces on both the front and the rear sides of the pseudomorphs. The relations of the changed orientation to the normal orientation of glauberite are given in Figure 13. The new positions are shown solely for the purpose of illustrating this report, and it is not proposed to suggest a new orientation for glauberite, though it may be well, at some future time, to give careful consideration to such a change, involving chiefly making the unit pyramid *s* the prism form, as already suggested by Wherry.[70]

The orientations chosen for illustrating these pseudomorphs are related as follows:

Orientation I is the normal one for glauberite.

Orientation II makes *s* (the long form of the pseudomorphs) the unit prism, changes the orthopinacoid *a*(100) to the positive unit orthodome (101), and makes the base *c*(001) the rear orthodome ($\bar{3}$01). The form (301), not known on glauberite, then becomes the base, the pyramid *e*($\bar{3}$11) changing to the unit clinodome (011). The orthopinacoid *a*(100) becomes the positive unit orthodome (101).

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[70] Wherry, E. T., The lozenge-shaped cavities in the First Watchung Mountain zeolite deposits: Washington Acad. Sci. Jour., vol. 6, p. 183, 1916.

Orientation III turns orientation II through 180° and, still keeping *s*(111) as the unit prism (110), makes the base (orientation I) the positive unit orthodome (101) and the orthopinacoid *a*(100) (orientation I) the negative unit orthodome $(\bar{1}01)$. The axial elements and the symbols for the common forms are given below for the three orientations chosen.

Three orientations of glauberite used for purposes of illustration

	I		II		III	
a	1.2199		0.7137		0.6319	
c	1.0275		0.4670		0.9675	
β	67° 49′		60° 31′		79° 27′	
p'_0	0.9096		0.7518		1.5574	
q'_0	1.0275		0.4670		0.9675	
e′	0.4078		0.5654		0.1862	
	Gold-schmidt	Miller	Gold-schmidt	Miller	Gold-schmidt	Miller
Forms:						
c	0	001	−30	$\bar{3}01$	+10	101
	0∞	010	0∞	010	0∞	010
a	∞0	100	+10	101	−10	$\bar{1}01$
m	∞	110	+14	141	−12	$\bar{1}21$
	+10	101	∞0	100	∞0	100
	−10	$\bar{1}01$	−10	$\bar{1}01$	0	001
	01	011	−34	$\bar{3}41$	+12	121
y	+⅔	223	−11.8	$\overline{11}.8.1$	+54	541
s	+1	111	∞	110	∞	110
n	−1	$\bar{1}11$	−12	$\bar{1}21$	01	011
e	−31	$\bar{3}11$	01	011	−½	$\overline{11}2$

The transformation symbols for the forms are as follows:

$$pq(\mathrm{I}) = \frac{p+3}{p-1} \quad \frac{4q}{p-1}(\mathrm{II})$$

$$pq(\mathrm{I}) = -\frac{p+1}{p-1} \quad \frac{2q}{p-1}(\mathrm{III})$$

The average character and distribution of the terminal forms of these pseudomorphs in orientations II and III are shown in orthographic projection in Figures 14 and 15. These projections also show well the monoclinic symmetry of the distribution of the forms occurring on the pseudomorphs.

In the following crystallographic descriptions of the pseudomorphs the various types and combinations observed and measured are illustrated by clinographic projection drawings accompanied by the interfacial angles actually measured. So many of the terminal faces are small and uneven that their interfacial angles could not be measured accurately. This is particularly true where the contact protractor could not be accurately held exactly normal to the intersection edge of the two faces concerned. In measuring the angle between faces it is absolutely essential to hold the protractor at right angles to the intersection line of the two faces. How far off the readings may otherwise become can be shown, for example, for the angle $c \wedge s$, which is very difficult to measure on these pseudomorphs, even though the faces present are the largest faces on the specimens. On several of the pseudomorphs the angle $c \wedge s$ was measured as follows:

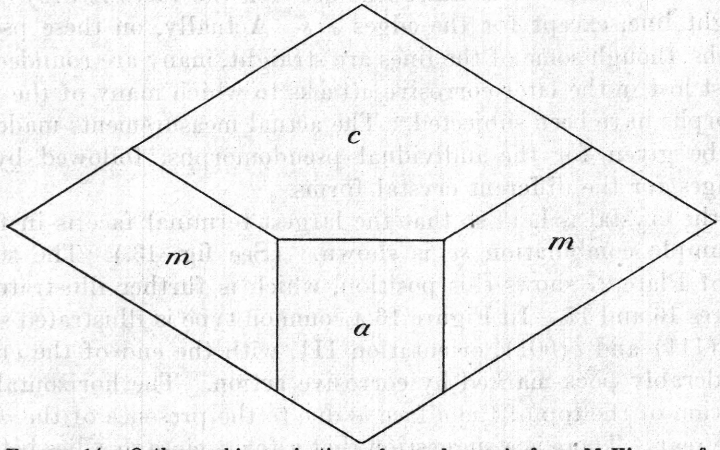

Figure 14.—Orthographic projection of pseudomorph from McKiernan & Bergin's quarry, Paterson, N. J., showing monoclinic symmetry. Forms: *c*(001), *a*(100), *m*(110). Orientation II

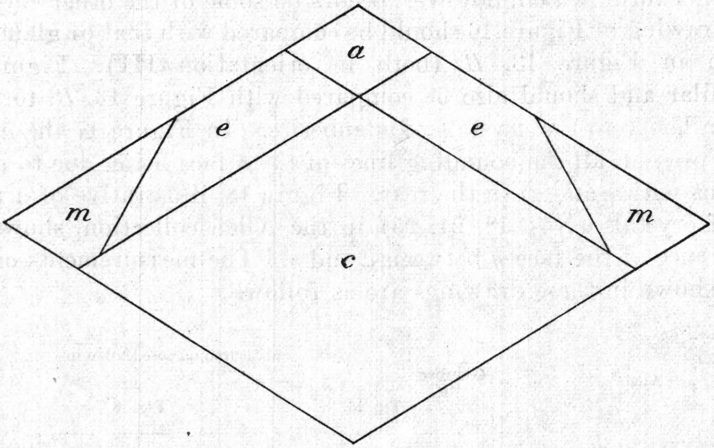

Figure 15.—Orthographic projection of pseudomorph from McKiernan & Bergin's quarry, Paterson, N. J., showing monoclinic symmetry. Forms: *c*(001), *a*(100), *m*(110), *e*($\bar{3}11$). Orientation III

Protractor correctly held	Protractor incorrectly held	Glauberite
°	°	
42	32	$c \wedge s = 43° 02'$.
43	33	$c \wedge (101) = 30° 37'$.
42	33½	
42½	31	
41½	31½	
42½	31½	

Obviously the results of measurements, where the contact protractor is incorrectly held, can easily be misinterpreted.

In the drawings the contact line between the faces is drawn as a straight line, except for the edges *s s*. Actually, on these pseudomorphs, though some of the lines are straight, many are rounded and almost lost in the later corrosive attacks to which many of the pseudomorphs have been subjected. The actual measurements made will first be given for the individual pseudomorphs, followed by the averages for the different crystal forms.

If the crystal is held so that the largest terminal face is in front, the simple combination *sc* is shown. (See fig. 13.) The second row of Plate 27 shows this position, which is further illustrated by Figures 16 and 17. In Figure 16 a common type is illustrated showing *s*(111) and *c*(001), orientation III, with the end of the crystal considerably pock-marked by corrosive action. The horizontal termination of the top of the *c* face is due to the presence of the *a* face in the rear. There is a suggestion that a form, close to *s*, lies between *s* and *c*, but the corrosive action has obliterated all definite evidence of such a form, which, however, occurs on some of the other crystals. The drawing of Figure 16 should be compared with that of glauberite shown in Figure 13, *B* (both in orientation III). Figure 17 is similar and should also be compared with Figure 13, *B*, to show its similarity to the crystals of glauberite. In Figure 17 the *a* face is not present, all the bounding lines of the *c* face being due to intersections with *s* and *m* in the rear. Figure 18, illustrative of a number of crystals (Nos. 18, 24, 25) in the Allen collection, shows the occurrence of the face *y* between *c* and *s*. The measurements on the faces shown in these drawings are as follows:

Angle	Glauberite	Measured on core shown in	
		Fig. 16	Fig. 18
	° ′	°	°
$s \wedge s'$	63 42	63½	62, 62, 62, 62, 62 (Allen Nos. 18, 22, 23, 24, 25).
$c \wedge s$	43 02	41	31, 31, 33, 31 (Allen Nos. 22, 23, 24, 25).[a]
$c \wedge s'$	43 02	35	30–35, 28–35, 35, 35 (Allen Nos. 22, 23, 24, 25).[a]
$c \wedge$ edge $s \wedge s'$	31 51	31	30 (Allen No. 18).
$s \wedge y$	8 57	--------	7, 10–12, 10 (Allen Nos. 18, 22, 24).

[a] Angle too small, as protractor was not held in correct position. See p. 61.

It will be noted that the angle $c \wedge s$ shows considerable divergence from the corresponding angle for glauberite. This divergence is not real; it is due to the difficulty of placing the protractor normal to the intersection edge of *c* and *s*. Most of the pseudomorphs are considerably corroded in the vicinity of *c*, in consequence the faces *s* and *s′*, adjoining *c*, are very uneven and generally rounded, so that it is difficult to place the edge of the protractor correctly on *s*. Later measurements of this angle, with extra precautions to hold the protractor in the correct position, have given angles in close agreement with the glauberite angle. It was found that on pseudomorphs giving the correct measurement for the angle $c \wedge s$ results from 10° to 15° too low (as given above for figs. 16 and 18) would be obtained if the protractor were laid on the large surfaces of *s* but not then in a position normal to the intersection edge $c \wedge s$.

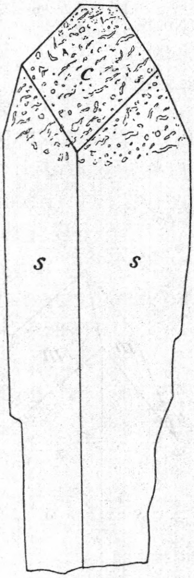

FIG. 16

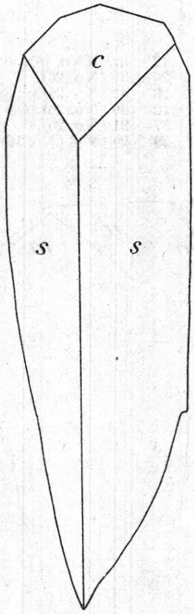

FIG. 17

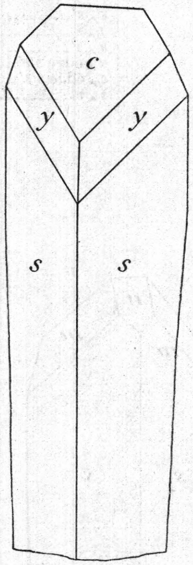

FIG. 18

FIGURE 16.—One side of pseudomorph (U. S. N. M. catalog No. 92981) showing combination *cs*, with end considerably pock-marked by corrosion. Typical of many of these pseudomorphs. Orientation III. The pseudomorph measures 32 by 11½ by 6 millimeters, in the direction of the *c*, *b*, and *a* axes. (Pl. 27, No. 6.) The other side is shown in Figure 19

FIGURE 17.—Crystal combination of the pseudomorph shown reversed in Plate 28, No. 5. The unsymmetrically developed bounding lines of the *c* face, on top, are due to the presence of faces of *s* and *m* in the rear. Orientation III

FIGURE 18.—Pseudomorphs showing *c*, *s*, and the faces of a pyramid *y*(223) lying between. Allen collection, Nos. 18, 22, 23, 24, 25. Orientation III

Figure 19 illustrates the other side of the pseudomorph shown in Figure 16. The measurements on this specimen, carefully made, are as follows:

Angle	Glauberite		Measured
	°	′	°
$s \wedge s$	63	42	62½ to 63½, average 63.
$c \wedge a$	67	49	65 to 69, average 67.
$m \wedge m'$	96	58	93 to 94, average 94.
$s \wedge m$	32	29	32 to 34, average 33.
$a \wedge$ edge s/s'	37	12	40.
$a \wedge s$	47	26	50.
$c \wedge m$	75	31	77.
$c \wedge s$	43	02	42, 43.
$c \wedge$ edge s/s'	30	37	29.

Figure 20 (Allen collection, No. 26) shows a large development of *a* with small faces of *m*, whereas Figure 21 (Allen collection, No. 19) shows large faces of *m* as the only terminal. The measurements are as follows:

Angle	Glauberite		Measured
	°	′	°
$s \wedge s'$	63	42	62½ (No. 26), 59 to 61½ (No. 19).
$a \wedge s$	47	26	39 (No. 26).
$a \wedge s'$	47	26	42 (No. 26).
$a \wedge$ edge s/s'	37	12	40 (No. 26).
$c \wedge$ edge s/s'	30	37	31 (No. 26).
$s \wedge m$	32	29	29 to 38 (No. 19).

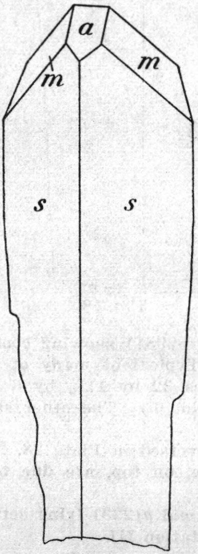

FIG. 19

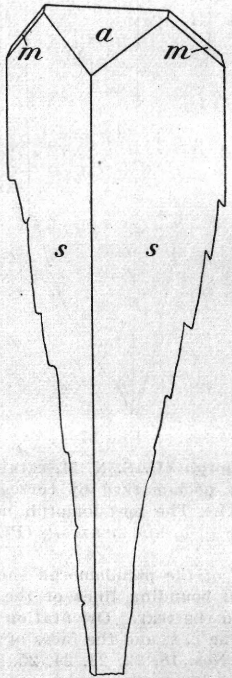

FIG. 20

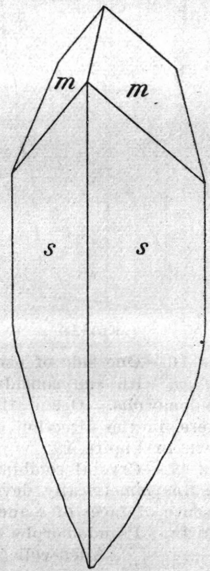

FIG. 21

FIGURE 19.—Other side of pseudomorph (U. S. N. M. catalog No. 92981) shown in Figure 16. Forms: *s*(111), *a*(100), *m*(110). Specimen measures 32 by 11½ by 6 millimeters in direction of *c*, *b*, and *a* axes. Orientation II

FIGURE 20.—Pseudomorph (Allen collection, No. 26) showing small faces of *m*. Orientation II

FIGURE 21.—Pseudomorph (Allen collection, No. 19) showing large faces of *m* as only termination. Orientation II. (See pl. 28, No. 9)

Figure 22 illustrates a more complicated crystal, in the collection of Mr. Gilman S. Stanton, of New York. The crystal is also shown in Plate 28 (No. 2). The length is 57 millimeters, and the width tapers gradually from 14 millimeters near the termination to 9½ millimeters just above the sharp-pointed termination at the bottom.

The pseudomorph is partly broken at the top, and the other side shows only a face of *c* with a considerable rough break in it. The face *x*($\bar{3}31$) could not be measured. The tapering lower termination, due apparently to four triangular faces, is discussed on pages 69–70.

Figure 23 shows a crystal (Allen collection No. 21) with a distorted, apparently unsymmetrical termination, but the measurements show that the apparent unsymmetrical development is due only to distortion. Figure 22 likewise shows some distortion in the Stanton specimen. The measurements made on these two crystals are as follows:

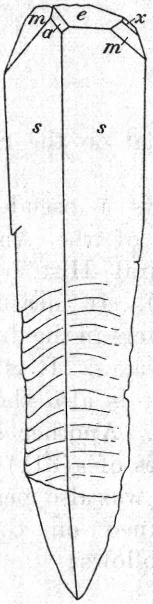

FIG. 22

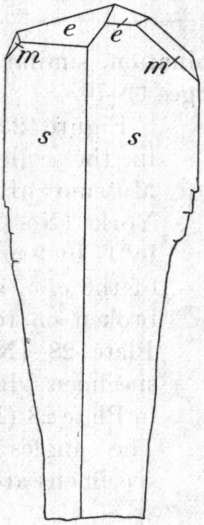

FIG. 23

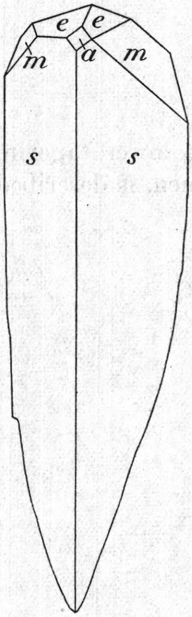

FIG. 24

FIGURE 22.—Pseudomorph in the collection of Mr. Gilman S. Stanton, New York. Forms: *s*(111), *a*(100), *e*($\bar{3}11$), *m*(110), *x*($\bar{3}31$). Orientation II

FIGURE 23.—Distorted termination on pseudomorph in the Allen collection (No. 21). Forms: *s*(111), *e*($\bar{3}11$), *m*(110). Orientation II

FIGURE 24.—Pseudomorph in the collection of Col. W. A. Roebling. Forms: *s*(111), *a*(100), *e*($\bar{3}11$), *m*(110). The crystal, also shown in Plate 28 (No. 5), is 45 millimeters long and 14 millimeters wide at its thickest part. Orientation II

Angle	Glauberite		Measured	
			Fig. 22	Fig. 23
	°	′	°	°
$s \wedge s'$	63	42	62½ to 64	--------
$s \wedge e$	54	07	56 to 58	59, 57 (best).
$s \wedge e'$	79	08	81 to 82	79, 80.
$a \wedge$ edge s/s'	37	12	39	--------
$a \wedge e$	31	42	30½	--------
$a \wedge s$	47	26	49	--------
$a \wedge m$	48	29	48	--------
$s \wedge m$	32	29	31½ to 35½	20 to 30.

A finely terminated crystal in the collection of Col. W. A. Roebling (this specimen could not be found when the Roebling collection was unpacked in Washington) is shown in Figure 24, also in Plate 28, No. 5. The measurements are as follows:

Angle	Glauberite		Measured
	°	′	°
$s \wedge {}'s$	63	42	62
$a \wedge s$	47	26	44 to 47½
$s \wedge e$	57	07	55½, 56
$s \wedge m$	32	29	33½, 32½
$a \wedge e$	31	42	30, 31

The lower tapering termination, similar to that on the Stanton specimen, is described on pages 69–70.

Figure 25 shows a pseudomorph in the collection of the American Museum of Natural History, New York (No. 18027). It measures 71 by 17 by 9 millimeters in the direction of the *c*, *b*, and *a* axes. It is partly broken on top. It is also shown in Plate 28 (No. 3). Another similar specimen with faces of *e*($\bar{3}11$) shown in Plate 28 (No. 1) was also measured. The angles obtained on the two specimens are as follows:

Angle	Glauberite		Measured
	°	′	°
$s \wedge s'$	63	42	60 to 62.
$c \wedge$ edge s/s'	30	37	29 to 33, 29 to 30½.
$a \wedge s$	47	26	49, 47 to 48½.
$m \wedge m'$	96	58	96, 96.
$a \wedge$ edge s/s'	37	12	39½ to 42.
$s \wedge m$	32	29	32 to 33, 31.
$a \wedge e$	31	42	32.
$e \wedge m$	32	14	33, 30½.
$a \wedge m$	48	29	49, 48.
$s \wedge e$	54	07	55½, 56.
$s \wedge y$	8	57	6.
$s' \wedge e$	79	08	81, 79½.

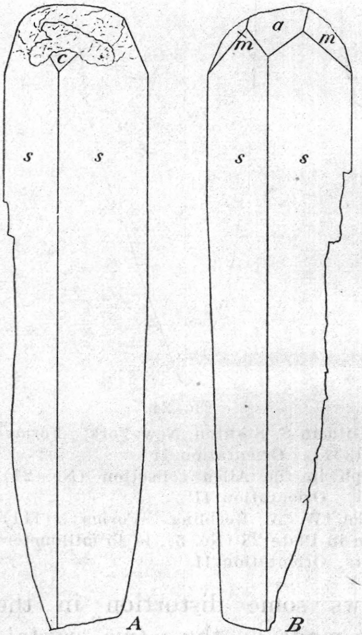

FIGURE 25.—Pseudomorph showing the two sides of the termination. (Am. Mus. Nat. Hist. catalog No. 18027 B). *A* is drawn in orientation III and *B* in orientation II. In these drawings the actual appearance of the pseudomorph is shown, with its imperfect termination on one side

A third imperfect specimen in this group, measuring 43 by 13 by 8 millimeters (pl. 28, No. 6), shows only the pointed termination present on the Stanton and Roebling specimens.

Another pseudomorph of the Canfield collection (No. 6264), now in the United States National Museum, and similar in form development to the Roebling specimen, gave the following measurements:

Angle	Glauberite		Measured
	°	′	°
$s \wedge s'$	63	42	61 to 62.
$c \wedge a$	67	49	68½.
$a \wedge s$	47	26	48 to 50.
$a \wedge e$	31	42	30.
$c \wedge m$	75	31	75½.
$s \wedge e$	54	07	56½.
$e \wedge m$	32	14	30½.
$s \wedge m$	32	29	30 to 32.
$c \wedge s$	43	02	42, 42½.
a edge s/s'	37	12	39.

Another specimen in the collection of the United States National Museum gave $c \wedge s = 41½°$, $42½°$ (glauberite=43° 02′) and $a \wedge c = 67½°$ (glauberite=67° 49′).

If all these measurements are averaged, exclusive of a few that are obviously discordant, the following compilation is obtained, from which the close similarity of the angles of the crystal faces of the pseudomorphs to those of glauberite can readily be seen. The angle $s \wedge s'$ was carefully measured on 26 different pseudomorphs (not all terminated), with an average of 63°.

Comparison of average measured angles of pseudomorphs with corresponding angles of glauberite

Angle	Glauberite		Measured	
			Average	Limits
	°	′	°	°
$s \wedge s' = 111 \wedge 1\bar{1}1$	63	42	63	61½ to 64
$s \wedge a = 111 \wedge 100$	47	26	48½	46 to 50
$s \wedge m = 111 \wedge 110$	32	29	32½	31 to 33½
$s \wedge e = 111 \wedge 31\bar{1}$	54	07	56½	55½ to 59
$s \wedge e' = 111 \wedge 3\bar{1}\bar{1}$	79	08	80	79 to 81½
$s \wedge c = 111 \wedge 001$	43	02	42	41 to 43
$a \wedge e = \bar{1}00 \wedge \bar{3}11$	31	42	30½	30 to 32
$c \wedge y = 001 \wedge 223$	8	57	8½	6 to 11
$m \wedge m' = 110 \wedge 1\bar{1}0$	96	58	95	93½ to 96
$c \wedge m = 001 \wedge 110$	75	31	76	75½ to 77
$a \wedge m = 100 \wedge 110$	48	29	48	48 to 49
$e \wedge m = 31\bar{1} \wedge \bar{1}10$	32	14	31	30½ to 33
$c \wedge a = 001 \wedge 100$	67	49	68	67½ to 68½
$a \wedge$ edge s/s′ $= 100 \wedge 101$	37	12	39	36½ to 41
$c \wedge$ edge s/s′ $= 001 \wedge 101$	30	37	30½	30 to 31

As can readily be seen, the agreement between the angles of the faces on the pseudomorphs and the angles for glauberite is remarkably close—so close, in fact, that there seems to be no question as to the crystallographic identity of the two.

Similar angular measurements were made 37 years ago on plaster casts of rhombic cavities from the Osborne & Marsellis quarry (then called McDowell's), Upper Montclair, by Moses,[71] who said: "I am

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[71] Moses, A. J., Hollow pseudomorphs of quartz after an unknown mineral: School of Mines Quart., vol. 16, pp. 230–231, 1895.

unable to suggest the original mineral." Without an understanding of the unusual geologic features of the region, a saline mineral like glauberite would have received scant consideration. Moses describes these cavities as commonly radiating from a center and reaching a width of 1 inch in their "rhombic cross section." He further states:

> It would seem that some unknown mineral occurring in radiating crystals of approximately the form shown in the figure [here reproduced as fig. 26] had first been incrusted with a uniform layer of white opaque silica and that the original mineral had been completely dissolved away, leaving a shell of quartz. The crystalline quartz must have filled in all interstices, before the dissolving away of the unknown mineral. * * * The symmetry seems to call for a monoclinic species. * * * Casts were made of several cavities, and these were measured with the hand goniometer. In most cases the casts showed four longitudinal or prismatic planes *m*, Figure 8 [here reproduced as fig. 26], and one plane *d* parallel to the longer diagonal as figured. Planes parallel to the shorter diagonal were indistinctly suggested. The plane *d* did not in any of the casts obtained form a complete termination but was interrupted by another growth of the prism.

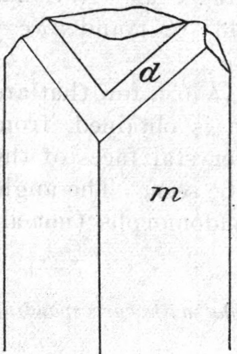

FIGURE 26.—Drawing of plaster casts of rhombic cavities, published by Moses in 1895. His $m=s$ (111), his $d=c$ (001), and the indistinctly suggested planes parallel to the shorter diagonal, in the upper right corner of the drawing but not lettered, $=m$ (110)

The measurements made by Moses on the casts of these cavities gave results similar to those obtained on the quartz cores from McKiernan & Bergin's quarry at Paterson. Moses gives $m \wedge m'$ $(=s \wedge s')=118\frac{1}{2}°$, varying from 117° to 120°. The supplement of this angle, or $61\frac{1}{2}°$, is comparable with the angle $s \wedge s'$ measured on the Paterson cores ($61\frac{1}{2}°$ to 64°) and for glauberite (63° 42′). The average of the measurements of $m \wedge d$ (Moses gives 139°, supplement 41°) compares with the angle measured on the cores of $c \wedge s$ (41° to 43°) and for glauberite (43° 02′).

It is obvious that the plaster casts of the rhombic cavities examined by Moses were similar to the cores from Paterson shown in Plate 27, Nos. 5 to 9, and illustrated in Figures 13, 16, and 17.

A plaster cast of a similar cavity in quartz from the same locality as the occurrence described by Moses was made by Mr. Gilman S. Stanton, of New York. This specimen is very similar to the one shown in Plate 21, *B*. The cast measured 2 inches in length, 1 inch in width, and slightly over half an inch in thickness. The cast was similar to the one illustrated by Moses (fig. 26), except that the *c* face was larger and extended across the entire front of the termination, and on the back there were two faces corresponding to *m* (similar in their relative development to the faces of *m* illustrated in fig. 21). The measurements, all very poor, as the faces of the plaster cast were rough, gave similar results:

Angle	Measured	Quartz cores from Paterson	Glauberite	
	°	°	°	′
$s \wedge s'$	63	61½ to 64	63	42
$m \wedge m'$	96	93½ to 96	96	58
$s \wedge m$	36½	31 to 33½	32	29
$c \wedge$ edge s/s'	30±	30 to 31	30	37

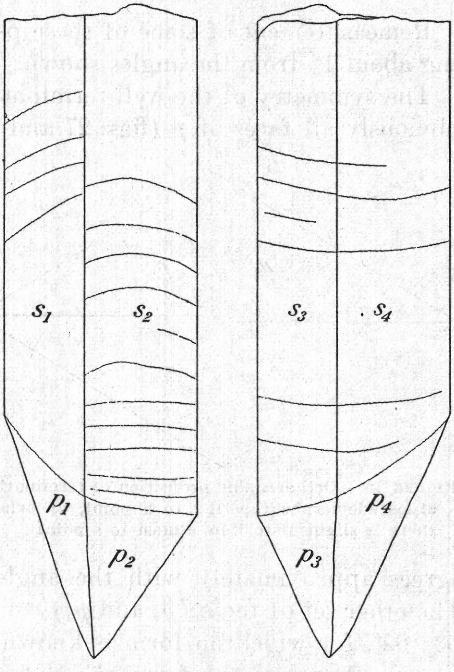

FIGURE 27.—Pseudomorph showing the lower end (orientations II and III) tapering to a point. (Am. Mus. Nat. History, catalog No. 18027)

There seems to be no doubt of the agreement in angles of the faces of the rhombic cavities with crystals of glauberite.

On several of the pseudomorphs illustrated (figs. 21, 22, and 24; pls. 27 and 28) and similarly on several additional specimens not illustrated the pseudomorph, well terminated on its upper end, tapers more or less evenly to a point. Such an occurrence is illustrated in Figure 27, showing the two sides of a crystal in the collection of the American Museum of Natural History, New York. The specimen, broken at one end, is 43 millimeters long and measures 13 by 8 millimeters across. An orthographic projection of such a termination would be a rhomb with two diagonals, which on several of the specimens showing such a tapering end are continuous lines and on a few other specimens have the position shown in Figure 28 due to a slight distortion.

With the notation shown in Figure 27, the measured angles of the apparent faces on the tapering end of the pseudomorphs are as follows:

Angle	A. M. N. H. No. 18027		A. M. N. H. No. 18213 [a]	Stanton [b]	Roebling [b]	U. S. N. M. [b]
	(a)	(b)				
	°	°	°	°	°	°
$s_1 \wedge p_1$	9½	10	25	12	9	9½
$s_2 \wedge p_2$	11	10	27	11½	9	9½
$s_3 \wedge p_3$	12	11	27	12	9½	9
$s_4 \wedge p_4$	12	12	27	12	10½	10½
$p_1 \wedge p_2$	66	--------	68	65	--------	70–80
$p_3 \wedge p_4$	68	--------	67	68	--------	--------
$p_1 \wedge p_4$	95	--------	91	75	--------	--------
$p_2 \wedge p_3$	112	--------	112	115	--------	--------
$p_1 \wedge p_3$	158½	--------	127½	152	--------	--------
$p_2 \wedge p_4$	159	--------	123	152	--------	--------

[a] Measured by H. P. Whitlock (personal communication). [b] Measured by W. T. Schaller.

Remeasurement of some of these pseudomorphs gave results varying about 1° from the angles shown.

The symmetry of the well-terminated upper end being monoclinic, obviously all faces of *p* (figs. 27 and 28) can not belong to the same form. One pair of faces, p_1 and p_2, are positive pyramids (orientation I—that of glauberite in normal position), lying between *c* and *s*, and the other pair are also positive pyramids, lying between *a* and *s*. The pyramids p_1 and p_2, in orientation I, with an average angle $s \wedge p$ of 10°, would have an angle $c(001) \wedge p$ of 33° 02′, which agrees approximately with the angle $c(001) \wedge y(223)$ of 34° 05′. The other set of faces (p_3 and p_4) would have an angle $c(001) \wedge p$ of 53° 02′, for which no form is known. This angle of 53° 02′ corresponds closely to the form (553), for which the angle (001) : (553) is 53° 17′. Glauberite has never been reported as being hemimorphic, and the absence of any faces of the form (553) on the other end of the crystal with *c*, *a*, *e*, *m* throws doubt on the validity of the faces of *p* as true crystal faces. On account of the symmetry the boundary lines of *s* and p_1 and of *s* and p_2, and similarly for the two corresponding boundary lines sp_3 and sp_4, in the back, should slope in opposite directions, regardless of whether the indices of *p* are of the type of *hhl* or *hkl*. But, as the drawing of Figure 27 shows, these boundaries slope in the same direction. On another specimen in the American Museum of Natural History the four faces of *p* are much shorter and their angles to the faces of *s* are much larger, being $s \wedge p_1 = 30°$,

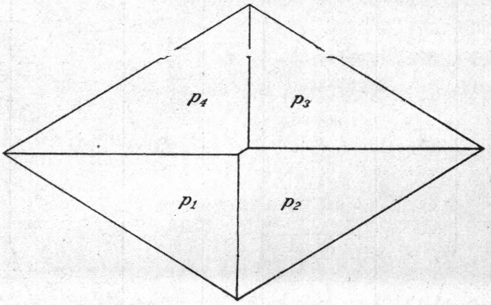

FIGURE 28.—Orthographic projection of termination of pseudomorphs tapering to a point, or, where there is slight distortion, almost to a point

$s \wedge p_2 = 31°$, $s \wedge p_3 = 31°$, $s \wedge p_4 = 32°$. If these faces of *p* are not crystal faces, then what do they represent?

An examination of the matrix holding these crystals (pl. 22, *A*, *B*) shows that the original mineral, considered to be glauberite, grew in radiating groups, as well shown by Plates 21, *A*, 22, *B*, 23, *B*, and 24. Careful examination of the matrix of the pseudomorphs (pl. 22, *A*) shows that not only did the original mineral grow in radiating groups, like part of a large spherulite, but also in a single group the original crystals were not all equally spaced but were commonly aggregated together in small groups of a relatively small number of individuals, usually from 4 to not more than 10. This is well shown in the specimen illustrated in Plate 22, *A*. If now a group of such radiating crystals of the original mineral grew from essentially a point, then only the free ends could develop their characteristic crystal form with perfect development of their crystal faces. At the attached end, on account of mutual interference, no crystal faces could develop, but plane surfaces would result which would be merely the contact of several individual crystals. If, for example, three such crystals were considered as growing essentially from a common point, as shown in Figure 29, then the inclination of such contact faces to the *c* axis (or vertical direction) of the central crystal would be half the mutual inclination of the crystals to one another. If, as in Figure 29, such inclination of the crystals were 20°, then the resultant inclination of the contact planes of the central crystal to the direction of elongation (= faces of *s*) would be half of 20°, or 10°. That several of the pseudomorphs (but not all) should show a constant inclination of these planes to the *s* faces of about 10° naturally follows if the original crystals were inclined to one

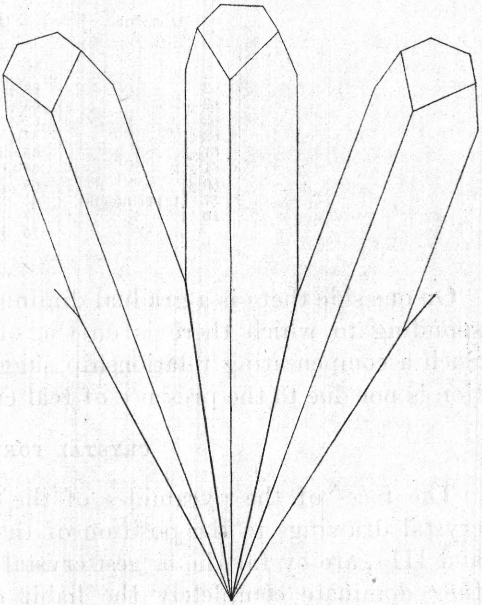

Figure 29.—Sketch of radiating crystals of glauberite grown from a common center, illustrating the development of the tapering lower end of these pseudomorphs as due to mutual interference

another at angles of 20°. Why a group of such crystals should be so uniformly inclined to one another is not known, but there is practically no information as to how radiating crystals grouped together grow. Perhaps, in general, in such groupings there is a regularity at present unrecognized.

On one crystal in the Allen collection (No. 17), similar to the Stanton and Roebling specimens, measurements of the angle $s \wedge s'$ were made 5 millimeters apart, beginning at the well-terminated end and leading down to the tapering end, as follows:

One side		Other side	
°		°	
62		63½	
62½		63½	
62½		63½	
62¼		63½	
61½		65	
61¼		63½	
60½		65	
57	tapering end	66	tapering end
50		67	
		70	

On one side there is a gradual diminution of the angle $s \wedge s'$, corresponding to which there is on the other side a gradual increase. Such a compensating relationship suggests that the sloping inclination is not due to the presence of real crystal faces.

CRYSTAL FORMS

The faces of the pyramid s of the pseudomorphs, shown in the crystal drawings in the position of the unit prism (orientations II and III), are by far the largest crystal faces present. Consequently they dominate completely the habit of the crystals. Though on casual inspection they seem to be plane surfaces, a close examination shows that they are far more irregular than is at first apparent.

The most striking irregularity is the one immediately observed—namely, that the four edges are not all parallel but two of the edges converge, usually at a small angle so that the crystals have a tapering effect, coming to a point if not broken off. Among all the specimens seen none were noticed in which all four edges of the pseudomorphic crystal were parallel throughout. There is, however, a marked difference between the boundary line of the faces s and s''' (and the corresponding edge s' and s'') and the boundary line of the faces s and s' (and the corresponding edges s'' and s'''). The edge between s and s''', which would be the position of the face (101) were it present, is on all crystals seen a straight line. The other edge, which would be the position of the clinopinacoid (010) if present, is always sawtoothed, and the pair of these edges always converge downward (orientations II and III). As a result all the pseudomorphs taper toward one end. This tapering may be fairly even and gradual, as shown by the lower row of pseudomorphs in Plate 27, or it may vary considerably at different places so as to yield a decidedly club-shaped figure, as shown particularly well in pseudomorphs Nos. 8 and 9, Plate 27. Where the side edges, corresponding to the position of the clinopinacoid (010), are not too much worn, the tapering can be seen to be due to an apparent overlapping of lamellae, successively narrower toward the base of the crystal (orientations II and III). There is, however, no real overlapping, as the faces of *s* are not steplike in character.

Numerous lines on these faces give them a corrugated appearance, and these lines are directly connected with the sawtooth appearance of the side edges. A diagrammatic sketch of the appearance of the *s* faces, with regard to these lines and their connection with the tapering character of the side edges of the *s* faces, is shown in Figure 30. Although these corrugations have a general constant direction in their inclination, as shown in Figure 30, in detail they are very crinkly and may slant both to the right and to the left. In general they approach parallelism with the directions that cleavage cracks (parallel to the base *c*) would make on the *s* faces, though in detail and in certain places they may vary considerably from the direction of such cleavage cracks. They probably represent an intermittent filling of the crystal cavities (if the pseudomorphs represent solely infiltration pseudomorphs). That the pseudomorphic formation was intermittent and did not follow as the result of a single uninterrupted filling is also suggested by the character of the transverse sections of some of these pseudomorphs, as shown by Plate 29. Some of these pseudomorphs may have been formed largely by actual replacement of the original mineral, but most of

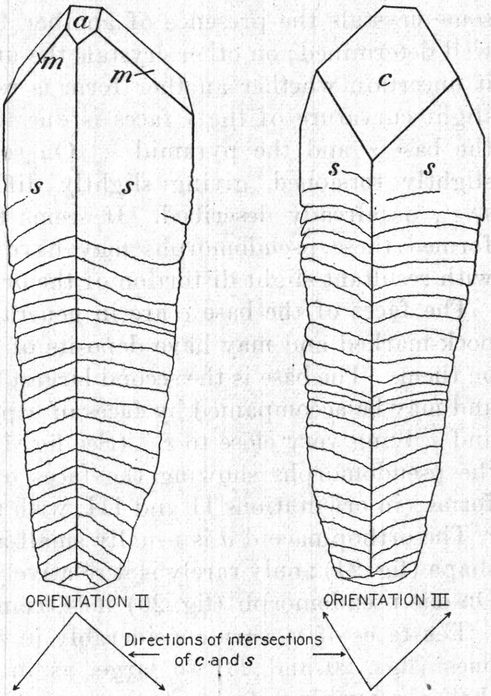

FIGURE 30.—Sketch of structure of the *s* faces of pseudomorphs, showing corrugations and tapering side edges

them were formed by infiltration into the cavity left by the original mineral, and others may represent a concomitant result of both kinds of pseudomorphism. The pock-marked effect shown by some of the pseudomorphs is restricted to the upper end and on the *s* faces covers only the upper part as shown in Figure 16. This pock-marked or corroded effect usually obscures a certain slight inclination of the *s* faces just below the base *c*. Where the corrosive action has not been too severe there seems to be evidence of the presence of another face, very close to *s* and inclined only a few degrees from it. On some crystals the presence of another face, probably *y*(223), seems well determined; on other crystals the unevenness of the faces makes it uncertain whether another form is really present or whether the slight curvature of the *s* faces is due to oscillatory combination of the base *c* and the pyramid *s*. On some crystals the *s* faces are slightly torsioned, giving slightly different values for the angle $s \wedge s'$, as already described. It seems that the mass of silica that formed these pseudomorphs may have undergone some shrinkage, with resultant slight distortion of the original crystal shape.

The faces of the base *c* are in general considerably corroded and pock-marked and may have deposits of small geodic quartz crystals on them. The base is the second largest form on these pseudomorphs and may be accompanied by faces of a pyramid (*y*(223)) between it and *s*, lying very close to *s*. (See fig. 18.) Otherwise, the sides of the pseudomorphs showing the faces of *c* show no other terminal forms (in orientations II and III, with the *s* faces taken as prisms).

The orthopinacoid *a* is usually small and square or rectangular in shape (fig. 24); only rarely is it relatively large (figs. 19, 20, and 25). On one pseudomorph (fig. 20) it is triangular.

The faces of *m* vary considerably in size, from small and narrow ones (figs. 20 and 23) to large, as in Figure 21, where *m* forms the only terminal face. It is present on most of the terminated pseudomorphs (figs. 19 to 25) but is as a rule considerably rounded, and the edges *ms* are nearly always corroded and rounded.

The only other form observed is *e*, which is present on many of the crystals, usually equal in size to the faces of *a* and *m*. It is the form most likely to show distortion in the development of its two faces. (See figs. 22, 23, and 24.) The small rounded face shown in Figure 22 may be $x(\bar{3}31)$, but it could not be measured nor definitely determined.

These cores are infiltration pseudomorphs rather than replacement pseudomorphs. This is demonstrated by their concentric structure in cross section, which is well brought out in Plate 29, where *A* shows the cross section of the upper smaller end of the large core shown in Plate 26, *B*. In *B* and *C* are shown enlarged cross sections of similar cores. All three of the specimens shown in Plate 29 are in the Allen collection. The concentric structure of these cores, following closely the rhombic outline of the cavity, indicates successive partial fillings. The material is essentially quartz (98.8 per cent SiO_2, 1.1 per cent Fe_2O_3=99.9).

The description of the crystallography of these pseudomorphs has brought out the following evidence, which on crystallographic grounds alone seems almost conclusive proof that the original mineral of the rhombic cavities was glauberite.

1. Crystal forms on the pseudomorphs (*c*, *a*, *m*, *s*, *e*) are those commonly occurring on glauberite crystals.
2. The extension of the *s* faces (chosen as unit prism faces in orientations II and III), as in the pseudomorphs, is common for glauberite.
3. The monoclinic symmetry of the terminal faces, as shown in orthographic projection in Figures 14 and 15 and in clinographic projection in the several drawings, is that of glauberite.
4. The very close agreement of the interfacial angles of the forms on the pseudomorphs with those of glauberite.

OTHER OCCURRENCES OF GLAUBERITE PSEUDOMORPHS

The occurrence of calcite and analcite pseudomorphs after glauberite in the Triassic formations has already been referred to (p. 4).

The pseudomorphs of glauberite from New South Wales, called glendonites and described by David and Taylor,[72] show a much elongated form for the original glauberite crystals. One specimen is now composed of gypsum, but all the others are calcium carbonate. The pseudomorphic crystals are from 3 to 20 inches in length and occur in abundance at certain horizons in the "Permo-Carboniferous" rocks, either singly or in groups of three, four, or six.

Some of the dark-colored fibrous radial calcite, almost opaque in parts, shows "all the characteristics of the 'crustification' of Posepny. In many of these cases it has a beautiful agatelike banding." Such banding suggests that these pseudomorphs, like so many of the cores from McKiernan & Bergin's quarry, in Paterson, (pl. 29) are likewise infiltration rather than replacement pseudomorphs. David and Taylor further state that arrowhead types and four-armed types are so common as to suggest twinning. All the glendonites seen show distinct curving of the faces, and many of the crystals show structures due to striations caused by oscillatory combinations of faces in the original crystal.

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[72] David, T. W. E., and Taylor, T. G., Occurrence of the pseudomorph glendonite in New South Wales: New South Wales Geol. Survey Records, vol. 8, p. 161, 1905.

The authors cited describe the habit of the pseudomorphic crystals as acute pyramidal and decidedly monoclinic, and they decipher the crystallographic forms to be essentially *m*(110) and *g*(021), with *s*(111) rather subordinate. The photographs shown, however, make the crystals appear to be long prismatic rather than like the crystal drawing accompanying the crystallographic interpretation, as the sides of the actual crystals are too nearly parallel to allow a long face to be formed essentially of *m*(110) and *g*(021).

They give the following measurements for the crystal forms *m*(110), *s*(111), *g*(021).

Angle	Mean of measurements	Calculated for glauberite	
	°	°	′
$(110) \wedge (1\bar{1}0)$ --	97	96	58
$(111) \wedge (1\bar{1}1)$ --	63	63	42
$(021) \wedge (0\bar{2}1)$ --	125	124	36
$(\bar{1}10) \wedge (111)$ --	94	93	03
$(\bar{1}10) \wedge (021)$ --	56	56	52
$(111) \wedge (021)$ --	38	36	11

These measurements agree well with their interpretation, though their photographs raise some question as to whether or not the elongated forms could be due to the extension of the pyramid *s*(111).

The opal " fossil pineapples " or groups of radiating crystals found in Upper Cretaceous sandstone and conglomerate in New South Wales have been identified [73] as originally glauberite. The irregular radial aggregates of acute tapering 4-sided pyramids have been identified with glauberite on the basis of general habit, curved faces, and marked cleavage after the base *c*(001). The comparison of angles is as follows:

Mean of measured angles:

$65° = (111:1\bar{1}1)$; calculated 63° 42′
$85\frac{1}{2}° = (1\bar{1}\bar{1}:11\bar{1})$; calculated 87° 08′
$80° = (111:11\bar{1})$; calculated 75° 58′
$80° = (1\bar{1}1:1\bar{1}\bar{1})$; calculated 75° 58′

Apparently the " fossil pineapples " represent aggregations of glauberite crystal similar to the specimen from Paterson shown in Plate 24.

The writer can not help but wonder if glauberite could be the original mineral of other pseudomorphs—the Sangerhausen " barleycorn," for example—occurring in various localities, the original mineral of which is still uncertain.

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[73] Anderson, C., and Jevons, H. S., Opal pseudomorphs from White Cliffs, New South Wales: Australian Mus. Records, vol. 6, p. 31, 1905.

MISCELLANEOUS CAVITIES

The formation of crystal cavities in a locality where the process of mineral formation has been long continued and has included numerous periods of different mineral development is not abnormal or unusual. Plates 30 and 31 illustrate crystal cavities after five minerals other than those which formed the rectangular, lamellar, and rhombic cavities.

In Plate 30, *A*, is shown a specimen composed essentially of natrolite, with crystal cavities after apophyllite. Measurements of the angles of a wax cast made from one of the cavities gave the following angles:

Angle	Measured	Calculated for apophyllite	
	°	°	′
$a(100) \wedge p(111)$	51½	52	00
$p(111) \wedge$ edge a/a'	29	29	28
$c(001) \wedge a(100)$	90	90	00
$a(100) \wedge a'(010)$	90	90	00

As the apophyllite preceded the natrolite, it is believed that apophyllite may belong, at least in part, to period 4 (p. 20), with prehnite, pectolite, and datolite, rather than to period 5, that of the zeolites. However, not all apophyllite is prior to the zeolitic period. Fenner[74] has suggested another explanation—namely, that the apophyllite and natrolite were formed simultaneously, or nearly so, on different walls of a single cavity and grew until they mutually interfered.

In Plate 30, *B*, is shown a specimen with many small crystal cavities, most of which are after quartz. Some of the cavities are bounded by six narrow triangular faces that come to a point at the bottom; others are irregular and difficult to decipher. Considerable (apparently residual) quartz, much corroded to long-pointed cone-shaped masses, without crystal faces, still remains. The matrix of the cavities is essentially greenish datolite, developed as large crystals on the other side of the specimen.

Plate 31, *A*, shows a specimen of quartz with many small crystal cavities after calcite. The original calcite crystals were not tabular parallel to the base, a crystallographic habit of early calcite formed at a higher temperature (p. 47), but the base was present as a large crystal face whose imprint on the bottom of the cavities shows the sets of striations in three directions, inclined 120° to one another and parallel to the boundaries of the face, as shown in Figure 31.

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[74] Personal communication.

Most of the calcite now present in the zeolite rock belongs to the latest period (period 6), but it seems probable that some calcite also formed very early, probably in period 2, along with anhydrite and glauberite. On the other hand, the quartz of the specimen illustrated may belong to a later period.

In Plate 31, *B*, is shown part of a specimen of natrolite with nearly rectangular cavities, which are due to the ends of natrolite prisms of another aggregate partly penetrating the aggregate shown. Some of the crystal cavities of the zeolite region were not formed by the chemical solution and removal of the mineral causing them, but by the mechanical dropping out or removal of the original mineral, as illustrated in Plate 31, *B*, for natrolite. Similar mechanically produced cavities were noted by Shannon,[75] who said, in describing the occurrence of datolite crystals at Westfield, Mass.: "The datolite crystals, when removed, left perfect molds in the calcite."

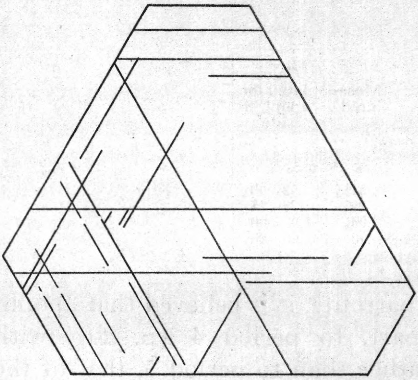

FIGURE 31.—Bottom face, c(0001), of crystal cavity after calcite, showing sets of striations in three directions, inclined 120° to one another and parallel to the boundaries of the face

Plate 31, *C*, shows a specimen of natrolite containing cavities formed by the removal of a radiating group of prismatic crystals, probably pectolite. The original mineral preceded natrolite in its genetic history and so could not well be a radiating zeolite, like stilbite or laumontite, as these, according to Fenner,[76] are later than natrolite. The few remaining walls or ridges in the cavities are opal, and it is possible that they may represent a group of glauberite crystals, though a reference to pectolite seems to be more probable. The mineral changes that have occurred in this field have many times so thoroughly obliterated the crystallographic character of the imprints left by the original mineral as to make its precise identification almost impossible.

BABINGTONITE AS THE ORIGINAL MINERAL OF THE CAVITIES

The only previous serious attempt to solve consistently the problem of what was the original mineral formerly occupying these crystal cavities was the one which proposed babingtonite. As at that time

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[75] Shannon, E. V., Famous mineral localities—the datolite locality near Westfield, Mass: Am. Mineralogist, vol. 4, p. 6, 1919.

[76] Fenner, C. N., The Watchung basalt and the paragenesis of its zeolites and other secondary minerals: New York Acad. Sci. Annals, vol. 20, p. 179, 1910.

it was thought that a single mineral species had occupied all these cavities, the babingtonite hypothesis was handicapped by having to explain the coexistence of two distinct crystal habits of the same mineral occurring more or less together. It was also difficult to identify the shapes of the cavities with the shapes of babingtonite crystals.

It must be remembered that nearly all the rectangular cavities have three structural directions, indicated by the walls of quartz (and prehnite) now present in the cavities, which are parallel to the three rectangular bounding walls of the cavities. (See pls. 4, *A*, *D*, 7, *A*, 10, *B*, and especially 7, *B*.) The direction and position of these walls correspond either to cleavage direction in the original mineral or to the crystal faces of groups of crystals in parallel position, or to both. Therefore, the original mineral must have had either crystal faces or cleavages parallel to such directions.

In Fenner's first article[77] ascribing babingtonite as the original mineral of these cavities, the two forms *h*(110) and *g*($2\bar{1}0$), Dauber's orientation of babingtonite, are given as the probable forms corresponding to the "nearly rectangular cross section" of the cavities. In his second article[78] the base *c*(001) is suggested as the third form, the mutual inclination of these three forms being

c(001) ∧ *h*(110) = 90° 47′:
c(001) ∧ *g*($2\bar{1}0$) = 85° 27′.
h(110) ∧ *g*($2\bar{1}0$) = 89° 18′ (Dauber gives 89° 22′).

These three forms, if they occurred alone on babingtonite, would give a nearly rectangular form, almost indistinguishable from a true rectangular form, in which all three planes are inclined exactly 90° 00′ to one another (as in anhydrite).

But how about the cleavages? Dana gives as the cleavages of babingtonite (changed to Dauber's orientation): *M*(Dana) = *c*(001), perfect; *m*(Dana) = *b*(010), less so. In a rectangular crystal of babingtonite, with the combination *c*(001), *h*(110), *g*($2\bar{1}0$), the perfect cleavage is parallel to one of these forms—namely, *c*(001). But the second cleavage, after *b*(010), is not parallel to either of the other two forms, *h*(110) and *g*($2\bar{1}0$), but is inclined thereto at a considerable angle, as

b(010), second cleavage, ∧ *h*(110) = 24° 43′.
b(010), second cleavage, ∧ *g*($2\bar{1}0$) = 64° 39′.

Such inclined cleavage walls have not been observed in any of the rectangular cavities.

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[77] Fenner, C. N., Babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, pp. 552–558, 1914.

[78] Fenner, C. N., Additional notes on babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, pp. 598–605, 1914.

The two cleavages listed, after *c*(001) and *b*(010), are themselves nearly at right angles (92° 36′), but there is no third form of babingtonite normal (or nearly normal) to both these forms. The form *a*(100) is nearly normal to *c*(001), the angle *a* ∧ *c* being 87° 28′, but the third angle, *b*(010) ∧ *a*(100), is only 67° 48′.

In a description of babingtonite from Japan, Watanabé[79] states that the cleavage "is perfect parallel to *c*(001) and less perfect parallel to *a*(100) and *b*(010)." These cleavages (*c*, *a*, *b*) are not normal to one another, the angle *b*(010) ∧ *a*(100) being 67° 48′, as just noted. Watanabé describes the base *c*(001) as the largest terminal form, striated parallel to the intersection edge of *c* ∧ *a*(100). Of the forms in the prism zone, *b*(010) is the largest, yielding platy crystals flattened parallel to this form. The prism *k*(1$\bar{1}$0) is the next largest form in this zone, faces of *h*(110), *g*(2$\bar{1}$0), and *a*(100) being narrow faces. The three largest forms, *c*, *b*. and *k*, likewise are not normal to one another, *b*′ ∧ *k* being 36° 22′.

Fenner[80] states that for babingtonite four cleavages "are probably present. Three of these make angles with each other which do not differ appreciably from 90°." But he does not state what they are. Dauber[81] states that the cleavages of babingtonite are distinct after *c*(001), less distinct after *b*(010), and doubtful after *o*(011) and *s*(0$\bar{1}$1). The angles of *o* and *s* to the two better cleavages, after *c* and *b*, are as follows:

c (001) ∧ *o* (011) = 45° 13′.
c (001) ∧ *s* (0$\bar{1}$1) = 42° 44′.
b (010) ∧ *o* (011) = 47° 23′.
b (010) ∧ *s* (0$\bar{1}$1) = 44° 40′.

These forms are all in one zone and so can not form a rectangular solid. There is, then, no published evidence for three rectangular cleavages in babingtonite.

Neither is there any published description of babingtonite crystals ever having been found in rectangular prisms, which would show the combination *c*(001), *h*(110), *g*(2$\bar{1}$0). In the 34 crystal drawings of babingtonite listed by Goldschmidt,[82] there is not a single one showing a combination that would produce shapes resembling those of the rectangular cavities.

The babingtonite now present in this area is of a habit entirely different from that of the crystals which have formed either the

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[79] Watanabé, Manjirô, On the babingtonite from the contact-metamorphic deposits of the Yakuki mine, Province Iwaki, Japan: Am. Jour. Sci., 5th ser., vol. 4, pp. 159–164, 1922.

[80] Fenner, C. N., op. cit., p. 603.

[81] Dauber, H., Untersuchungen an Mineralien dor Sammlung des Hrn. Dr. Krantz in Bonn; 7. Babingtonite von Arendal: Annalen Physik Chemie (Poggendorff), vol. 94, p. 403, 1855.

[82] Goldschmidt, Victor, Atlas der Krystallformen, Tafeln, vol. 7, pls. 53, 54, 1923.

rhombic cavities or the rectangular prismatic cavities, being distinctly in thin tabular plates, as shown in Figure 32 and Plate 32, *A* and *C*. Fenner likewise in his first description of babingtonite (then called amphibole, Variety I) made the following statement: "In its typical habit the mineral consists of groups of tabular crystals or somewhat scattered individuals resting upon or intergrown with quartz, datolite, pectolite, or albite." It is not impossible that if an earlier generation of babingtonite had formed, at a higher temperature, it may have crystallized in a different habit from that now found, as has been postulated for calcite, but there is no record in the literature of such rectangular babingtonite crystals ever having been described.

It is believed that the patches of babingtonite seen in the cavities which have small offshoots or projections, running into the matrix of the cavities, as described by Fenner in his two later papers, are more readily explained as being due to the formation of babingtonite soon after the formation of anhydrite and glauberite. Probably it was then attached to the saline minerals. As these became covered with quartz, or as their basaltic glass matrix was replaced by quartz, the attached babingtonite would be largely protected by the quartz matrix from later attack. Moreover, the conditions under which the sulphates anhydrite and glauberite became soluble and were dissolved are not the same as those under which the babingtonite, a silicate, would be dissolved and removed.

In his first paper on babingtonite[83] Fenner wrote:

> In several instances the small crystal remnants [of babingtonite] found occupy portions of the characteristic cavities of rectangular or lozenge-shaped [called rhombic in the present paper] sections in quartz or are intergrown in a bladelike form with quartz crystals.

According to this statement, the relations of babingtonite are the same to the rhombic cavities as to the rectangular ones. If the presence of remnants of babingtonite is to be taken as indicative of its having been the original mineral of the rectangular cavities, the same evidence would be indicative of its having been the original mineral of the rhombic cavities—a conclusion not supported by the facts and apparently no longer held by Fenner with the same conviction as at first, for in his last paper[84] he says:

> The origin of the lozenge-shaped cavities is more uncertain. They may have been occupied by babingtonite deposited under different conditions from those which prevailed during the deposition of the rectangular forms and therefore developing different crystal faces, or they may be due to some other material

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[83] Fenner, C. N., Babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, p. 554, 1914.

[84] Fenner, C. N., Additional notes on babingtonite from Passaic County, N. J.: Washington Acad. Sci. Jour., vol. 4, p. 605, 1914.

to whose nature we have little clue. It seems necessary to obtain more information before reaching a positive conclusion on this point.

The genetic relations of the occurrence of most of the babingtonite now present in the area are also adverse to the theory that it was the original mineral of the cavities, for most of the babingtonite did not form until much later in the mineral sequence. As shown by the specimens illustrated in Plate 32, the babingtonite is later than the quartz crystals, for in *A* it is perched thereon and in *C* it only slightly penetrates the quartz crystals. This same relation was noted by Fenner in the paper just cited, where he described some of the babingtonite as "intergrown in a bladelike form with quartz crystals." In his earlier paper Fenner noted that the babingtonite is "resting upon or intergrown with quartz, datolite, pectolite, or albite."

The specimen shown in Plate 32, *B*, is particularly suggestive of this genetic relation, as it shows the babingtonite perched on quartz which contains the lamellar cavities. Obviously, the mineral that caused the lamellar cavities was earlier than either the quartz or the babingtonite. In the lamellar cavities and in the surrounding quartz are round disks and concentric spherulites of hematite, which were present before the well-crystallized quartz and babingtonite and therefore do not represent an alteration of the babingtonite.

Specimens on which are perched crystals and groups of crystals of babingtonite, similar to those illustrated in Plate 32, clearly show that babingtonite belongs, genetically, to a late stage of the mineral changes. Several of these specimens consist largely of massive quartz on which are terminated crystals of quartz and of calcite, on which in turn is perched the babingtonite. In some of these specimens the massive quartz contains all three varieties of crystal cavities—rectangular, rhombic, and lamellar. Some of the platy babingtonite crystals partly penetrate the crystals of quartz and of calcite and, if removed, would leave gashes similar in shape to the lamellar cavities. But genetically much of the babingtonite is later than the quartz and calcite, which are themselves considerably later than the original minerals of the crystal cavities.

Babingtonite seems to belong in general to the contact-metamorphic and hydrothermal types of mineral occurrences and to have a long-continued period of formation. The proportion of babingtonite that forms during the later stages seems to be considerable. Thus Palache and Frapie [85] state that for the Somerville mineral

> The babingtonite is usually in distinct crystals implanted upon and in rare instances wholly embedded in prehnite. The crystals are often but slightly at-

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[85] Palache, Charles, and Frapie, F. R., Babingtonite from Somerville, Mass.; Babingtonite from Athol, Mass.: Am. Acad. Arts and Sci. Proc., vol. 38, pp. 383–393, 1902.

tached to the prehnite and are therefore not infrequently completely bounded by crystal planes.

For the mineral from Athol, the matrix specimen

is a fragment of chloritic gneiss bounded on two surfaces by what were clearly veins. These faces are coated with a thin drusy layer of dark-green epidote, upon which, on one side, the babingtonite is implanted.

The fact that the babingtonite is implanted upon prehnite and epidote suggests that much of it was formed during the later stages of mineral formation.

In his description of babingtonite from the Yakuki mine, in Japan, Watanabé[86] states:

> In short, the formation of the babingtonite in the Yakuki mine seems to have commenced at a certain stage of the formation of skarn masses and to have continued after the brecciation of the skarn and lasted to some stages of fissure-filling deposition of quartz and calcite. Throughout the whole duration the mineral is most intimately associated with garnet. * * * In other cases the babingtonite appears in minute veinlets, which cut the hedenbergite, magnetite, and ilvaite. * * * As it cuts hedenbergite, babingtonite often replaces a part of hedenbergite on both sides of the fissure and still preserves the original texture.

Such a long duration of the time of formation of babingtonite, with a considerable part of it later than the other minerals, seems to agree well with its period of formation at Paterson.

The well-formed crystals of babingtonite now present on some specimens are in thin plates. The crystals on the specimens shown in Plate 32 are of this habit, as shown in Figure 32. Two groups of crystals perched on well-formed crystals of quartz and of calcite (now in the U. S. National Museum, formerly in the Canfield collection, Nos. 4370 and 5902), both from Great Notch, show terminated crystals of babingtonite. Several of these were detached and measured, with the results given below.

All the crystals seen are less than 10 millimeters long. They average about 5 to 8 millimeters long, 2 to 3 millimeters wide, and less than 1 millimeter thick. Some of the platy crystals are not over 0.2 millimeter thick; the largest one seen is 3 millimeters thick. Most of the crystals were platy and covered with a pale-green fibrous alteration product, and their faces were dull and gave poor reflections. Moreover, what appears at first to be a single crystal is seen on closer examination to consist of several similar platy crystals in nearly parallel growth but diverging several degrees from strict parallelism. One pair of parallel large faces, vertically striated, constitute the dominant form. This is interpreted as the orthopinacoid *a*(100). A second much smaller prismatic form is *g*$(2\bar{1}0)$. The clinopinacoid *b*(010) is present only as a line face. All these three

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[86] Watanabé, Manjirô, On the babingtonite from the contact-metamorphic deposits of the Yakuki mine, Province Iwaki, Japan: Am. Jour. Sci., 5th ser., vol. 4, p. 160, 1922.

forms in the prism zone are striated vertically. The third form whose presence can be recognized by the unaided eye is the base *c*(001), whose faces are fairly bright but uneven and faceted, and the terminations of some apparently simple crystals are composite, being formed of many faces which may be as much as 20° apart. Parallel to this face there is a good cleavage. Minute faces of *s*(011) generally appear in one corner.

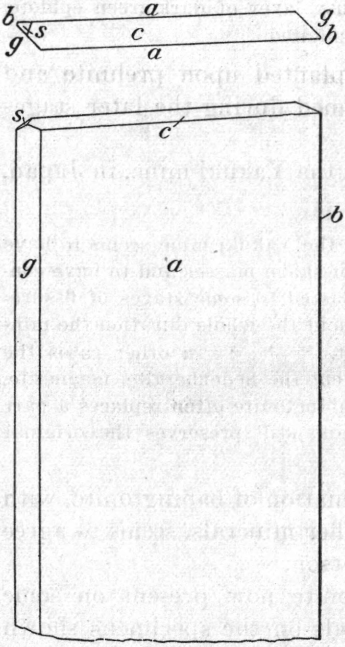


FIGURE 32.—Platy crystal of babingtonite from Great Notch, N. J. Forms: *b*(010), *a*(100), *c*(001), *g*(2$\bar{1}$0), *s*(0$\bar{1}$1)

The measurements are so poor that it can not be definitely determined that the interpretation of the crystals is the correct one. The vertical striations in the prism zone and the good cleavage nearly normal to the prism zone make it seem probable that the orientation chosen is the correct one. Considering the poor quality of the reflections, the angular agreement is likewise in accord with that of babingtonite. The drawing of Figure 32 shows the habit of the crystals, which is very different from that of the crystal cavities.

The angles measured on three crystals are given in the following table:

Measurements of babingtonite crystals from Great Notch, N. J.

Form	Crystal No.	Measured		Calculated	
		φ	ρ	φ	ρ
		° ′	° ′	° ′	° ′
b (010)	1	0 39	90 00	0 00	90 00
	1	10	90 00		
	2	28	90 00		
	3	2 01	90 00		
	3	07	90 00		
a (100)	1	68 31	90 00	67 48	90 00
	1	66 42	----------		
	2	66 47	----------		
	2	68 38	----------		
	3	68 19	----------		
	3	67 50	----------		
g (2$\bar{1}$0)	1	115 46	90 00	115 24	90 00
	1	116 17	----------		
	2	109 33	----------		
	3	113 13	----------		
	3	114 59	----------		
c (001)	1	(a)	4 05	124 24	4 36
	2	(a)	4 14		
	3	(a)	4 26		
	3	[b] 126 10	5 32		
s (0$\bar{1}$1)	2	175 41	45 21	176 15	45 29
	3	173 00	45 16		

---

[a] The φ angle could not be measured on the natural faces of *c*(001), as the multiplicity of faces gave reflections stretching over 20°.

[b] Cleavage face on bottom of crystal.

In addition to these well-formed crystals, others were observed (U. S. National Museum, Canfield collection, No. 6661) from Paterson, completely covered with the grayish-green alteration product, except for the cleavage surfaces of *c*(001). These had a cross section as shown in Figure 33, *A* and *B*. The entire prism zone was so rounded that the forms present could not be definitely determined, but they are similar to the crystal shown in Figure 32, except that the faces of $g(\bar{2}10)$ have a development nearly equal to that of *a*(100). In Figure 33, *C*, is shown a cross section of a crystal with an angular prism zone. In this crystal the angles measured are as follows:

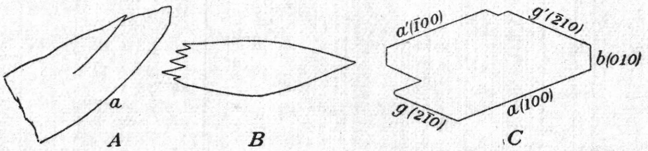


FIGURE 33.—Cross sections of babingtonite crystals from Paterson, N. J. Parallel to the cleavage *c*(001). *A* and *B*, prism zone rounded; *C*, prism zone angular

$a'\ (\bar{1}00) \wedge g'\ (\bar{2}10) = 43^\circ$, calculated 47° 36′.
$g'\ (\bar{2}10) \wedge b\ \ (010) = 67\tfrac{1}{2}^\circ$, calculated 64° 36′.
$b\ \ (010) \wedge a\ \ (100) = 67\tfrac{1}{2}^\circ$, calculated 67° 48′.
$a\ \ (100) \wedge g\ \ (2\bar{1}0) = 46\tfrac{1}{2}^\circ$, calculated 47° 36′.

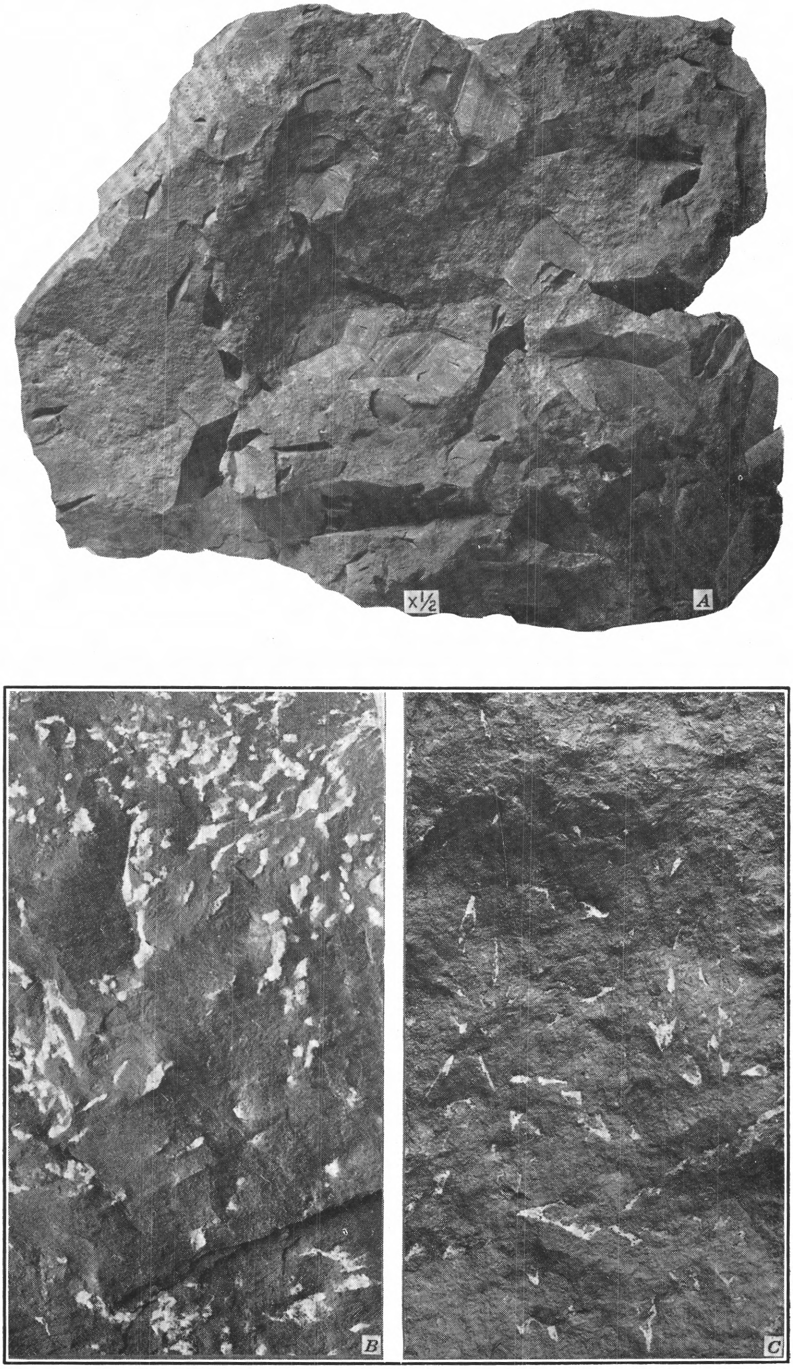
The shapes of the babingtonite crystals from this area, shown in Figures 32 and 33, do not agree at all with those of the rectangular or rhombic crystal cavities. They bear but little resemblance to most of the lamellar cavities. The relation of babingtonite to some of the lamellar or gashlike cavities, as sketched by Fenner in Figure 14 of his paper on paragenesis of the zeolites, above cited, suggests that it may be the original mineral of a few of such cavities.

PLATES

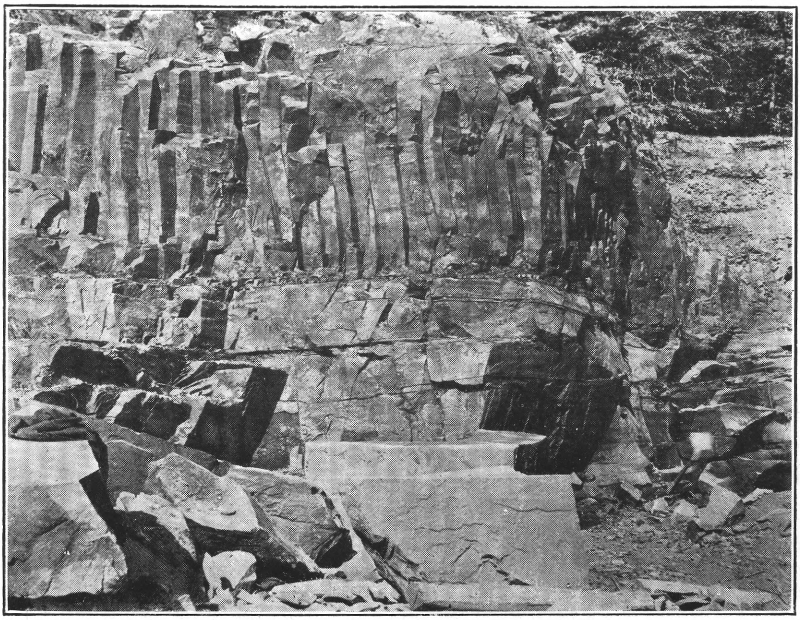
PLATE 1

EVIDENCE OF THE FORMER PRESENCE OF GLAUBERITE IN THE TRIASSIC SEDIMENTARY ROCKS

A, Crystal cavities, after glauberite, in Triassic shale collected by E. T. Wherry near Steinsburg, Bucks County, Pa. (U. S. N. M. catalogue No. 92931.) The cavities vary in habit from tabular to slightly elongated forms; maximum length about 2 inches. *B*, Pseudomorphs of calcite after glauberite in Triassic shale collected by E. T. Wherry near Dolington, Bucks County, Pa. Note rhombic outlines of white calcite. *C*, Pseudomorphs of calcite after glauberite in Triassic shale collected by W. T. Schaller near Princeton, N. J. (U. S. N. M. catalogue No. 95862.) The rhombic outline of skeletal white calcite is readily apparent.

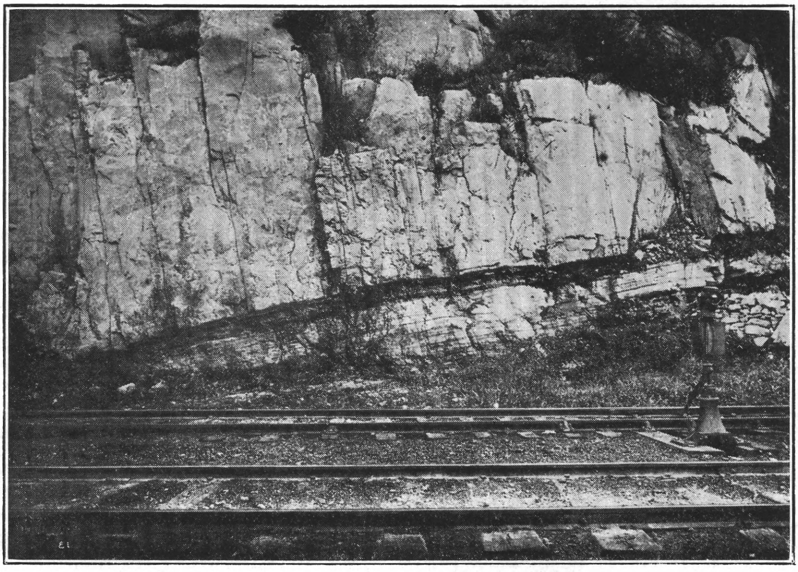


EVIDENCE OF THE FORMER PRESENCE OF GLAUBERITE IN THE TRIASSIC SEDIMENTARY ROCKS



A. BASE OF SECOND WATCHUNG MOUNTAIN TRAP SHEET AT LITTLE FALLS, PASSAIC COUNTY, N. J.

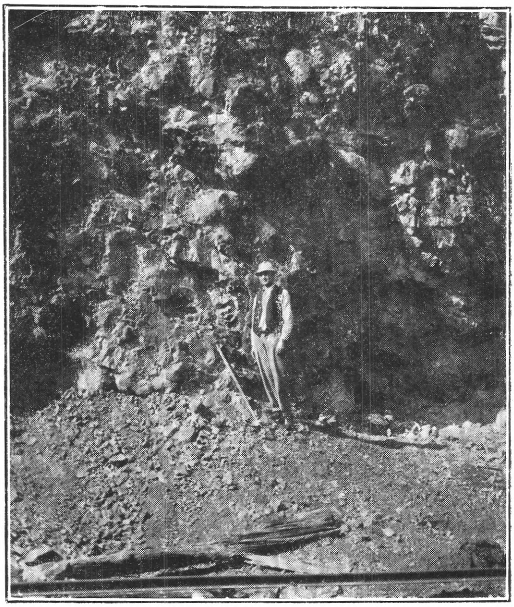
Note well-developed columnar structure. Crystal cavities absent because no saline beds or lake waters were present in underlying sedimentary rocks. Photograph by N. H. Darton.



B. BASE OF PALISADE DIABASE AT WEEHAWKEN, HUDSON COUNTY, N. J.

Intrusive, massive, and jointed but not spheroidal; crystal cavities absent because no saline beds or lake waters were present in the intruded sedimentary rocks. Photograph by N. H. Darton.

TRAP ROCK FREE FROM CRYSTAL CAVITIES, OVERLYING THE TRIASSIC SEDIMENTARY ROCKS WHERE NO LAKE BEDS OR LAKE WATERS WERE PRESENT



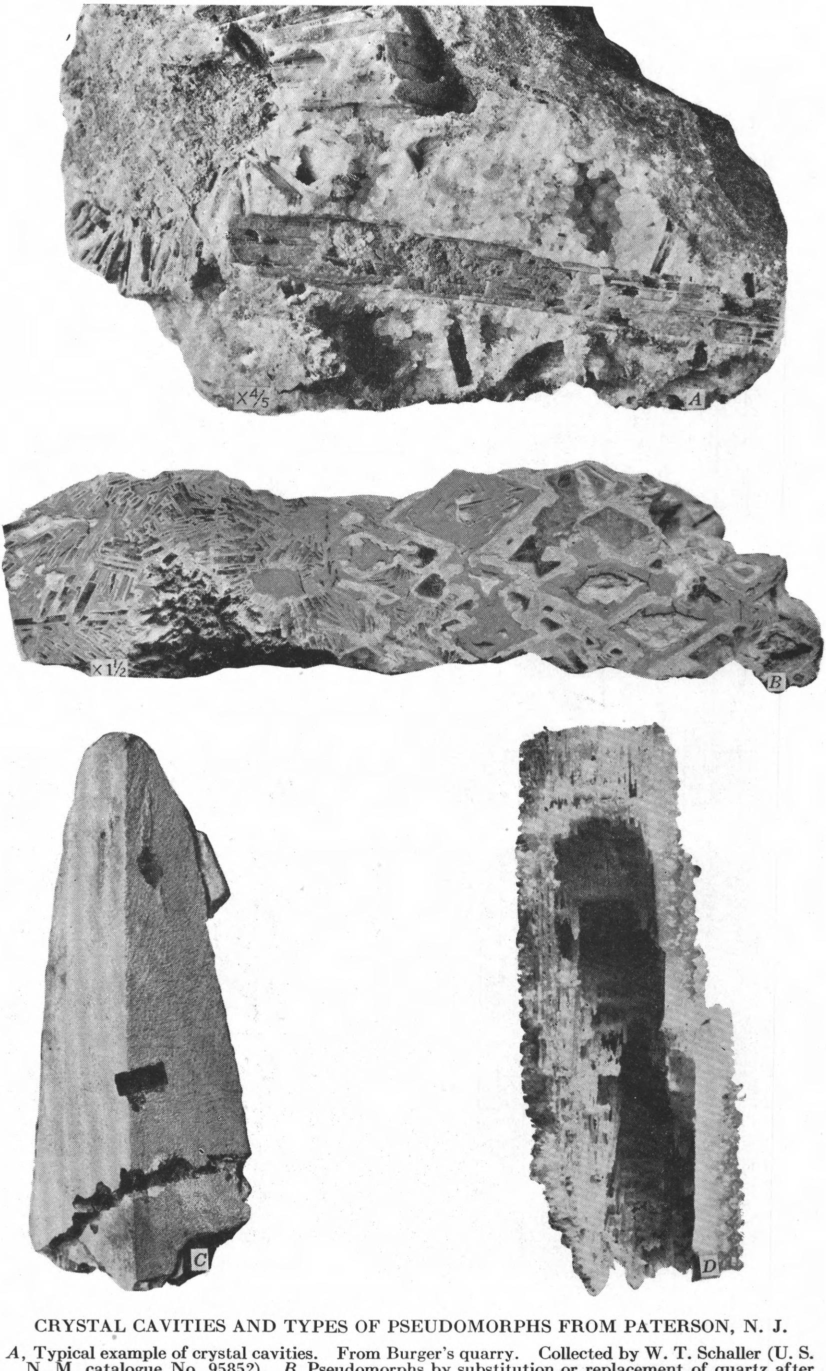
A. SPHEROIDAL STRUCTURE IN LAVA DUE TO THE EFFECT OF LAKE WATERS

From Burger's quarry, West Paterson, N. J. Spaces between spheroids originally filled with basaltic glass, since changed by solutions to "zeolitic rock" that contains crystal cavities.

B. SPHEROIDAL STRUCTURE IN LAVA OVERLAIN BY MASSIVE AND JOINTED LAVA

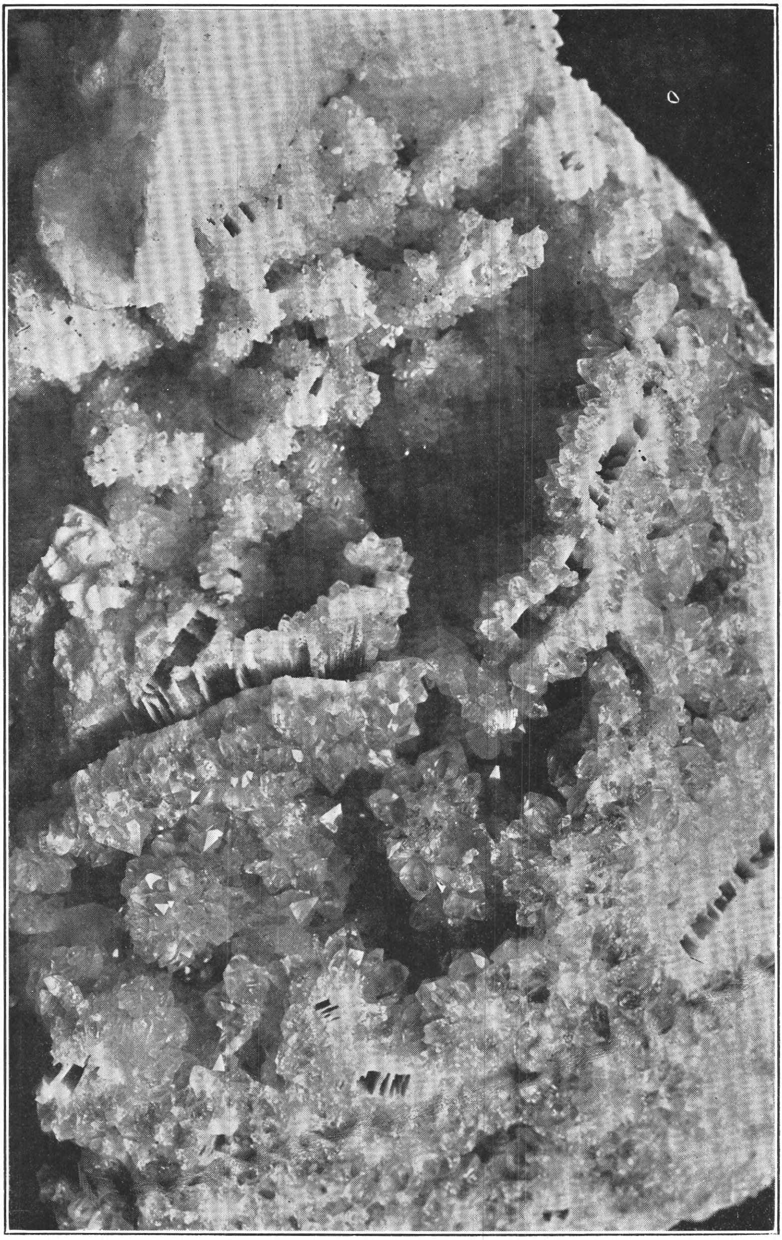
From Francisco Bros.' quarry, Great Notch, N. J. Hammer marks contact of the two varieties of lava. Crystal cavities only in spheroidal variety.

TRAP ROCK CONTAINING CRYSTAL CAVITIES AND ZEOLITIC ROCK, OVERLYING TRIASSIC SEDIMENTARY ROCKS WHERE THE LAVA POURED OVER LAKE BEDS AND LAKE WATERS



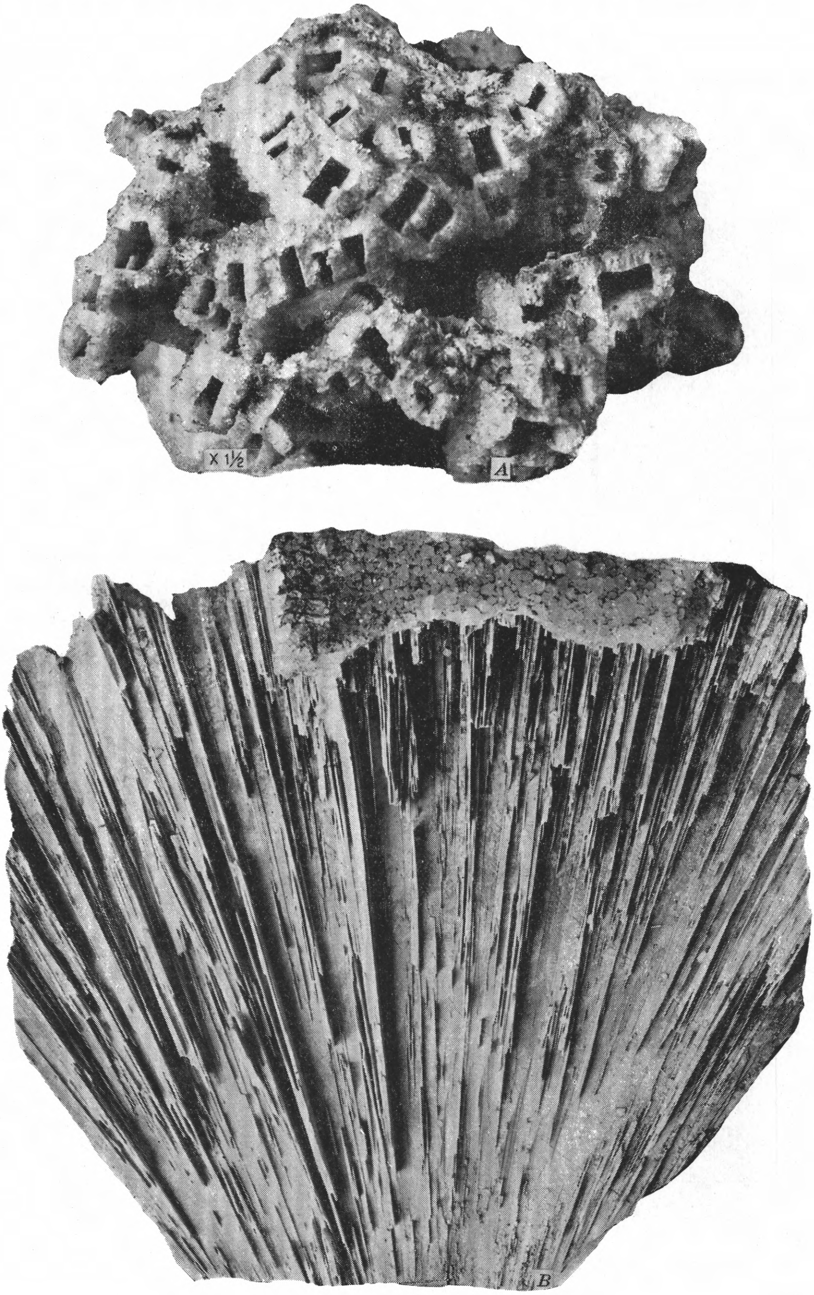
CRYSTAL CAVITIES AND TYPES OF PSEUDOMORPHS FROM PATERSON, N. J.

A, Typical example of crystal cavities. From Burger's quarry. Collected by W. T. Schaller (U. S. N. M. catalogue No. 95852). *B*, Pseudomorphs by substitution or replacement of quartz after anhydrite (rectangular, to the left), and after glauberite (rhombic, to the right). From Burger's quarry. Collected by W. T. Schaller (U. S. N. M. catalogue No. 96031). *C*, Infiltration pseudomorph of quartz after glauberite. From McKiernan & Bergin's quarry (collection of F. I Allen, New York, N. Y.). The specimen also contains in the lower center a smaller rectangular cavity after anhydrite. *D*, Incrustation pseudomorph of quartz after anhydrite. From Burger's quarry (collection of F. I. Allen, New York, N. Y.).



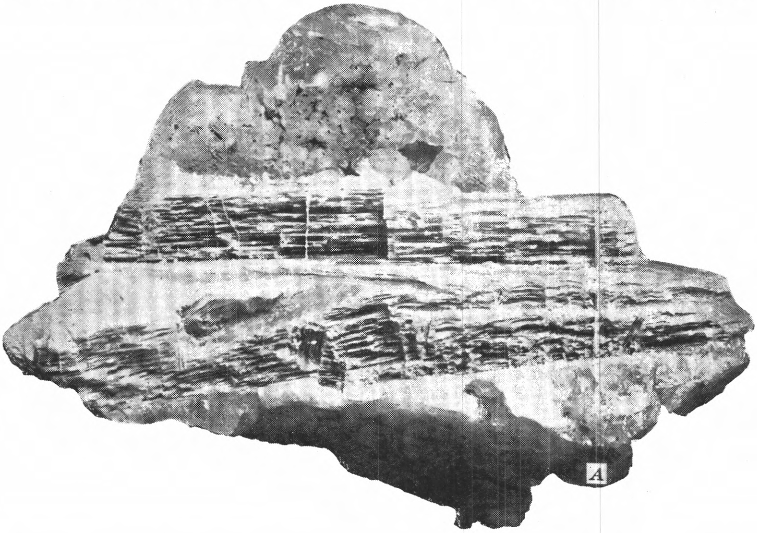
GROUPS OF RADIAL RECTANGULAR CAVITIES OF THICK TABULAR HABIT, AFTER ANHYDRITE

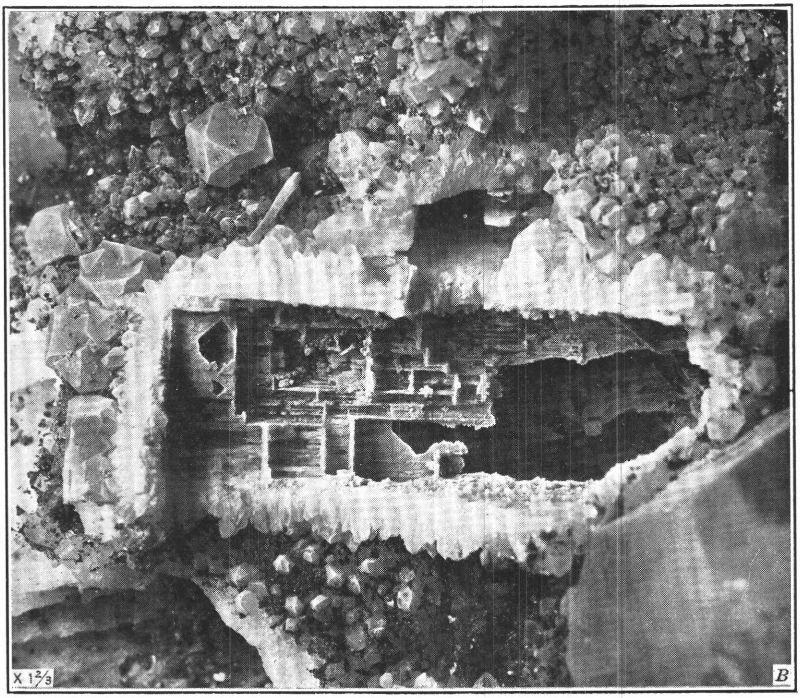
From Burger's quarry, West Paterson, N. J. (collection of F. I. Allen, New York, N. Y.). These cavities represent radiating groups of anhydrite, such as are shown in Plates 11 and 12, *A*. A few of the cavities are isolated, but most of them are in fan-shaped tabular aggregates (central left). The ends of some of them form a straight row of rectangular cavities, as shown in the lower right-hand corner and in the lower portion of the specimen.



RECTANGULAR CRYSTAL CAVITIES

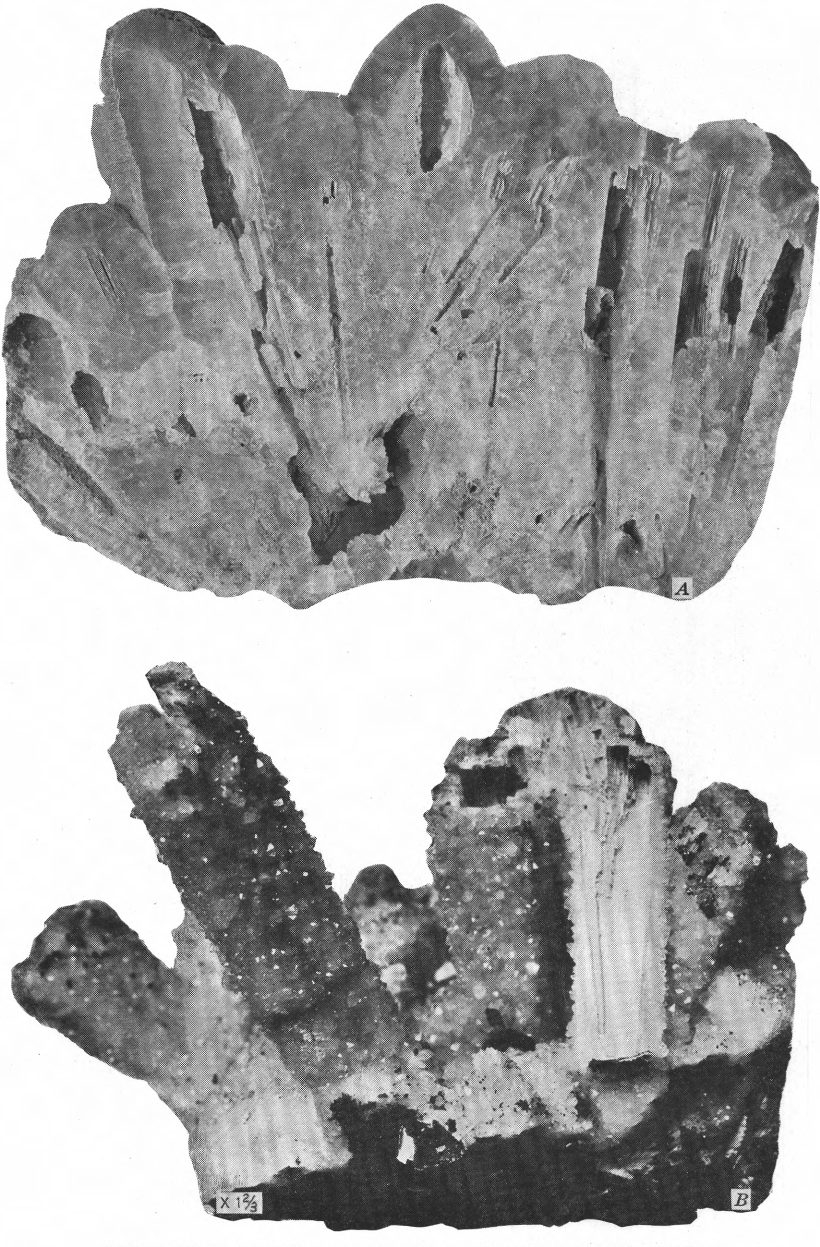
From Burger's quarry, West Paterson, N. J. *A*, Group of rectangular cavities in no regular order. Collected by W. S. Disbrow and presented by him to the United States National Museum (U. S. N. M. catalogue No. 96030). *B*, The radiating group is in one plane. (U. S. N. M. catalogue No. 92981.) A portion of the original capping of quartz crystals, partly coated with zeolites, still remains on the upper portion. Both of these specimens show cavities after anhydrite, radiating groups of which are shown in Plates 11 and 12, *A*.





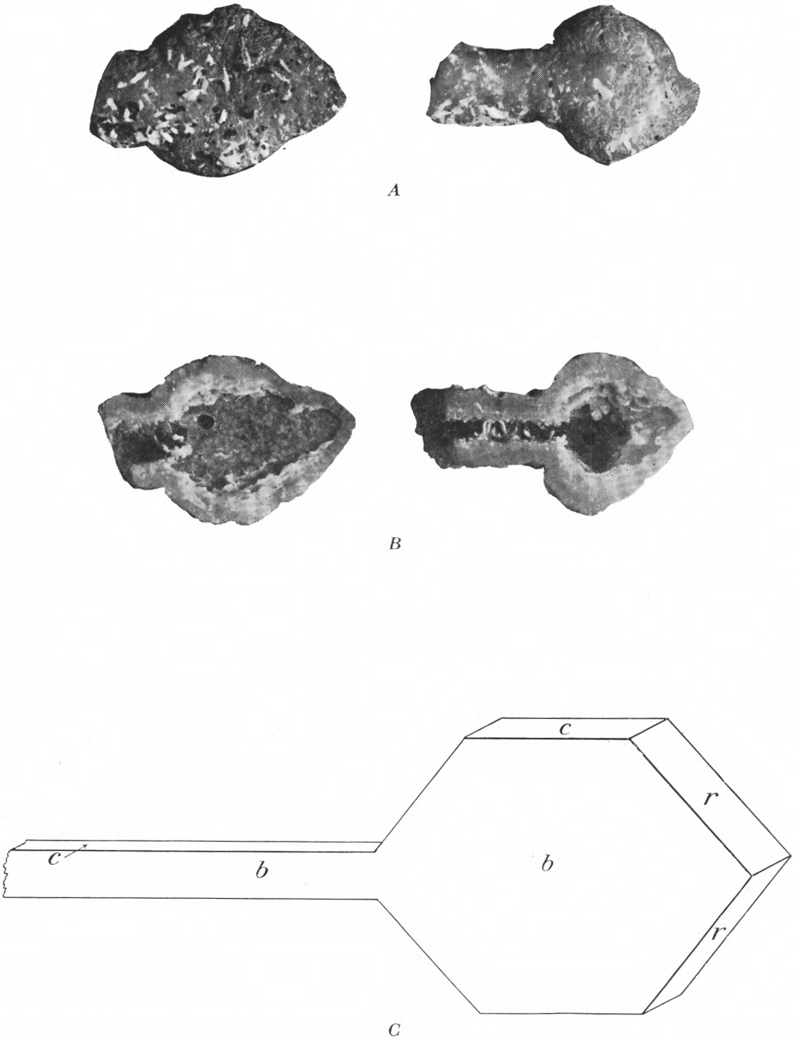
RECTANGULAR CRYSTAL CAVITIES WITH RECTANGULAR DIVIDING WALLS, AFTER ANHYDRITE

A shows the thin walls of quartz, which either entered the cleavage planes of the original anhydrite or replaced the trap rock between many nearly touching parallel tabular crystals. The two directions of the thin walls are at right angles to each other and parallel to the walls of the cavity. From Cedar Grove, N. J. Collected by W. S. Disbrow and presented by him to the United States National Museum (U. S. N. M. catalogue No. 95849). *B*, The thin walls of quartz, after the cleavages of the original anhydrite, are developed in three directions, at right angles to one another and parallel to the walls of the cavity. From Burger's quarry, West Paterson, N. J. (collection of F. I. Allen, New York, N. Y.). Specimen slightly coated with ammonium chloride film for better illustration.



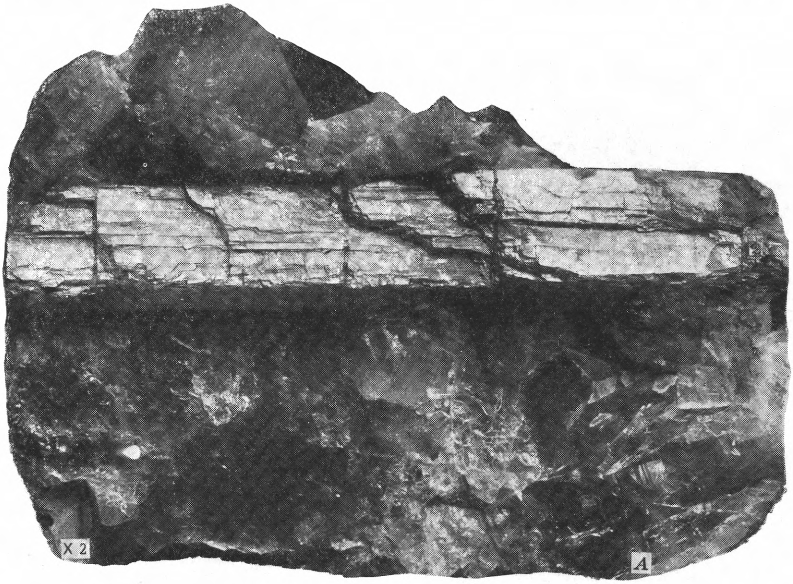
PSEUDOSTALACTITIC FORMS OF PREHNITE AND OF QUARTZ

These minerals cover preexisting prismatic crystals or groups of parallel thin tabular plates of anhydrite, now removed. From Burger's quarry, West Paterson, N. J. *A*, Prehnite (U. S. N. M. catalogue No. 96029); *B*, quartz (U. S. N. M. catalogue No. C–482).



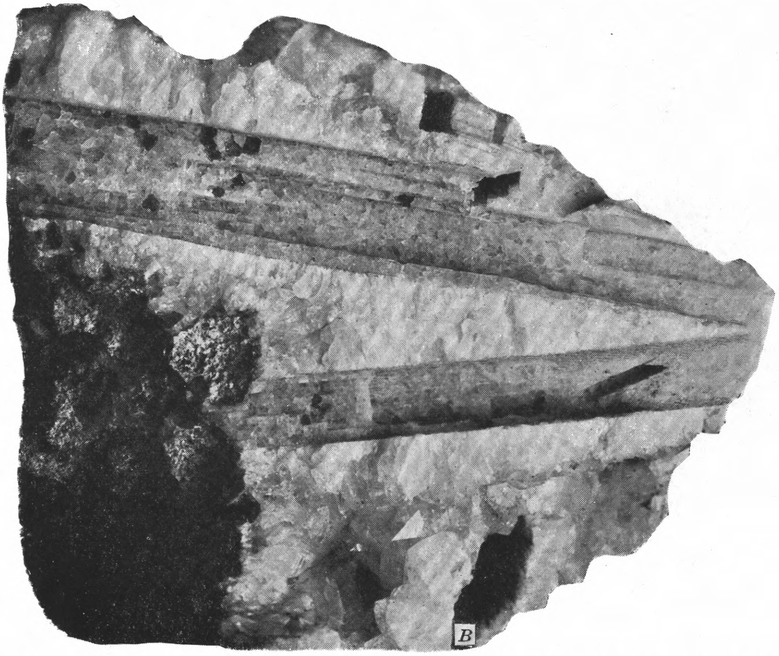
SPEARHEAD FORMS OF PREHNITE, COVERING FORMER SCEPTER CRYSTALS OF ANHYDRITE

From West Paterson, N. J. Collected by James G. Manchester and presented by him to the United States National Museum (U. S. N. M. catalogue No. 96035). *A*, The outside of two spearheads. The white mineral coating the prehnite is laumontite. *B*, The same specimens sawed in half to show the shape of the inclosed cavity. *C*, Crystallographic interpretation of cavity shown on the right, after a scepter crystal of anhydrite.



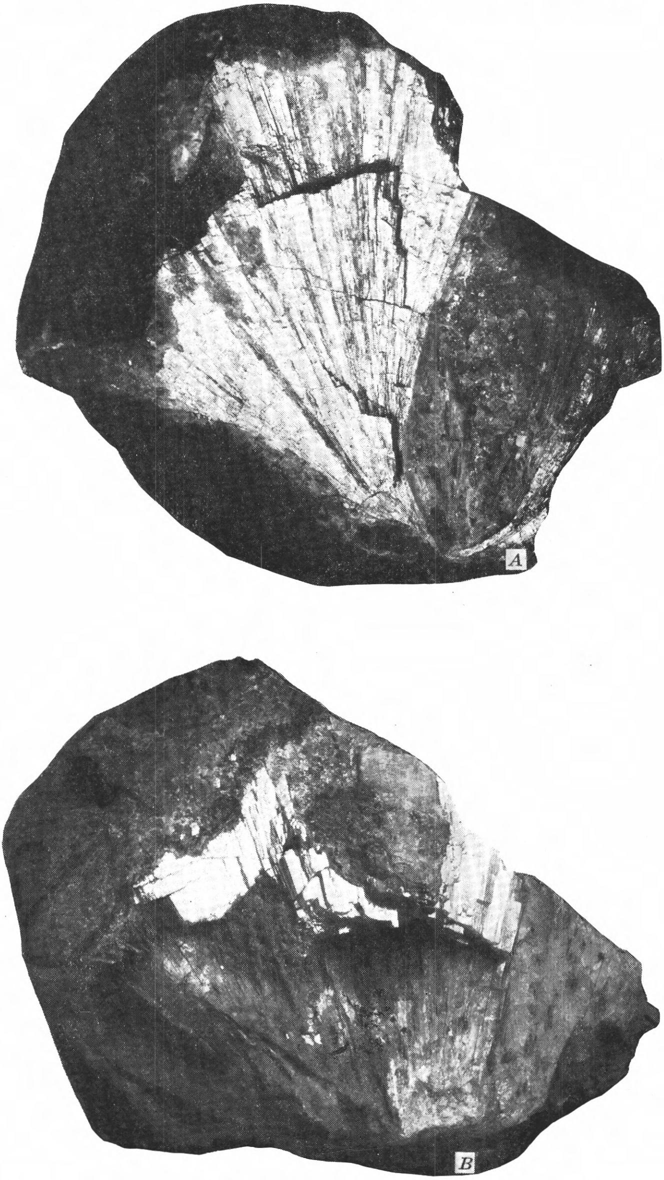
A. ANHYDRITE CRYSTAL IN QUARTZ

From Burger's quarry, West Paterson, N. J. Presented by Robert Mercer to the United States National Museum. (U. S. N. M. catalogue No. 95854.) Such crystals of anhydrite have yielded the type of cavity shown in *B*.



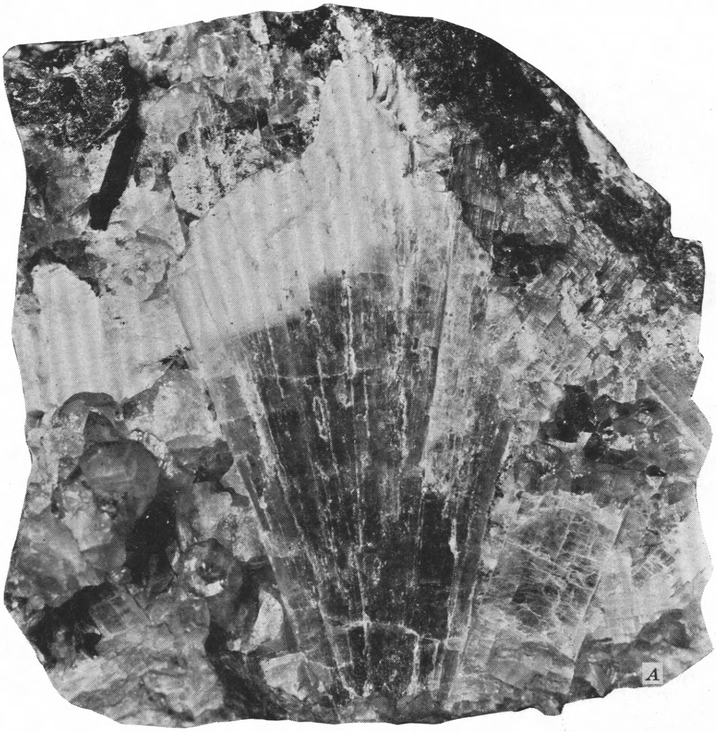
B. RECTANGULAR CAVITIES IN QUARTZ FORMED BY THE REMOVAL OF ANHYDRITE

From Burger's quarry, West Paterson, N. J. Formerly in the Roebling collection. Presented by Col. W. A. Roebling to the United States National Museum. (U. S. N. M. catalogue No. 93191.)



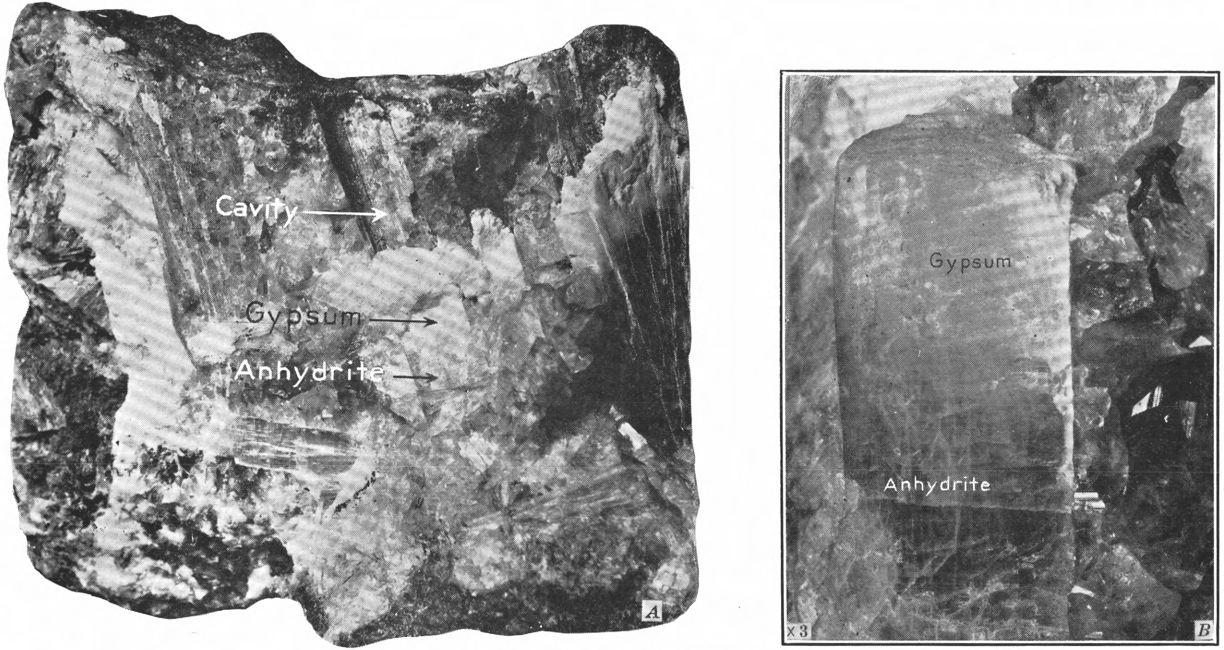
RADIATING ANHYDRITE

From Burger's quarry, West Paterson, N. J. In *A* most of the anhydrite still remains; in *B* most of the anhydrite has been removed, leaving radiating rectangular cavities. Both specimens presented by Robert Mercer to the United States National Museum. (*A*, U. S. N. M. catalogue No. 93911a; *B*, U. S. N. M. catalogue No. 93911b.) The high reflection from the anhydrite has caused it to appear nearly white in the photograph.



RADIATING ANHYDRITE GROUP, SHOWING ALTERATION

From Burger's quarry, West Paterson, N. J. In *A* the upper portion of the radiating anhydrite is altered to compact white gypsum (collection of F. I. Allen, New York, N. Y.); in *B* the radiating anhydrite is altered to thaumasite, a small portion of which has been removed forming a radiating group of rectangular cavities in the upper right corner. Collected by W. S. Disbrow and presented by him to the United States National Museum. (U. S. N. M. catalogue No. 95850.) Both of these specimens would yield cavities such as are shown in Plate 6, *B*, if the anhydrite and its alteration products had been completely removed.



ALTERATION OF ANHYDRITE

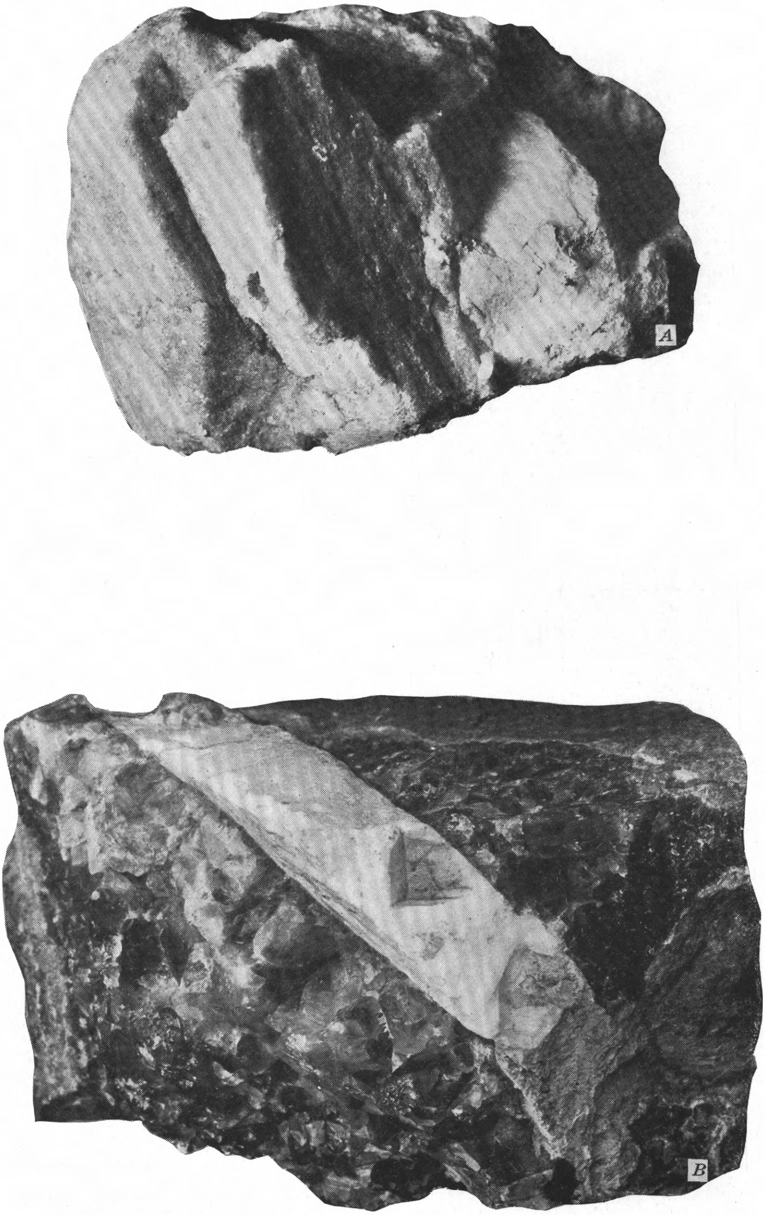
From Burger's quarry, West Paterson, N. J. (collection of F. I. Allen, New York, N. Y.). In the center of *A* is an anhydrite crystal partly altered to gypsum, which in its upper portion has been removed, leaving a rectangular cavity like those shown in Plates 4, *A*, and 10, *B*. To the left is a crystal of anhydrite changed to white gypsum, and to the right is the radiating group of anhydrite partly changed to gypsum, shown in Plate 12, *A*. *B* shows a crystal of anhydrite partly changed to gypsum. The straight white lines in the transparent anhydrite are in part thin seams of gypsum developing along the rectangular cleavage planes of the anhydrite. At the upper end of the crystal the gypsum has begun to recrystallize into selenite, with a slight increase of volume and curling up of the gypsum. The granular white opaque gypsum (upper third of specimen) occupies the same volume as the anhydrite from which it was formed.

RECRYSTALLIZATION OF OPAQUE WHITE GYPSUM INTO COLORLESS TRANSPARENT SELENITE

From McKiernan & Bergin's quarry, West Paterson, N. J. Presented by J. W. Hawkins to the United States National Museum. (U. S. N. M. catalogue No. 92981.) In *A* the anhydrite has been changed to opaque white gypsum, which still shows the radiating character of the prisms of the original anhydrite. A few walls of silica, like those shown in Plate 6, *B*, are embedded in the gypsum. On the lower side some of the gypsum has been dissolved away, showing the silica walls and illustrating how the specimen shown in Plate 6, *B*, was formed. *B* shows the other side of the same specimen, with some of the opaque white gypsum recrystallized into colorless transparent selenite (upper right). This recrystallized selenite exhibits its own crystallographic boundaries and no longer shows the radiating structure of the original anhydrite.

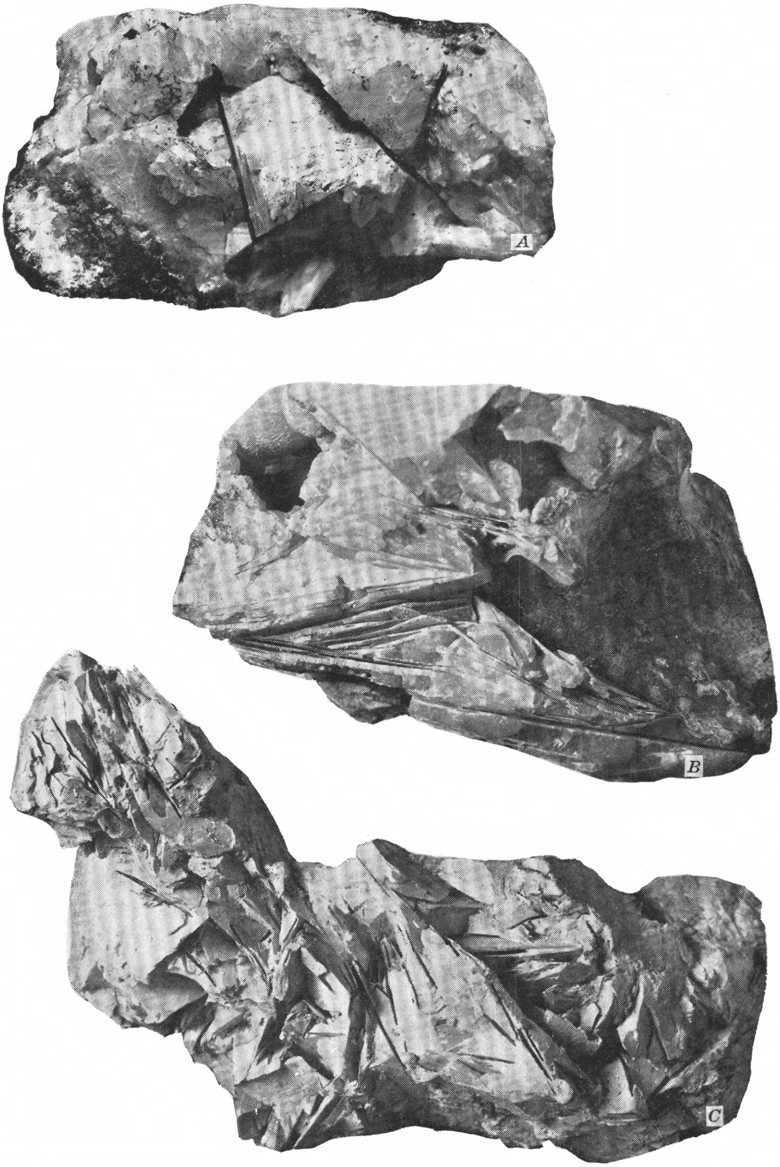
ANHYDRITE (a) PARTLY CHANGED TO GYPSUM (g) AND TO THAUMASITE (t)

From Burger's quarry, West Paterson, N. J. Presented by Robert Mercer to the United States National Museum. (U. S. N. M. catalogue No. 93911.)



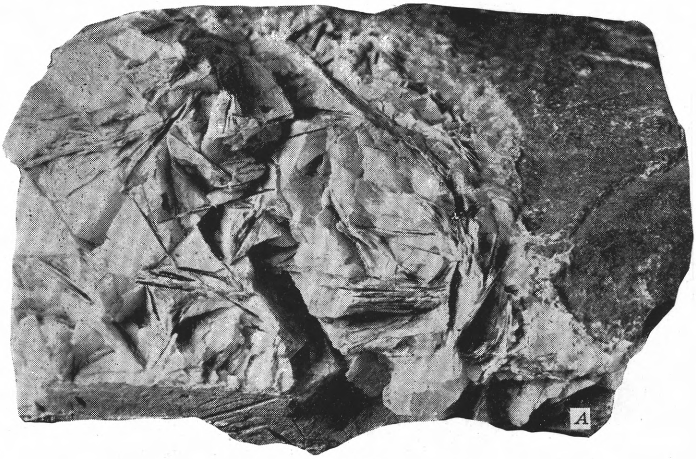
PSEUDOMORPHS OF THAUMASITE AFTER ANHYDRITE

From Burger's quarry, West Paterson, N. J. In *A* there has been a slight change in volume, the outlines of the rectangular pseudomorph in the center of the specimen being no longer sharp. (Am. Mus. Nat. Hist.) In *B* there has been no change in volume. Compare with the shape of the large white gypsum pseudomorph at the left of Plate 13, *A*. Presented by L. P. Gratacap to the United States National Museum. (U. S. N. M. catalogue No. 95850.)



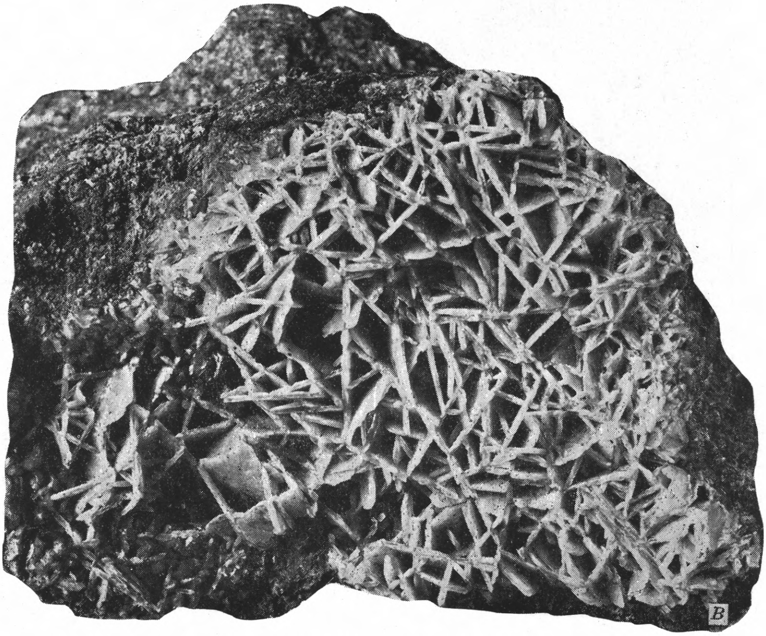
LAMELLAR CAVITIES

A, After anhydrite. From Francisco Bros.' quarry at Great Notch, N. J. Collected by W. S. Disbrow and presented by him to the United States National Museum (U. S. N. M. catalogue No. 95851). The cavities are intermediate in size between the more typical tabular cavities after anhydrite and the characteristic lamellar cavities. The striations on the quartz walls bounding the cavities show them to be after anhydrite. In *B* the cavities are in prehnite and give no definite clue to the original mineral. From Cedar Grove, N. J. Collected by W. T. Schaller (U. S. N. M. catalogue No. 95858). In *C* the cavities are in pectolite and likewise give no definite clue as to the original mineral. From Burger's quarry, West Paterson, N. J. Collected by W. S. Disbrow and presented by him to the United States National Museum (U. S. N. M. catalogue No. 95856).



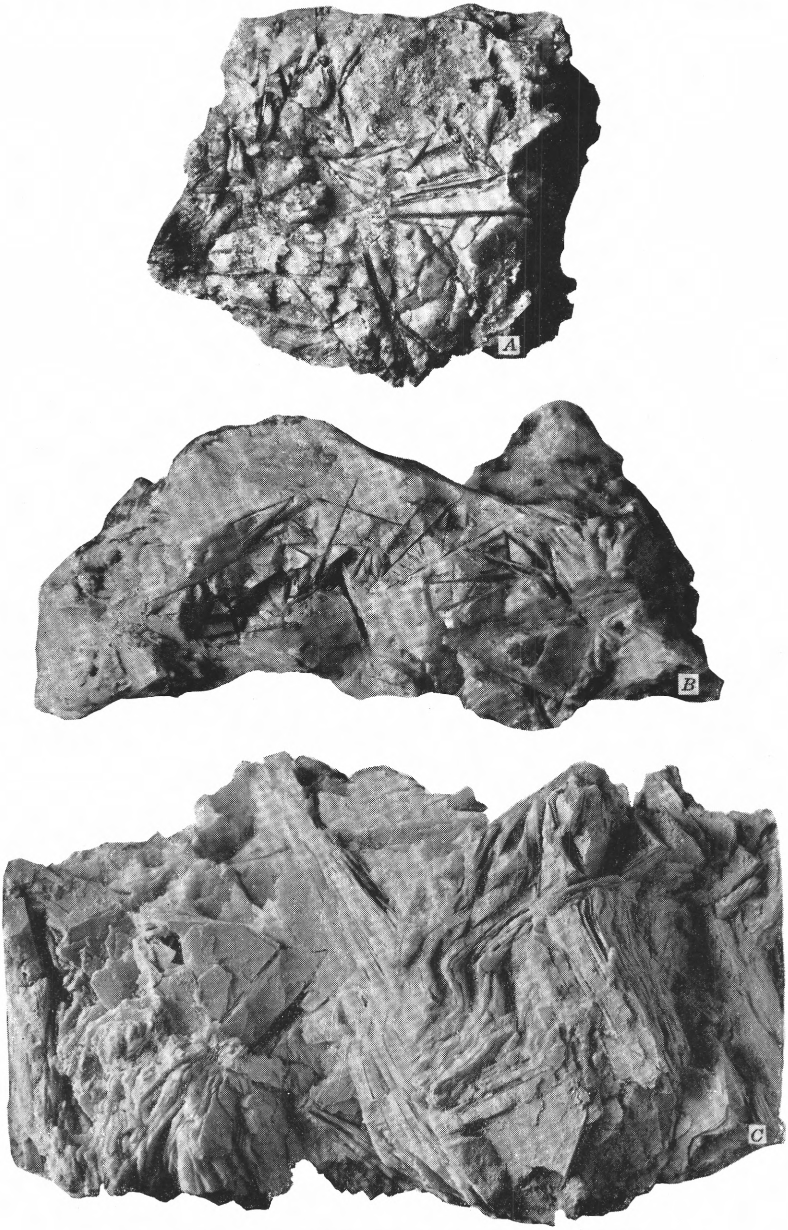
A. LAMELLAR CAVITIES

From Burger's quarry, West Paterson, N. J. Collected by W. S. Disbrow.



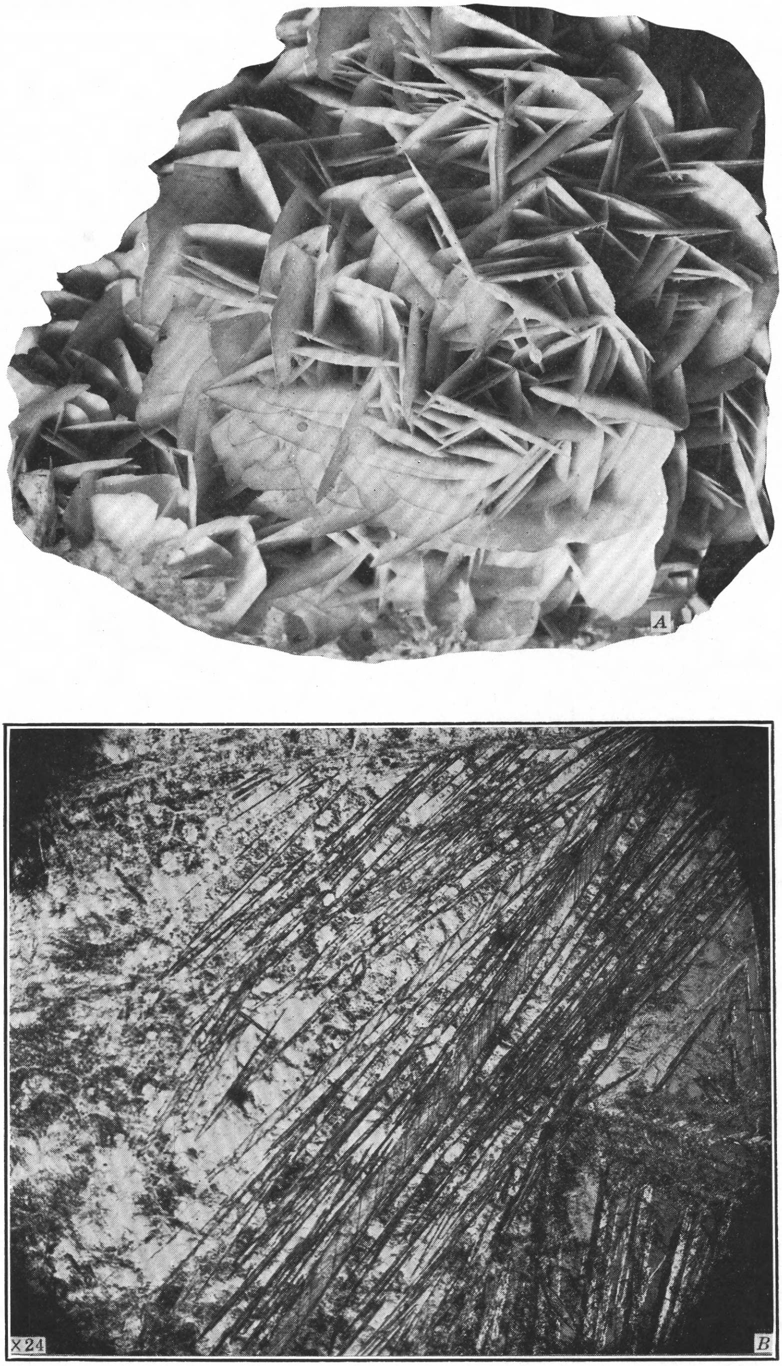
B. TABULAR CRYSTALS OF CALCITE, FROM MOORES STATION, N. J.

Presented by Col. W. S. Roebling to the United States National Museum. (U. S. N. M. catalogue No. 95864.)



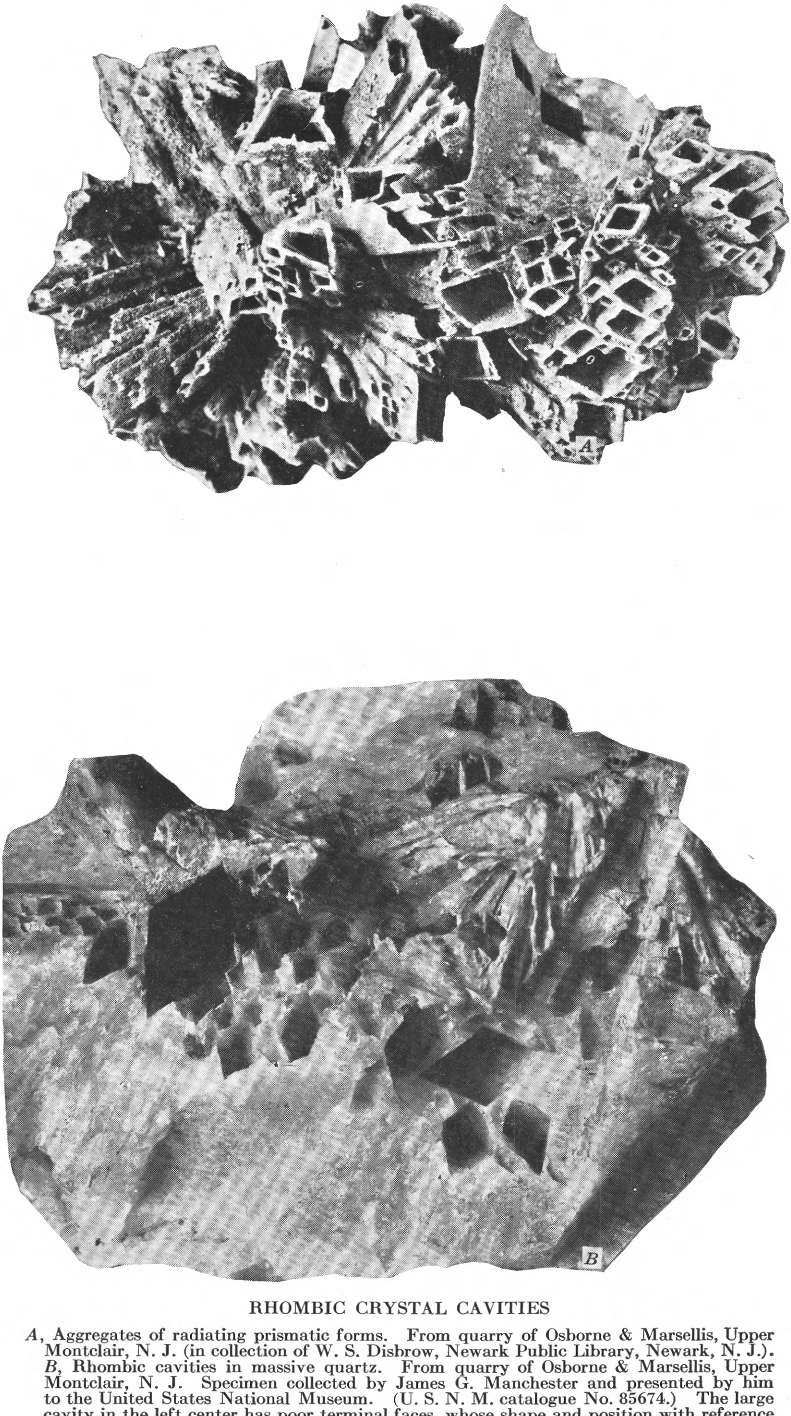
LAMELLAR CAVITIES AFTER TABULAR CALCITE

A, *B*, From De Lamar mine, Silver City, Idaho (U. S. N. M. catalogue Nos. 96032, 96033); *C*, from Wonder mine, Wonder, Nev. (U. S. N. M. catalogue No. 96034).



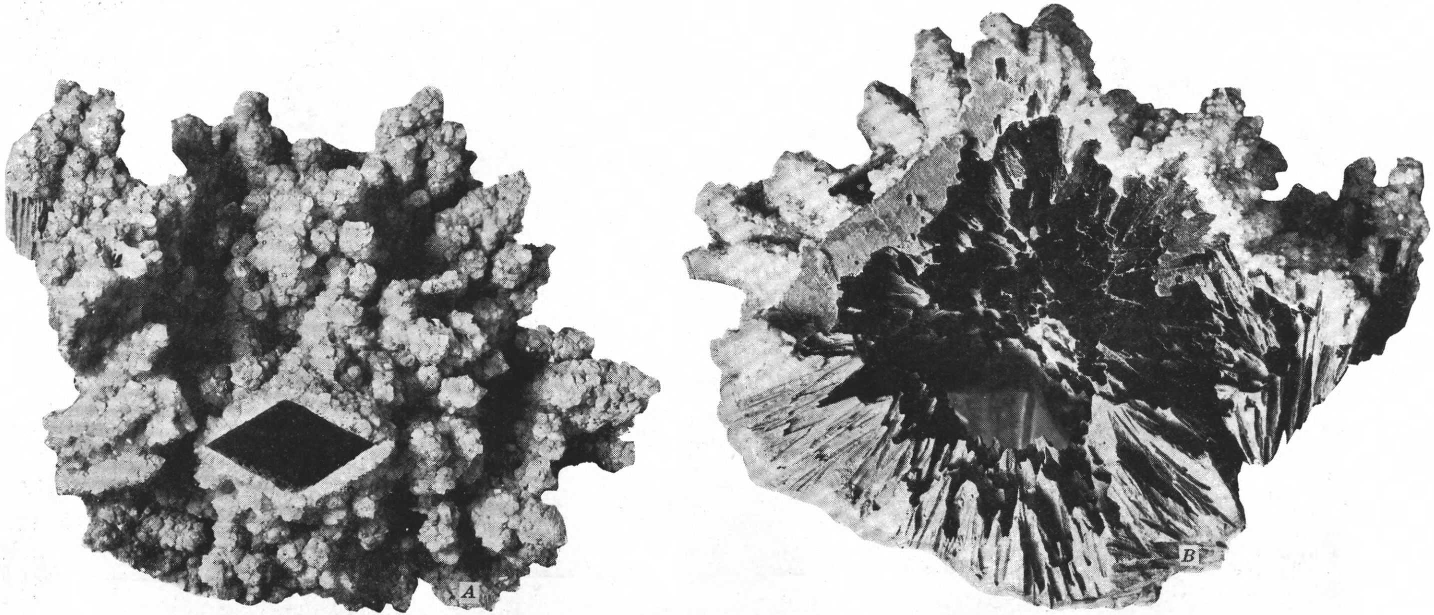
LAMELLAR CALCITE

A, Group of lamellar crystals of calcite from Andreasberg, Germany (U. S. N. M. catalogue No. 80389). *B*, Photomicrograph of thin section of rock containing lamellar calcite from the Marysville district, Montana. Furnished by Adolph Knopf, of the United States Geological Survey. The removal of such lamellar calcite would yield lamellar cavities resembling those found in the New Jersey zeolite region and illustrated in Plates 17, *A*, *B*, *C*, and 18, *A*.



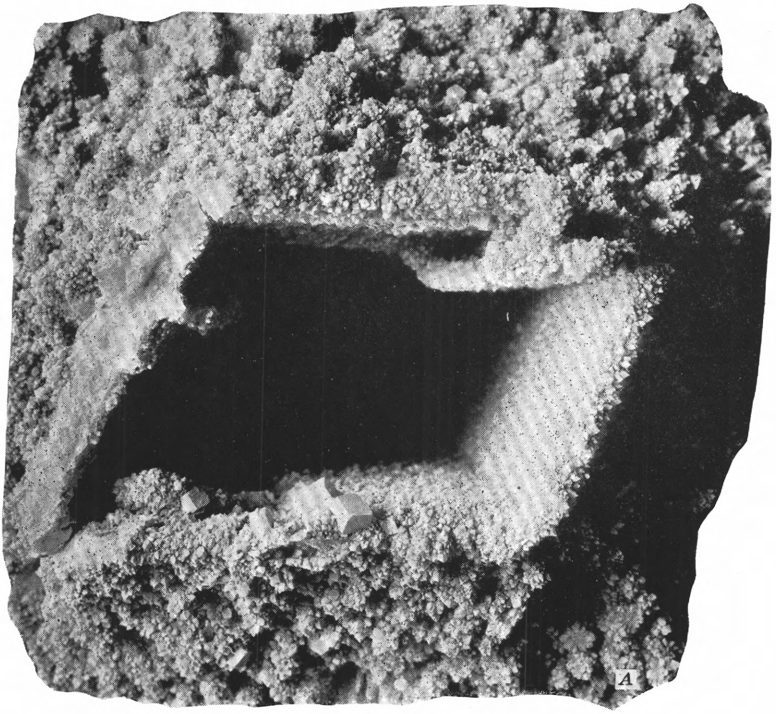
RHOMBIC CRYSTAL CAVITIES

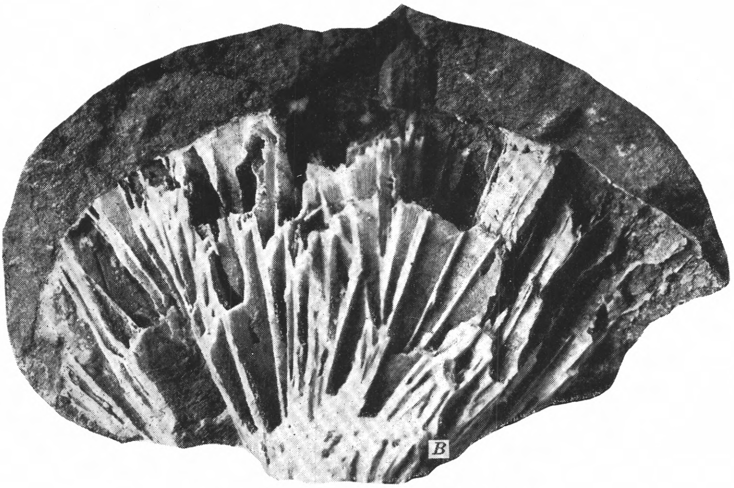
A, Aggregates of radiating prismatic forms. From quarry of Osborne & Marsellis, Upper Montclair, N. J. (in collection of W. S. Disbrow, Newark Public Library, Newark, N. J.). *B*, Rhombic cavities in massive quartz. From quarry of Osborne & Marsellis, Upper Montclair, N. J. Specimen collected by James G. Manchester and presented by him to the United States National Museum. (U. S. N. M. catalogue No. 85674.) The large cavity in the left center has poor terminal faces, whose shape and position with reference to the side walls correspond to those of the cavities after glauberite in the Triassic shale described by Wherry. (See pl. 1, *A*.)



RHOMBIC CRYSTAL CAVITIES ORIGINALLY CONTAINING ONE OR MORE QUARTZ CASTS

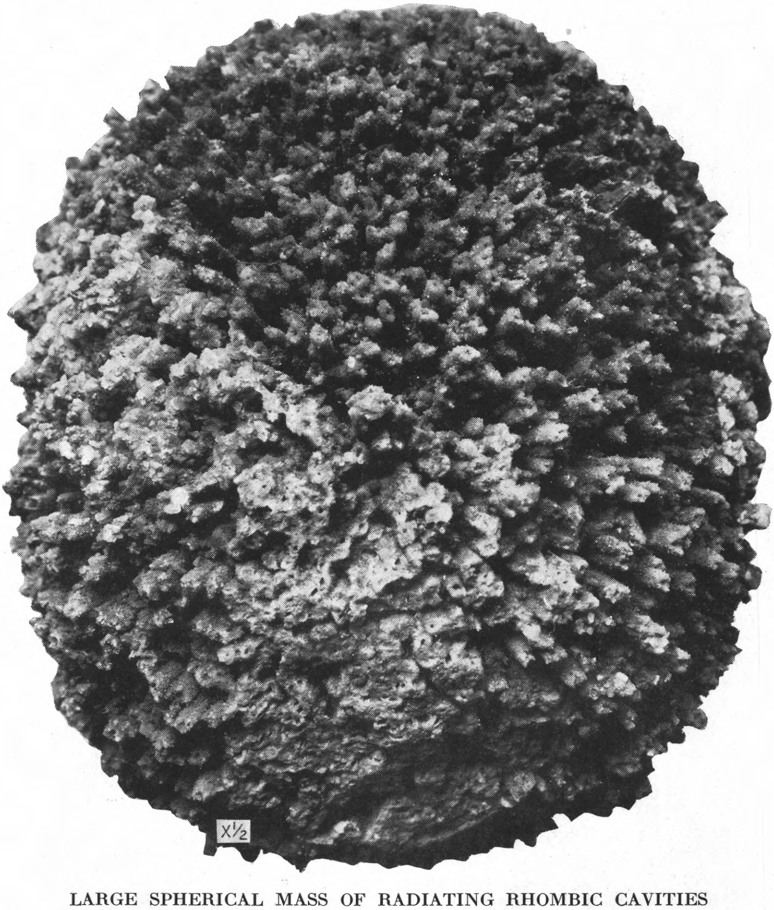
From McKiernan & Bergin's quarry, West Paterson, N. J. (collection of F. I. Allen, New York, N. Y.). *A* shows a single large rhombic cavity which when found contained a quartz cast, in an aggregate of many empty, smaller rhombic cavities, in quartz. The infiltration pseudomorphs after glauberite shown in Plates 27 and 28, whose crystallography is described in detail on pages 55–75, were obtained from similar matrices. *B*, The other side of the specimen. The single large cavity is faintly shown in the lower center. All the smaller cavities were empty and free from any cast or core; only the single large cavity contained one. The smaller cavities are capped by a thick coating of quartz crystals, as shown in *A*, which may have prevented the silica-bearing solutions from reaching them and depositing therein their load of silica to form pseudomorphs by infiltration.



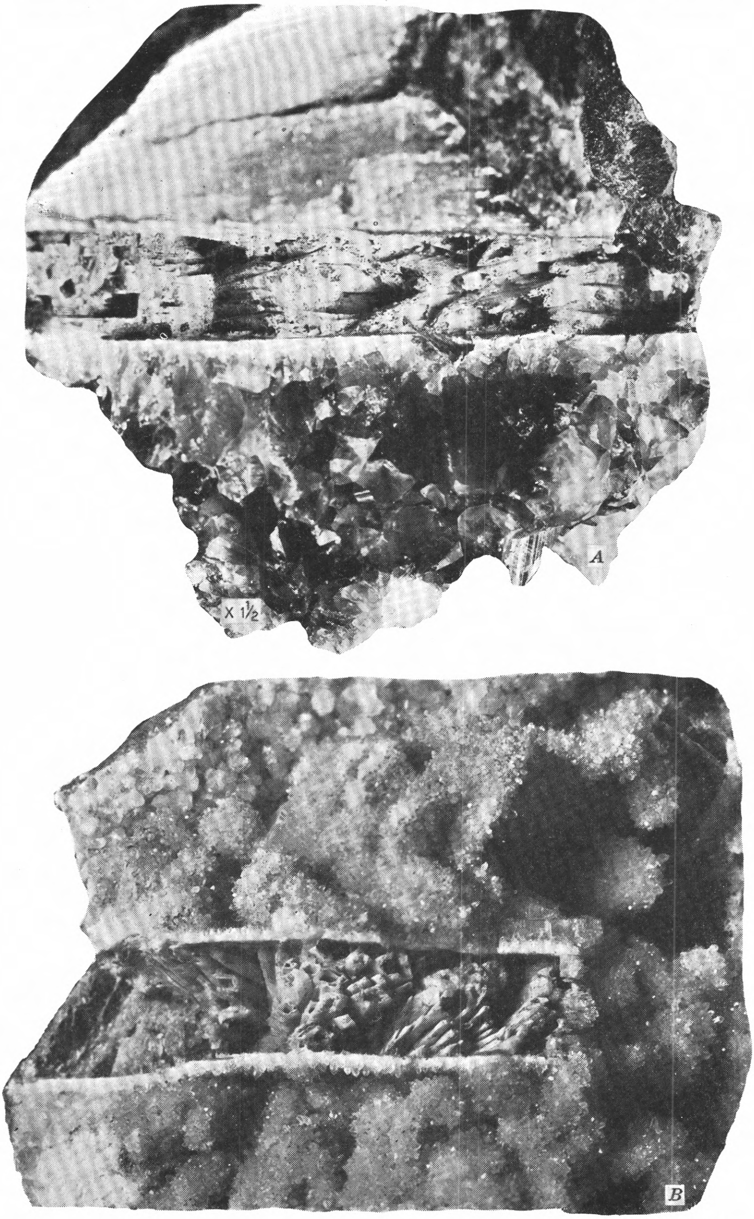


RHOMBIC CRYSTAL CAVITIES

A, Unusually large rhombic cavity. From Francisco Bros ' quarry, Great Notch, N. J. (Am. Mus. Nat. Hist.) The specimen was coated with ammonium chloride to avoid the sharp contrasts the brilliant faces of the quartz crystals would otherwise have given. *B*, Radiating group forming part of a spherulitic aggregate, the cavities not being in a single plane. In the trap rock from the Osborne & Marsellis quarry, Upper Montclair, N. J. Collected by E. T. Wherry. (U. S. N. M. catalogue No. 93101.)

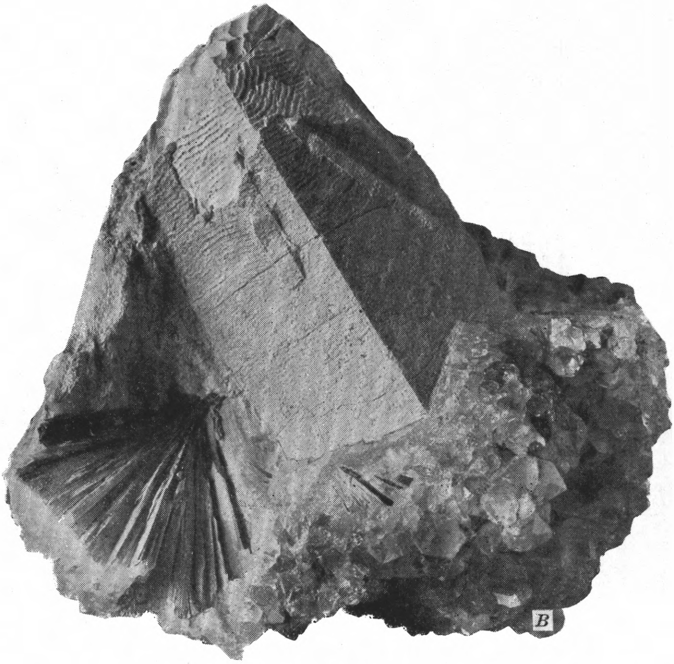


LARGE SPHERICAL MASS OF RADIATING RHOMBIC CAVITIES
From Burger's quarry, West Paterson, N. J. (U. S. N. M. catalogue No. 92980.)



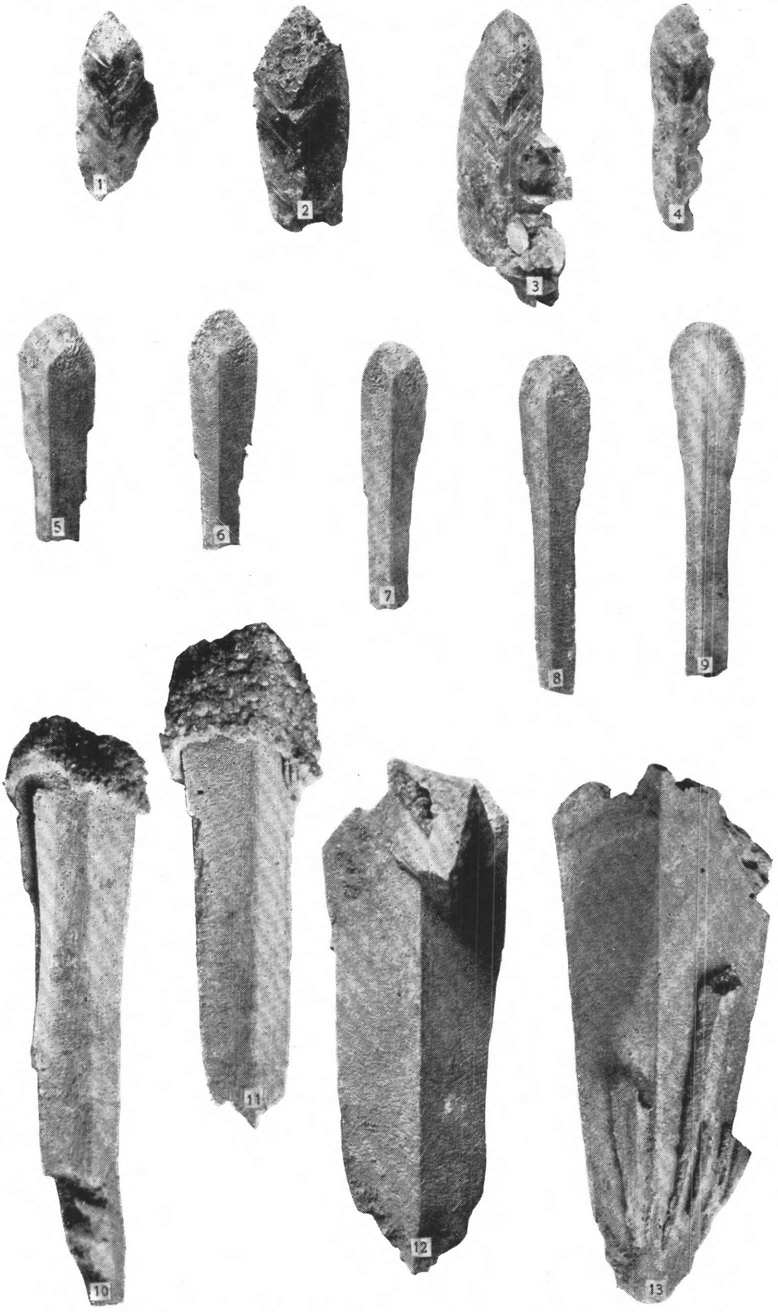
RHOMBIC CAVITIES INCLOSED IN A LARGER RECTANGULAR CAVITY

Showing that the anhydrite (the original mineral of the rectangular cavity) formed and was removed before the glauberite (the mineral of the rhombic cavities). *A*, From Burger's quarry, West Paterson, N. J. (collection of F. I. Allen, New York, N. Y.). *B*, From Francisco Bros.' quarry, Great Notch, N. J. Collected by W. S. Disbrow and presented by him to the United States National Museum. (U. S. N. M. catalogue No. 85674.)



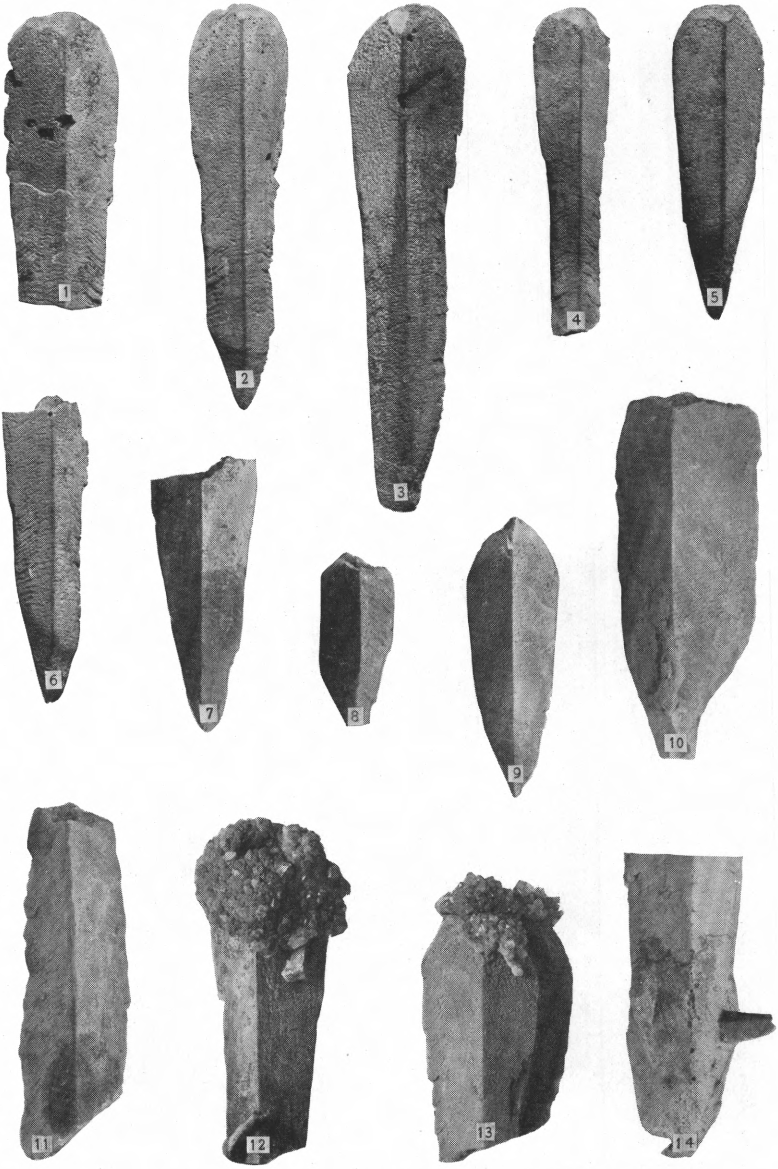
CORES FROM THE RHOMBIC CAVITIES

From McKiernan & Bergin's quarry, West Paterson, N. J. *A*, Very slender cores. Collected by W. T. Schaller (U. S. N. M. catalogue No. 95853). *B*, Very large core (collection of F. I. Allen, New York, N. Y.). The platy and corrugated character of the concentric plates is well shown. A transverse view of the broken end is given in Plate 29, *A*. The material now is almost pure silica.



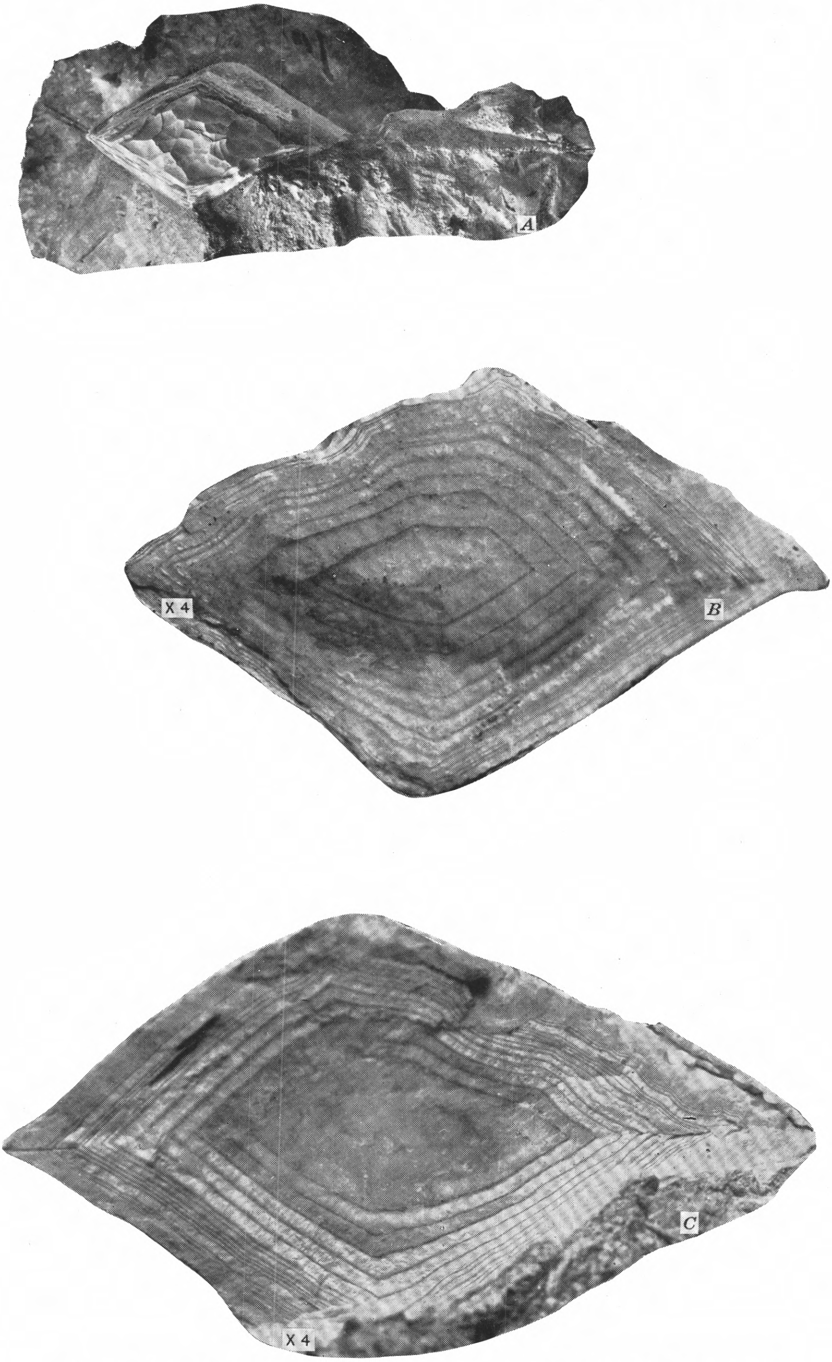
GLAUBERITE CRYSTALS AND CORES FROM RHOMBIC CAVITIES

The upper row (Nos. 1–4) shows four glauberite crystals from localities outside of New Jersey. Nos. 1, 2, and 3 are from Tarapaca, Chile (Am. Mus. Nat. Hist. catalogue No. 16239). No. 4 is from California (U. S. N. M. catalogue No. 93108). The middle and lower rows (Nos. 5–13) are cores from the rhombic cavities in specimens from McKiernan & Bergin's quarry, West Paterson, N. J. (collection of F. I. Allen, New York, N. Y.).



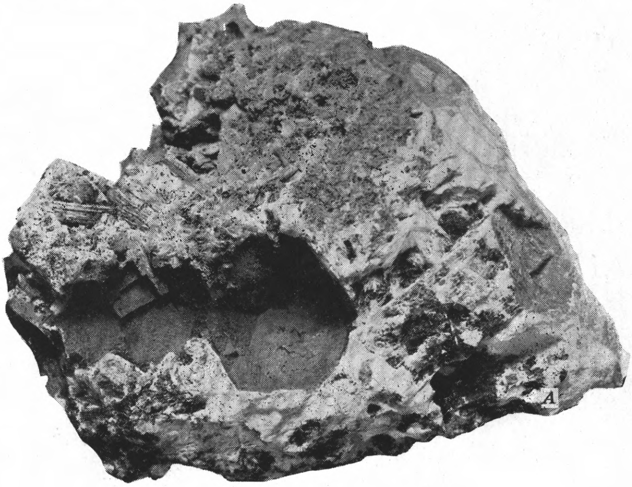
CORES FROM THE RHOMBIC CAVITIES

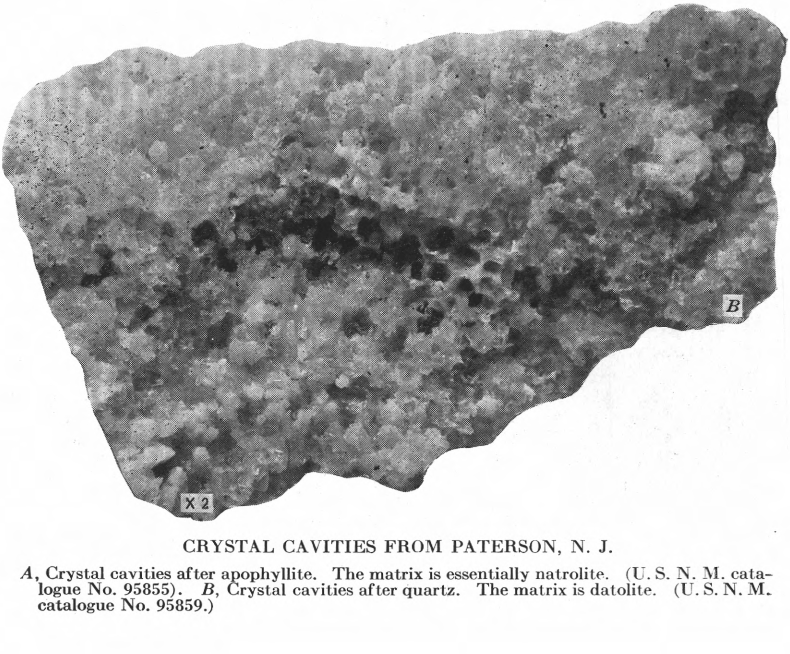
From McKiernan & Bergin's quarry, West Paterson, N. J. Nos. 1, 3, and 6 are in the American Museum of Natural History, New York (catalogue No. 18027); No. 2 is in the collection of Gilman S. Stanton, of New York; Nos. 4 and 5 in the Roebling collection (now in the U. S. National Museum); Nos. 7–14 in the collection of F. I. Allen, of New York.



CROSS SECTIONS OF THE CORES FILLING THE RHOMBIC CAVITIES

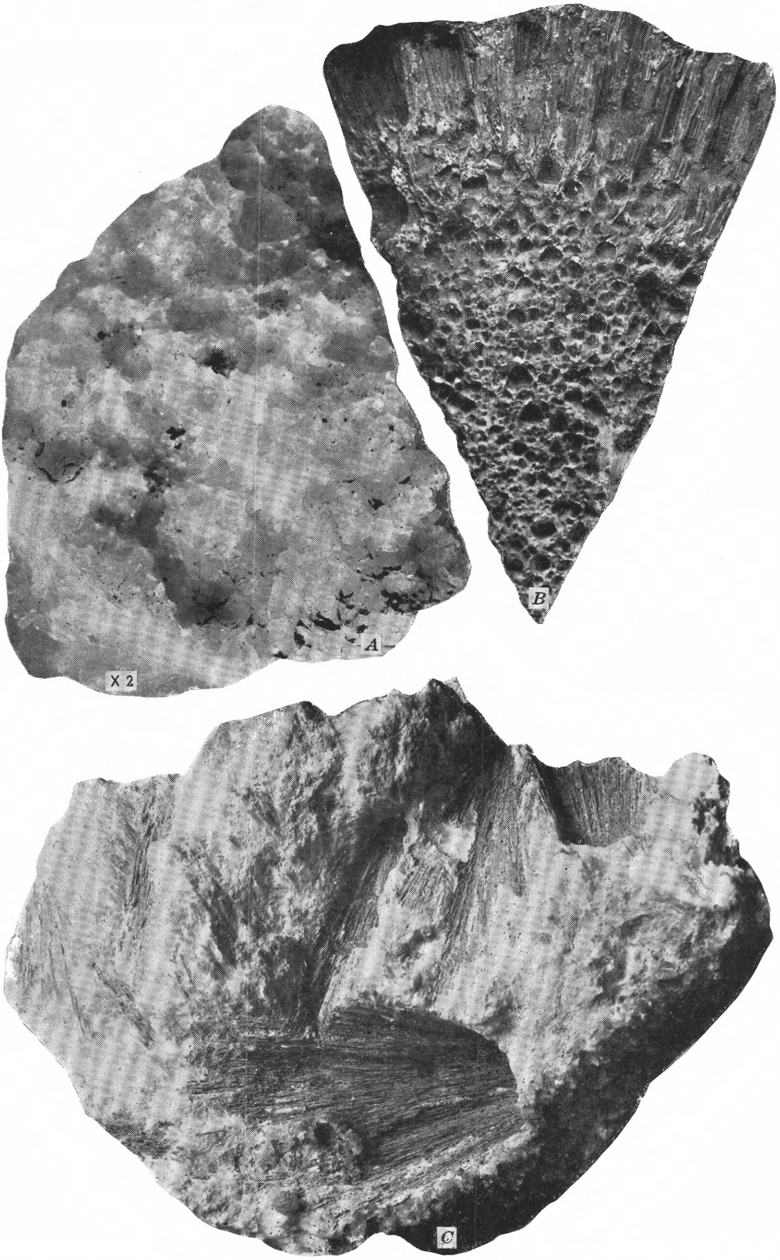
Showing concentric structure, following the rhombic outline of the cavities and indicative of successive fillings. From McKiernan & Bergin's quarry, Paterson, N. J. (collection of F. I. Allen, New York, N. Y.). *A*, End view of specimen shown in Plate 26, *B*; *B*, *C*, end views of two other cores.





CRYSTAL CAVITIES FROM PATERSON, N. J.

A, Crystal cavities after apophyllite. The matrix is essentially natrolite. (U. S. N. M. catalogue No. 95855). *B*, Crystal cavities after quartz. The matrix is datolite. (U. S. N. M. catalogue No. 95859.)



CRYSTAL CAVITIES FROM PATERSON, N. J.

A, Crystal cavities after calcite. The matrix is quartz (U. S. N. M. catalogue No. 95861). *B*, Crystal cavities after natrolite. Portion of a larger specimen. In the Disbrow collection, Newark Public Library, Newark, N. J. *C*, Crystal cavities after pectolite. The matrix is natrolite. Collected by W. S. Disbrow and presented by him to the United States National Museum (U. S. N. M. catalogue No. 95857).

BABINGTONITE

A, Rosette of babingtonite crystals on quartz and calcite. From Francisco Bros.' quarry, Great Notch, N. J. Collected by W. S. Disbrow and presented by him to the United States National Museum (U. S. N. M. catalogue No. 93973). *B*, Babingtonite crystals, with calcite and stilbite, on quartz containing lamellar cavities. From McKiernan & Bergin's quarry, West Paterson, N. J. Collected by W. T. Schaller (U. S. N. M. catalogue No. 95859). Obviously the original mineral of the lamellar cavities was present before the quartz, and the quartz was earlier than the babingtonite perched on it. *C*, Babingtonite crystals (black plates) on quartz, calcite, and other minerals. From Francisco Bros.' quarry, Great Notch, N. J. Collection of W. S. Disbrow in the Newark Public Library, Newark, N. J.

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