Bulletin 833

MINERALOGY OF DRILL CORES FROM THE POTASH FIELD OF NEW MEXICO AND TEXAS

BY

WALDEMAR T. SCHALLER

AND

EDWARD P. HENDERSON

CONTENTS

ILLUSTRATIONS

SUMMARY

The potash field of southeastern New Mexico and adjacent parts of Texas is confined to the southern part of the Permian salt basin, covering about 40,000 square miles. The potash and associated minerals lie in a body of Permian halite, whose top is at least several hundred feet below the present surface.

The material described in this report was obtained from drill cores and well cuttings. All the specimens illustrated are parts of drill cores that were shipped to Washington for examination and chemical analysis of their potash content.

The minerals identified are anhydrite, bloedite, calcite, carnallite, celestite, clays, dolomite, epsomite, glauberite, gypsum, halite, hematite, kainite, kieserite, langbeinite, leonite, lueneburgite, magnesite, opal, polyhalite, pyrite, quartz, and sylvite. Six of these minerals—kainite, kieserite, langbeinite, leonite, lueneburgite, and polyhalite—were first recorded in the United States from this field.

Sylvite was first recognized in the United States in cuttings analyzed by the Geological Survey from the Markham salt dome, Matagorda County, Tex.,[1] but the announcement by the Geological Survey in a press statement, dated April 3, 1926, of the presence of sylvite in well cuttings from the McNutt permit, in sec. 4, T. 21 S., R. 30 E., Eddy County, N. Mex., encouraged the private drilling of the first core-test hole in New Mexico. This test disclosed sylvite and associated minerals in beds sufficiently rich and thick to suggest commercial operation and in turn led to further private core drilling and ultimately to the sinking by the United States Potash Co. of the shaft of the first potash mine on the American continent.

Halite is by far the most abundant mineral disclosed in the cores and is followed in order by anhydrite, the clays, polyhalite, and sylvite, all of which occur in considerable quantity. The remaining minerals so far revealed by exploration are relatively of minor importance. Nearly all the material is compact and massive, very few natural cavities having been found. The core specimens can be classified in two groups—the sulphate group and the chloride group, each of which has certain characteristic mineral associations and modes of occurrence.

The minerals are described in alphabetic order. The sequence of their formation is of the greatest significance because many of them are shown to have originated by the reaction of preexisting saline minerals with liquors rich in potash. Others have suffered mineral changes and replacements in which potassium did not enter. The conclusion that the mineral associations now found have undergone many changes since the beginning of the original precipitation is amply confirmed by the list of such changes, here presented. The saline field, as now existent, in large part therefore does not represent the original minerals first laid down. The mineral formed earliest is anhydrite, which is characteristically banded by layers of much finer-grained magnesite.

At places a mineral, now absent but believed to have been gypsum, grew in the anhydrite rock, probably before its complete solidification, but later was either dissolved and the spaces filled with halite or was directly replaced by halite. In this halite, as well as in the anhydrite rock, polyhalite developed later. In fact, it is doubtful whether any of the polyhalite now present was precipitated directly

---

[1] DeGolyer, E., New light on the origin of North American salt domes: Mining and Metallurgy, vol. 6, p. 82. February, 1925.

from brines; at least no appreciable part of it was so formed, but nearly all of it originated as just stated, from earlier minerals, chiefly anhydrite. Occurrences are described where polyhalite has replaced anhydrite, glauberite, halite, kieserite, leonite, and sylvite.

The series of mineral replacements observed is as follows:

Anhydrite has been replaced by halite (pls. 11, A; 12, A), by leonite (fig. 10), by magnesite (pl. 16, C), by polyhalite (pls. 5, 26, 28, B, 35, 36; figs. 12, 13), and by a mixture of halite and polyhalite (pl. 11, A). No evidence was seen that anhydrite has replaced any of the other minerals, though its recrystallization from a finer-grained aggregate into larger crystals has been common.

Carnallite seems to have replaced anhydrite, halite, and polyhalite.

Glauberite has developed in the anhydrite rock in such a manner that it seems to have replaced the anhydrite. Glauberite is clearly replaced by halite (pl. 11, B), by polyhalite, and by a mixture of halite and polyhalite (pl. 7, C).

Halite has replaced anhydrite (pl. 11, A), glauberite (pls. 7, C, 11, B), and possibly polyhalite but has itself been abundantly replaced by polyhalite (pls. 22, B, 23, 25, 29).

Kainite has replaced langbeinite and possibly some of the other minerals, but in its few occurrences here seen it seems to have developed as a secondary product through the reaction of two or more minerals along their contact rather than as a product of replacement.

Kieserite has been replaced by leonite and by polyhalite (pls. 13, B, 33, B).

Langbeinite seems to have replaced sylvite, but definite evidence of replacement effects of other minerals by langbeinite were not seen. Langbeinite itself has been replaced by kainite.

Leonite has replaced anhydrite (fig. 10) and kieserite and has itself been replaced by polyhalite (pl.15).

Magnesite, in its nodular mode of occurrence, has replaced the anhydrite rock (pl. 16, C), but the genetic relation of the bands of magnesite to the anhydrite rock is not known. Undoubtedly some of the magnesite has been acted on by solutions and has yielded magnesium to form polyhalite and probably other minerals, but no definite replacement effects were observed.

Polyhalite has replaced anhydrite (pls. 5, 26, 28, B, 35, 36; figs. 12, 13), glauberite (pl. 7, C), halite (pls. 22, B; 23, 25, 29), kieserite (pls. 13, B, 33, B), leonite (pl. 15), and sylvite (pl. 23, C) and may in part and to a slight degree have been replaced by carnallite, though no direct evidence of such a change was seen.

Sylvite has been replaced by langbeinite and by polyhalite (pl. 23, C) to a very minor extent. Its relations to many of the minerals occurring with it are obscure and not known at present. The relations of halite and sylvite are particularly difficult to decipher, because the criteria of reaction and of possible replacement for these two minerals are contradictory and confusing.

The optical method was found to be the quickest and most convenient for the identification of these saline minerals. Their refractive indices and other optical properties were determined by the oil immersion method and the use of a petrographic microscope. For this purpose a chart has been developed, on which the refractive indices of these minerals have been plotted, using for reference the increasing value of β, the middle index.

MINERALOGY OF DRILL CORES FROM THE POTASH FIELD OF NEW MEXICO AND TEXAS

By Waldemar T. Schaller and Edward P. Henderson

INTRODUCTION

The portion of the great Permian salt basin that lies in southeastern New Mexico and western Texas, which has been found to contain potash-bearing minerals of prospective commercial value, has become known as the New Mexico and Texas potash field. The potash
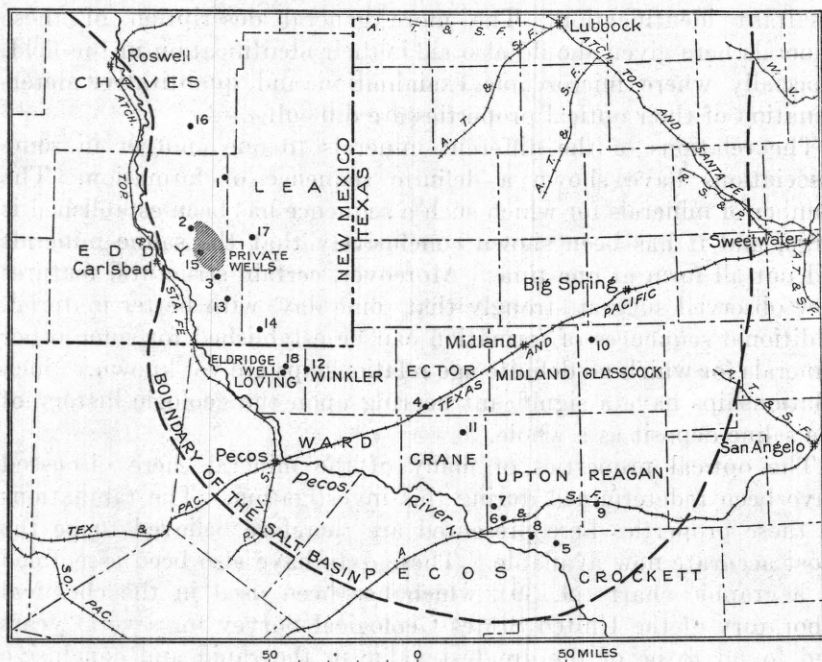
FIGURE 1.—Location of the New Mexico and Texas potash field and of the wells from which cores were obtained. (For explanation of numbers see table on p. 5)

minerals, with their associates, occur underground in large deposits, but these have not yet (October, 1929) become accessible to direct examination. The results here presented were obtained by studying cores drilled in the potash field under both private and governmental auspices. Figure 1 shows the location of the Government and private

1

wells from which were obtained the cores that furnished the material described. A few mineralogic observations were also made on some well cuttings, of which a very large number have been collected and analyzed for their potash content. The results obtained up to 1925 are given in more detail in reports by Hoots [1] and Lang,[2] and those up to 1928 by Mansfield and Lang.[3]

The minerals described in this report include halite, anhydrite, and others, relatively common, together with rarer minerals, such as langbeinite and leonite. A description of these minerals is a contribution to the science of mineralogy. The optical properties of some of the species are not given in the literature with the exactness that present knowledge permits. A tabulation of the optical properties of such minerals, accurately determined, serves better than any other guide for their determination, particularly where the minerals occur in such intimate mixtures as to make it almost impossible to separate any one species in a pure state suitable for chemical analysis and resultant identification. The more general description of these minerals here given should also aid in their identification in the field, especially where microscopic examination and quantitative determination of their optical properties are difficult.

The relations of the different minerals to one another in some associations have shown a definite sequence of formation. The number of minerals for which such a sequence has been established is large, and it has been shown conclusively that the saline minerals did not all form at one time. Moreover, certain structural features now observed suggest strongly that some day, with better material, additional sequences of formation can be established for some other minerals for which no definite age relationships are yet known. Such relationships have a significant bearing upon the geologic history of the saline deposit as a whole.

The optical properties of many of the minerals here discussed have been redetermined during this investigation. The tabulations of these properties here presented are therefore believed to be the most accurate now available. These data have also been assembled in a graphic chart (pl. 39), which has been used in the chemical laboratory of the United States Geological Survey for several years and found to be of the greatest value in the rapid and conclusive identification of these saline minerals.

The occurrences and relations of the minerals here described are based only on the parts of the cores received in Washington. These necessarily represent essentially only the possible commercial sections,

[1] Hoots, H. W., Geology of a part of western Texas and southeastern New Mexico, with special reference to salt and potash: U. S. Geol. Survey Bull. 780, pp. 33–126, 1926.

[2] Lang, W. B., Potash investigations in 1924: U. S. Geol. Survey Bull. 785, pp. 29–43, 1926.

[3] Mansfield, G. R., and Lang, W. B., Government potash exploration in Texas and New Mexico: Am. Inst. Min. and Met. Eng. Tech. Pub. 212, 1929; Am. Inst. Min. and Met. Eng. Yearbook, 1929, pp. 241–255.

which constitute but a small fraction of the entire core from each hole. A study of the entire core might modify some of the statements here made as to occurrence and association of the individual minerals.

Mineral identifications of well cuttings from this field were first made in the Geological Survey by E. S. Larsen. The detailed mineralogic study of the cores was initiated by W. T. Schaller, later assisted by E. P. Henderson. Recently J. J. Fahey has continued this study, and E. T. Erickson has made most of the quantitative determinations of K_2O and tests for boron, bromine, and iodine. The writers are indebted to George Steiger for the analyses of polyhalite, to J. J. Fahey for the analyses of carnallite, kainite, and langbeinite, and to all these gentlemen for continued assistance, both mineralogic and chemical, during the preparation of this report.

GEOLOGY

As stated by Mansfield and Lang, the potash field, at least the portion that contains the potash-bearing salts most likely to have commercial value, is confined to the southern part of the Permian salt basin, covering about 40,000 square miles and occupying about 22 counties in New Mexico and Texas. The Permian salt basin as a whole extends from southeastern New Mexico and western Texas northeastward, through the Panhandle sections of Texas and Oklahoma and northward through Kansas and enters eastern Colorado.

No attempt is here made to give any more geologic setting than has been presented in the papers on this subject already published. The following notes have been abstracted from papers by Darton[4] and those by Hoots and Lang already cited.

The potash and associated minerals collectively referred to as the saline minerals lie in a body of Permian halite, whose top is at least several hundred feet below the present surface. Above it lie Permian and Triassic red beds; the underlying formations are Permian and upper Pennsylvanian.

The rocks of the region, all sedimentary and all unconformable, are, in descending order, Recent, Pleistocene or Pliocene, Comanche (Lower Cretaceous), Triassic, Permian, and upper Pennsylvanian. All these rocks except the Pennsylvanian are exposed in the saline area.

The Recent rocks, which reach a maximum thickness of 260 feet, are stream deposits of sand, gravel, and clay, with windblown sand and caliche ("cap rock"). The Pleistocene or Pliocene sand, gravel,

---

[4] Darton, N. H., Permian salt deposits of the south-central United States: U. S. Geol. Survey Bull. 715, pp. 205-223, 1921; "Red Beds" and associated formations in New Mexico: U. S. Geol. Survey Bull. 794, 1928.

and clay reach a thickness of about 50 feet. The Comanche (limestone and sandstone) has a maximum thickness of about 500 feet, and the dark-red clay and sandstone of the Triassic may extend for about 1,200 feet. The Permian is many thousand feet thick and contains the saline beds. For example, Hoots[5] says:

Bordering the region here considered on the east, south, and west are Permian strata with a thickness of 4,000 to 10,900 feet, which pass below the younger rocks that form the surface of the High Plains.

The Permian strata containing the saline beds are thinnest near the eastern and southeastern borders of the basin and thickest farther west. At places the entire halite-anhydrite series is at least 4,500 feet thick. The top of the underlying eroded Pennsylvanian is believed to be more than 6,000 feet below the surface. The ending of the thick halite beds is very abrupt on the west side. According to Hoots.[6]

The Toyah-Bell well (No. 38) passed through 1,024 feet of salt [halite] interstratified with approximately 2,550 feet of anhydrite and anhydrite with dolomite. The Ira J. Bell well (No. 58), 8 miles west of the Toyah-Bell, encountered less than 15 feet of salt in its upper 2,600 feet and not much more in the next 1,900 feet.

Practically all the rock encountered in the Bell well is anhydrite and dolomite. The desiccation of the large body of ocean water that yielded the saline minerals was influenced by further influx of sea water, rains, and inflowing streams. There was therefore an interruption to the normal process of evaporation with consequent deposition of the salines, and the ratio of halite to anhydrite differs greatly in different places. In the Means well 34 per cent is halite, in the Toyah-Bell well 28.7 per cent, and in the Bell well 5 per cent. In northern trans-Pecos Texas the Capitan limestone, Castile gypsum, Rustler limestone, and Delaware Mountain formation are considered to be the equivalents of the buried halite, anhydrite, and red-bed series east of the Pecos River. The salt deposits underlie an area of nearly 70,000 square miles. The area is about 360 miles long from north to south and about 275 miles wide from east to west.

MATERIAL AVAILABLE

With the exception of the calcite, celestite, opal, and the samples of polyhalite completely analyzed, all the minerals here described were obtained from cores ranging from 2 to $2\frac{5}{8}$ inches in diameter, from holes drilled by governmental and private agencies and submitted to the Geological Survey at Washington. But before these cores were available considerable material had already been received

from oil-well cuttings. These had been analyzed for their potash content, and the polyhalite contained in them had been studied.

The cores from which the minerals described were obtained are listed below in two groups, those from holes drilled by the Government and those from holes drilled by private enterprise. The Government drilling was done by the Bureau of Mines under the terms of the act which provides for joint potash investigations by the Departments of the Interior and of Commerce.

Cores furnishing material for study

Government cores

Government well No.	State	County	Location	Laboratory No.
1	New Mexico	Eddy	Sec. 13, T. 17 S., R. 31 E	P-268
2	do	do	Sec. 14, T. 20 S., R. 29 E	P-275
3	do	do	Sec. 34, T. 22 S., R. 30 E	P-298
4	Texas	Ector	Sec. 16, block 16 (public school land survey)	P-314
5	do	Crockett	Sec. 16, block HH, G. C. & S. F. survey (Harris ranch)	P-301
6	do	Upton	Sec. 100 (Burleson-Sun lease)	P-316
7	do	do	Sec. 4, William Teer survey (Roxana-Hughes lease)	P-317
8	do	Crockett	Sec. 5, block 14 (University land)	P-355
9	do	Reagan	Sec. 1, block 2 (University land)	P-383
10	do	Glasscock	Sec. 14, block 35, T. 2 S., Texas & Pacific (Houston ranch)	P-384
11	do	Crane	Sec. 3, block B-25	P-407
12	do	Winkler	Sec. 33, block 75 (Leeman ranch)	P-408
13	New Mexico	Eddy	Sec. 5, T. 24 S., R. 31 E	P-410
14	do	Lea	Sec. 1, T. 26 S., R. 32 E	P-431
15	do	Eddy	Sec. 34, T. 21 S., R. 29 E	P-440
16	do	Chaves	Sec. 12, T. 14, S. R. 28 E	P-441
17	do	Lea	Sec. 28, T. 20 S., R. 33 E	P-510
18	Texas	Loving	Sec. 5, block 28 (public school land)	P-524

Private cores

Name	State	County	Location Sec.	T. S.	R. E.	Company	Laboratory No.
McNutt No. 1	New Mexico	Eddy	4	21	30	United States Potash Co.	P-235
McNutt No. 2	do	do	5	21	30	do	P-286
Martin Yates No. 1	do	do	9	21	30	do	P-288
Joe Mitchell	do	do	33	20	31	do	P-300
Amy McNutt No. 1	do	do	10	21	31	do	P-322
Wm. Dooley No. 1	do	do	6	21	30	do	P-345
Wm. Dooley No. 2	do	do	31	20	31	do	P-351
Martin Yates No. 2	do	do	17	21	30	do	P-367
Kern No. 1	do	do	1	21	29	do	P-369
Wm. McGinn	do	do	31	20	31	do	P-381
Ballard No. 1	do	do	18	21	30	do	P-382
Blanchard No. 1	do	do	12	21	29	do	P-385
Kelly No. 1	do	do	23	21	29	do	P-401
Blanchard No. 2	do	do	12	21	29	do	P-403
State No. 1	do	do	14	21	29	do	P-404
State No. 1	do	do	2	21	29	do	P-427
Hastings No. 1	do	do	21	21	29	do	P-453
Blanchard No. 3	do	do	10	21	29	do	P-454
Gypsy No. 1	do	do	19	20	30	Gypsy Oil Co.	P-310
Gypsy No. 2	do	do	16	20	30	do	P-307
Gypsy No. 3	do	do	4	22	30	do	P-308
Gypsy No. 4	do	do	8	22	30	do	P-309
Eldridge	Texas	Loving	22	Block C-26.			P-171

All the private cores described, with the exception of the one from the Eldridge well, came from Eddy County, N. Mex. The location is shown by the shaded area in Figure 1.

MINERALOGY

LIST OF MINERALS

The minerals identified are anhydrite, bloedite, calcite, carnallite, celestite, clay, dolomite, epsomite, glauberite, gypsum, halite, hematite, kainite, kieserite, langbeinite, leonite, lueneburgite, magnesite, opal, polyhalite, pyrite, quartz, and sylvite. Clay is here used as a general term, for no attempt was made to determine the particular species. The calcite, celestite, and opal were recognized only in some of the well cuttings.

Six of these minerals—kainite, kieserite, langbeinite, leonite, lueneburgite, and polyhalite—have their first recorded occurrence in the United States in this field. As stated on page VII the first reported occurrence of sylvite in the United States was in the Markham salt dome in Matagorda County, Tex.

On the basis of their chemical composition, the minerals mentioned above may be grouped as follows:

Chlorides:
    Carnallite (hydrous potassium-magnesium chloride).
    Halite (sodium chloride).
    Sylvite (potassium chloride).
Sulphates:
    Anhydrite (calcium sulphate).
    Bloedite (hydrous sodium-magnesium sulphate).
    Celestite (strontium sulphate).
    Epsomite (hydrous magnesium sulphate).
    Glauberite (sodium-calcium sulphate).
    Gypsum (hydrous calcium sulphate).
    Kieserite (hydrous magnesium sulphate).
    Langbeinite (potassium-magnesium sulphate).
    Leonite (hydrous potassium-magnesium sulphate).
    Lueneburgite (hydrous magnesium phospho-borate).
    Polyhalite (hydrous potassium-calcium-magnesium sulphate).
Chloride-sulphate:
    Kainite (hydrous potassium-magnesium chloride-sulphate).
Other compounds:
    Clays (hydrous aluminum silicate).
    Calcite (calcium carbonate).
    Dolomite (calcium-magnesium carbonate).
    Hematite (iron oxide).
    Magnesite (magnesium carbonate).
    Opal (silicon dioxide and water).
    Pyrite (iron sulphide).
    Quartz (silicon dioxide).

Halite is by far the most abundant mineral, making up at least three-quarters of the saline portion of each core. Anhydrite is next in abundance, and after it come the clays. Polyhalite is next and is by far the most abundant potash mineral, followed by sylvite.

Nearly all the material is compact and massive, though crystalline. Practically all the anhydrite and polyhalite is fine grained, showing no crystal structure to the unaided eye. The halite and sylvite, on the other hand, are coarser grained, some of the uniform cleavage masses measuring as much as 5 centimeters (2 inches) across. A very little of the anhydrite, glauberite, langbeinite, and polyhalite is in crystals readily seen by the eye. The largest anhydrite crystal observed measured 2 centimeters (three-quarters of an inch) across. The largest single crystal of altered langbeinite was 2 centimeters long. Some of the crystals of glauberite and thin prismatic crystals of polyhalite are nearly as long.

There are almost no natural cavities in the specimens studied except for a few small cubical cavities (negative crystals) observed in some of the halite. The outer surface of a few cores has been partially dissolved by the drilling brines, and in some of them it is uncertain whether the cavities observed in the central part of the core were original or produced by these brines. Such partial solution is shown in Plate 3, *A*, for halite, Plate 6, *A*, for carnallite, and Plate 37, *D*, for sylvite.

Anhydrite, clay, halite, hematite, magnesite, and polyhalite are ubiquitous, occurring in varying quantities in all the cores of both groups. The recorded occurrence of all the minerals in these cores is given in the following table. Some of these minerals, especially kieserite and lueneburgite, may be much more widespread in their occurrence than is shown. The cores were examined chiefly for the presence of potassium minerals, and some of the others, present in very small quantities, may easily have escaped detection.

In the 41 cores listed, 18 governmental and 23 private, sylvite was identified in 26, kieserite in 20, carnallite in 13, kainite and langbeinite in 11, leonite in 8, glauberite in 6, gypsum in 4, lueneburgite and quartz in 3, and pyrite in 2.

Occurrence of minerals in cores

Core	Anhydrite	Carnallite	Clay	Glauberite	Gypsum	Halite	Hematite	Kainite	Kieserite	Langbeinite	Leonite	Lueneburgite	Magnesite	Polyhalite	Pyrite	Quartz	Sylvite
Eldridge	X		X			X	X		X				X	X			
McNutt No. 1	X	----	X	----	X	X	X	X	X	X	----	----	X	X	----	----	X
Government No. 1	X	X	X	----	----	X	X	----	X	X	----	----	X	X	----	----	X
Government No. 2	X	X	X	----	----	X	X	X	X	----	----	----	X	X	----	----	X
McNutt No. 2	X	X	X	----	----	X	X	X	X	----	----	----	X	X	----	----	X
Martin Yates No. 1	X	X	X	----	X	X	X	----	X	X	X	----	X	X	----	----	X
Government No. 3	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	----
Joe Mitchell	X	X	X	----	----	X	X	X	X	----	X	----	X	X	----	----	X
Government No. 5	X	----	X	----	----	X	X	X	X	----	----	----	X	X	----	----	X
Gypsy No. 2	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	X
Gypsy No. 3	X	----	X	----	X	X	X	----	----	----	----	----	X	X	----	----	X
Gypsy No. 4	X	----	X	----	----	X	X	X	----	X	X	X	X	X	----	----	X
Gypsy No. 1	X	----	X	----	----	X	X	----	X	----	----	----	X	X	X	X	X
Government No. 4	X	----	X	X	----	X	X	----	----	----	----	----	X	X	----	----	----
Government No. 6	X	----	X	X	----	X	X	----	----	----	----	----	X	X	----	----	X
Government No. 7	X	----	X	X	----	X	X	----	----	----	----	----	X	X	----	----	X
Amy McNutt No. 1	X	X	X	----	----	X	X	----	X	----	----	----	X	X	----	----	X
Dooley No. 1	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	X
Dooley No. 2	X	----	X	----	----	X	X	----	X	----	----	----	X	X	----	----	X
Government No. 8	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	X	X
Martin Yates No. 2	X	X	X	----	----	X	X	X	X	X	X	X	X	X	----	----	----
Kern No. 1	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	X
McGinn	X	----	X	X	----	X	X	----	----	----	----	----	X	X	----	----	X
Ballard No. 1	X	X	X	----	----	X	X	X	X	X	----	----	X	X	----	----	X
Government No. 9	X	----	X	----	----	X	X	----	X	----	----	----	X	X	----	----	X
Government No. 10	X	----	X	----	----	X	X	----	X	----	----	----	X	X	----	----	----
Blanchard No. 1	X	X	X	----	X	X	X	X	X	X	----	----	X	X	----	----	X
Kelly No. 1	X	----	X	----	X	X	X	----	----	----	----	----	X	X	----	----	----
Blanchard No. 2	X	X	X	----	----	X	X	X	X	X	X	----	X	X	----	----	X
State No. 1	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	----
Government No. 11	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	----
Government No. 12	X	X	X	----	----	X	X	----	X	X	----	----	X	X	----	X	X
Government No. 13	X	----	X	----	----	X	X	X	X	X	----	----	X	X	X	----	X
State No. 1	X	----	X	X	----	X	X	----	----	----	----	----	X	X	----	----	----
Government No. 14	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	----
Government No. 15	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	----
Government No. 16	X	----	X	----	----	X	X	----	X	----	----	----	X	X	----	----	----
Hastings No. 1	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	----
Blanchard No. 3	X	----	X	----	----	X	X	----	----	----	----	----	X	X	----	----	X
Government No. 17	X	X	X	----	----	X	X	----	----	----	----	----	X	X	----	----	X
Government No. 18	X	X	X	----	----	X	X	----	----	----	----	----	X	X	----	----	X

ASSOCIATION

Several characteristic associations of different minerals are noted. Much of the entire core is simple in mineral content, consisting essentially of only one mineral, as, for example, halite, polyhalite, or anhydrite. However, other parts are complex mineralogically and show several different combinations of minerals. Some general associations are rather conspicuous. A typical sequence, repeated many times in the same core, begins with a layer of clay at the bottom, grading upward into anhydrite (pl. 3, *B*), on which rests polyhalite (not shown in the illustration). This sequence is followed by halite with a little polyhalite ("blebby salt") scattered all through it, over which comes nearly pure halite. Characteristic pairs of minerals, such as clay and magnesite, polyhalite and anhydrite, halite and sylvite, are very common and naturally suggest genetic relationships, with definite age relations or sequence of formation between the minerals. Some of the minerals occur in sharply defined layers as well as in intimate admixture, and the same two minerals

may show both modes of occurrence on a single specimen only a few inches long. Thus polyhalite occurs in layers in halite (pl. 28, *D*) as well as scattered conspicuously through it (pl. 25).

If the individual sections of cores are regarded as mineral assemblages, each may be assigned for convenience to one of two groups, the sulphates or the chlorides. Accompanying this chemical grouping are a number of other features.

The sulphate group consists of few minerals, essentially anhydrite and polyhalite, and the associations of these minerals are relatively simple. The only chloride mineral present in any great quantity is halite. A very characteristic feature of the generally fine-grained sulphate group is that nearly all its members are distinctly banded, chiefly by the presence of layers of magnesite and to a lesser extent of clay.

The chloride group, composed essentially of halite and sylvite, contains the rarer minerals (carnallite, kainite, langbeinite, and others) in complex mineral association, and many of the minerals themselves are complex in their chemical composition. This group is much coarser grained than the sulphate group and generally shows no banding. Some pieces of core that contain considerable anhydrite exhibit locally a nearly vertical mineralogic structure which suggests that considerable chemical reaction has affected the original structure of the mineral assemblage.

The characteristics of the two groups may be tabulated as follows:

Sulphate group	Chloride group
Banded structure.	No banded structure.
Fine grained.	Coarse grained.
Mineralogically simple.	Mineralogically complex.
Essentially insoluble.	Essentially soluble.
Minerals:	Minerals:
Anhydrite.	Halite.
Polyhalite.	Halite+sylvite.
Anhydrite+polyhalite.	Halite+polyhalite.
Anhydrite+halite.	Halite+anhydrite.
Polyhalite+halite.	Halite+carnallite.
Anhydrite+polyhalite+halite.	Carnallite.
Kieserite.	Kainite.
Magnesite.	Langbeinite.
Glauberite.	Leonite.
	Lueneburgite.
	Sylvite.

Clay is present in both groups, but that in the sulphate group occurs generally in layers or wavy bands, whereas the clay in the chloride group occurs more commonly as irregular masses than it does in layers.

The rarer minerals of either group, such as glauberite and kieserite of the sulphate group and langbeinite, leonite, and others of the chloride group, are seldom found outside of their group and then only in very small quantity. For example, kieserite and magnesite are common in the anhydrite and polyhalite zones but not in the chloride zones.[7] Carnallite, langbeinite, leonite, and other minerals occur commonly with halite and sylvite and only rarely with anhydrite and polyhalite. The occurrence of carnallite in small quantities in anhydrite and polyhalite for a vertical distance of 553 feet in Government hole No. 12 is unusual. The specimens (that is, the sections of core, generally less than a foot in length, as received in Washington) that can not quickly and definitely be placed in one of these two groups are very few.

The association of anhydrite with polyhalite is very common. Many cores that consist essentially of anhydrite are found to contain a little polyhalite. In many specimens these two minerals grade into each other, although others show sharply defined contacts between them. Halite is generally present in quantities ranging from a trace to over 50 per cent, and intergrowths of anhydrite and halite are common.

Both anhydrite and polyhalite are commonly disseminated in small irregular masses through halite. By selecting such a mixture and dissolving out the halite with water, the disseminated sulphate minerals can be frequently obtained in a more or less continuous skeleton.

Bodies of rather dense fine-grained polyhalite or anhydrite in contact with halite may show along their borders a more coarsely crystalline development, expressed as euhedral forms penetrating the halite or inclosed in it, as if the halite had aided the formation of larger crystals.

Clay is commonly associated with fine-grained anhydrite and polyhalite in small seams distributed throughout the cores. As seen on polished surfaces small areas of the fine-grained sulphate minerals have apparently recrystallized, and the clay has been expelled from the area, resulting in more or less concentration of the clay around the borders of the recrystallized material. The clay is invariably magnesitic. Magnesite occurs in the anhydrite and polyhalite in forms similar to those of the clay. Few layers of anhydrite or massive polyhalite as much as an inch thick have been seen which did not contain grains of magnesite scattered through them.

---

[7] Later study in the field of noncommercial sections of the cores and of the shaft of the United States Potash Co. near Carlsbad, N. Mex., has suggested that the occurrence of some of the rarer minerals may be more general than stated. Thus, kieserite is probably as widely disseminated in the chloride group as in the sulphate group.

Bloedite has been observed only as minute particles scattered through halite, although its extremely low birefringence may have prevented its detection elsewhere.

Carnallite was found as seams of the pure mineral as much as 4 inches thick. Above and below it was halite. Carnallite is also found as blebs about the size of a walnut in halite. It occurs as very narrow, nearly vertical seams in clay shale. Small masses of carnallite commonly occur in clay, perhaps because the carnallite is very soluble in water and the solutions can easily migrate along the clay seams. Clay is commonly found near the large blebs of carnallite but is generally restricted to the halite. Sylvite and carnallite are occasionally found together, and where so found one generally greatly predominates over the other. Anhydrite has been observed in close proximity to carnallite, but such an occurrence is not common, except in the core from Government hole No. 12. Carnallite is much less widely distributed through the different cores and at different depths than either polyhalite or sylvite, and in several cores no appreciable quantity was noted.

Glauberite in massive form is associated with polyhalite, halite, anhydrite, and magnesite.

Halite occurs in such abundance that it can be found with every other mineral listed in this report, and little need be said regarding any of its definite mineral associations.

Hematite as a coloring pigment is generally restricted to the potash minerals, being common and abundant in polyhalite, sylvite, carnallite, and leonite and occurring to a lesser and more irregular degree in langbeinite. Kainite is not colored appreciably by the hematite, being of a pale-yellowish color. The nonpotash minerals are usually free from the reddish coloration, with the exception of glauberite, most of which is as deeply colored as the polyhalite and the sylvite. Halite, too, is in places as deeply colored as sylvite, though by far the greatest quantity of halite is colorless. Here and there the anhydrite rock has a pinkish tint, but such rock will be found to contain small quantities of disseminated polyhalite, which color the entire specimen. The formation of the hematite may be connected with bacterial or algal growths. The insoluble residue obtained by dissolving the deeply colored polyhalite in hot water has a stringy structure, and ignition of this residue seems to confirm its organic origin. The relation of such bacterial or algal growths has not been studied.

Kainite, as well as leonite and lueneburgite, where present, is scattered in small masses through the sylvite-halite mixture.

Kieserite is rather widely scattered through the cores but is seldom found in masses of appreciable size. The association of anhydrite and also of polyhalite with kieserite is very common. Kieserite

occurs as small isolated masses distributed throughout the other minerals but is probably more common and abundant in the polyhalite. In some of the pieces of core that are mineralogically more complex, where several different minerals occur throughout a layer of halite, some kieserite is found, but it is less likely to occur in such an association than in that of anhydrite and polyhalite. Kieserite readily takes on water and effloresces to a mixture of more hydrous magnesium sulphates. Though the trend of the efflorescence is toward epsomite, some of the higher hydrates produced have less than the 7 molecules of water required by epsomite.

Langbeinite is found in the mineralogically complex portions of the chloride group, associated with halite, sylvite, and kainite and more rarely with a little polyhalite. In a few cores it constitutes over half the material for a distance of a foot or more, halite being the chief associated mineral. Langbeinite when exposed to moist air effloresces slightly, forming some of the hydrous magnesium sulphates. These sulphates are so fine grained and intermixed that their exact identification is apparently impossible. This efflorescence forms after the core is taken from the well, but it serves as an indication of the possible presence of langbeinite. Some of the individual crystals of langbeinite have altered to an opaque dull-white mass, whereas others have been replaced by kainite.

Leonite has been found only as small blebs in the rather complex sections of the cores of the chloride group. Halite, polyhalite, sylvite, and kainite are associated with it. Small seams and inclusions of clay are scattered throughout much of the associated halite.

Lueneburgite also is restricted in its occurrence to the chloride zones, where it occurs as small blebs surrounded by halite. The associated minerals immediately surrounding lueneburgite but showing no genetic relationships with it are halite, sylvite, clay, and magnesite. (See, however, p. 48.)

Magnesite is universally present in the cores of the sulphate group, usually in minor quantity. A few layers nearly an inch thick were encountered. Every sample of clay tested has been found to contain a carbonate that effervesced only in hot acid. All gradations between almost pure magnesite and almost pure clay can be found. The common associates of magnesite are anhydrite, polyhalite, glauberite, and the clays. Thin light-gray bands of fine-grained magnesite can be seen in nearly every specimen of anhydrite and polyhalite. Where the fine-grained anhydrite or polyhalite has locally recrystallized into coarser material the original bands of magnesite have been broken and the magnesite pushed out around the edges of the coarser material.

Polyhalite belongs with the widespread minerals, occurring in quantity in all the cores. Anhydrite and halite are its most abundant

associates. The rare minerals—carnallite, kainite, langbeinite, leonite, and lueneburgite—are but seldom found with large masses of polyhalite. Small particles of magnesite and less commonly of kieserite are present in nearly all samples of polyhalite where this material is associated with anhydrite. On the other hand, where anhydrite is absent and halite is the chief material associate of the polyhalite (blebby salt), practically no kieserite or magnesite is present.

Sylvite occurs only in the chloride group of cores, associated with halite and considerable clay, irregularly scattered throughout the core. Much of the sylvite-halite mixture is essentially free from other minerals, but it is in this mixture that carnallite, kainite, langbeinite, leonite, and lueneburgite are occasionally found. Associations of carnallite with sylvite and of polyhalite with sylvite are rare.

Many of the mineral associations now present in the deposit, as represented by the pieces of core received by the Geological Survey, suggest that large proportions of these minerals do not represent the primary minerals originally laid down or precipitated in the Permian waters but consist of reaction products formed by the later action of different kinds of solutions on the first minerals that formed. Such reaction products are of different varieties and have been formed by different processes.

The process to which probably the greatest quantity of secondary minerals should be ascribed is the reaction between an already formed mineral and liquors rich in chemicals not present in the original minerals. As an example may be cited the process whereby massive fine-grained anhydrite rock is changed to massive polyhalite rock. There occur also many individual mineral replacements, as already outlined. These changes are usually accompanied by a recrystallization of one of the minerals, which either precedes, occurs simultaneously with, or follows the reactions whereby new minerals are formed. In the recrystallization the main result is a change in size of grain and perfection of single crystal development, such as the formation of secondary euhedral crystals of anhydrite or of polyhalite in a mass of the same mineral. The very wide variations in forms of polyhalite, which in many places occur together, are typical examples of the results of such recrystallization without change of mineral identity.

In some specimens a reaction product has formed along the contact of two minerals, each of which has contributed largely to the composition of the new product. The mineral replacements may have been chemically related, such as the change of anhydrite or kieserite to polyhalite, in which new material has been added to the chemical components of the older mineral. Other mineral replacements, such as the replacement of halite by polyhalite, have

had no common chemical radicle. In the change from gypsum crystals to halite there apparently intervened a stage in which the gypsum was dissolved and removed. The halite then filled in the spaces thus left.

All these reaction products were formed in the presence of solutions that may have been dilute or rich in dissolved minerals. The solutions that changed anhydrite to polyhalite evidently must have been rich in potash and magnesium, else they could not have added these elements to the calcium of the anhydrite. In other reactions there may have been essentially only an interchange of constituents with almost no addition of new mineral matter. Moving water, however, must have been the universal medium in which these changes took place.

Some of the first cores were drilled with water, which dissolved considerable portions of some of the more soluble minerals. Later drilling brines were used, largely solutions of magnesium chloride. On halite, langbeinite, and polyhalite the drilling brines had practically no solvent action, but they did dissolve appreciable quantities of carnallite and sylvite (see pls. 6, A, 37, D) and had a slight solvent action on the kainite pseudomorphous after langbeinite. Depressions on the outside surface of a core may generally be taken as indicative of the presence of either carnallite or sylvite or both.

The small quantity of drilling brine remaining on and partly in the cores probably also accelerated the later formation of thin crusts and efflorescences of secondary minerals on the surfaces of the cores.

In the following descriptions, especially those relating to the commoner minerals, such as halite and anhydrite, the rare and unusual features are emphasized at the expense of the more common ones. The detailed description of the different varieties of halite, for example, belongs more to a geologic report than to the present mineralogic report. It is hoped that the mineralogic descriptions of some of the unusual features, here given, may be of value in deciphering the geologic history of the salt deposit of this region. The genetic sequence of mineral changes is stressed throughout the paper.

To polyhalite is given what may seem to be undue prominence. It has served, however, as a key mineral in demonstrating the large number of mineral changes that have taken place. It is readily identified both in hand specimens and in thin sections, and to judge by its widespread occurrence it seems to have taken part in most of the mineral changes of this field.

ANHYDRITE

Nearly all the cores composed essentially of anhydrite, $CaSO_4$ (CaO, 41. 2; SO_3, 58. 8 per cent), are banded, as shown in Plates 1, 2, and 3. Thin sections show that most of these bands are caused by layers of magnesite. Other bands in the anhydrite rock are due

essentially to clay, which, however, was found to contain magnesite whenever tested.

The four specimens illustrated in Plate 1 show the general character of the anhydrite rock cores as received in Washington. In Government holes Nos. 11 and 13 the anhydrite rock, for a short vertical distance, shows this banding more strikingly developed, as illustrated by the three specimens illustrated in Plate 2. The bands of magnesite are thicker than usual, and their difference in color brings out the structure very well. Plate 3 shows the occurrence of anhydrite with other minerals, resulting in similar banded structure.

The bands or laminations in anhydrite here described are not nearly so perfect or abundant as those shown by Udden[8] in an anhydrite from the Gresham & McAlpine farm, in section 42, block 54, State school land, Culberson County, Tex. (about 22 miles west-northeast of Toyah), at a depth of 2,118 feet, and illustrated in his Plate 7, Figure 1. In thin sections the bands from the Eldridge and Government cores somewhat resemble those shown by Udden in his Plate 10, although the individual crystals forming the bands are not so coarse and consist of magnesite rather than calcite or dolomite.

Particular attention is here called to the banded anhydrite shown in Plates 1, 2 and 3, because a similar banded structure is shown by much of the polyhalite, and this similarity may have genetic significance. Streaks and irregular masses of coarser anhydrite are to be found in the finer-grained mass of anhydrite, and in places isolated crystals, many times as large as the average, are present. The anhydrite crystals embedded in the finer-grained anhydrite matrix show less extensive corrosion than those embedded in fine-grained polyhalite, such as those shown in Figure 2, *d*. Small wisps of fibers of polyhalite or small nests of fine granular polyhalite, though not particularly abundant, are rather widespread throughout some of the fine granular anhydrite, especially the fibers or nests of polyhalite from the Eldridge well. They are discussed beyond, under polyhalite (p. 54).

The specimens that consist chiefly of anhydrite are compact, massive, and fine grained. In thin section many of the crystals of anhydrite show no regular shape, whereas others show a decidedly rectangular outline. (See fig. 2, *a*.) Under higher magnification, even in the finely compacted mass of anhydrite, the individual crystals of anhydrite show a tendency to express their rectangular outlines. This expression is inhibited where other abutting anhydrite crystals are present. Even the larger crystals are thus influenced in their development by the abutting crystals, so that the resultant single large crystal, though optically a single unit, has no definite crystal outline. (See fig. 2, *b*.) Where larger crystals of anhydrite (probably

[8] Udden, J. A., Laminated anhydrite in Texas: Geol. Soc. America Bull., vol. 35, pp. 347–354, June 30, 1924.

a second or later generation) are developed in fine-grained massive polyhalite, they may be perfect (fig. 2, *c*), or else considerably corroded and have a most irregular boundary line (fig. 2, *d*).

Where the anhydrite has developed in crystals larger than those constituting the fine-grained compact granular mass, it may form a single crystal apparently composed of numerous individuals in strictly parallel position (fig. 2, *e*) or of a crystal with steplike edges (fig. 2, *f*) or, more rarely, of fan-shaped groups of radiating crystals (fig. 2, *g*).

The individual crystals of anhydrite differ in size within recognizable limits. Thus most of the individual grains or crystal units range from 0.01 to 0.1 millimeter in diameter. The smallest grains that show approximately rectangular outlines range from 0.01 to 0.02 millimeter in diameter. The average diameter of the moderate-sized grains is about 0.05 millimeter and of the larger grains 0.075 to 0.12 millimeter. Isolated rectangular and irregularly shaped crystals scattered through the anhydrite rock have diameters as long as 0.5 millimeter. Groups of radiating prisms and of individual well-formed crystals have a length as great as 10 millimeters.

FIGURE 2.—Shapes of anhydrite crystals, as observed in thin sections. *a*, Common shape; *b*, common shape with irregular boundaries due to abutting crystals of anhydrite; *c*, perfect crystal embedded in fine-grained polyhalite; *d*, remnant of anhydrite in fine-grained polyhalite; *e*, *f*, larger crystals with steplike boundaries; *g*, fan-shaped group of radiating crystals

The crystals of anhydrite found in association with other minerals are much larger than those forming the massive anhydrite rock. Relatively large crystals of anhydrite are developed in polyhalite, in radiating groups nearly an inch long and approximately vertical. (See pl. 7, A.) Similar crystals are associated with carnallite, others with glauberite, and still others with crystals of polyhalite in halite.

These larger crystals of anhydrite are clear and free from magnesite. In their recrystallization from the fine-grained anhydrite rock they have pushed the magnesite aside, as polyhalite has done.

Similar larger crystals of anhydrite from the German potash deposits have been described by several writers. Kling [9] mentions secondary anhydrite crystals as much as 4 centimeters (1½ inches) in length in the carnallite layer over the tachhydrite region. Engel [10] states that in part the anhydrite rock has been dissolved and recrystallized into well developed crystals. Some of these larger recrystallized anhydrite crystals are well formed and sharply bounded by crystal faces, others are corroded, especially where they are surrounded by fine-grained polyhalite. These occurrences are similar to those of the secondary anhydrite crystals in New Mexico and Texas.

The larger crystals in the cores that are composed chiefly of massive fine-grained anhydrite seem to have developed only as a result of
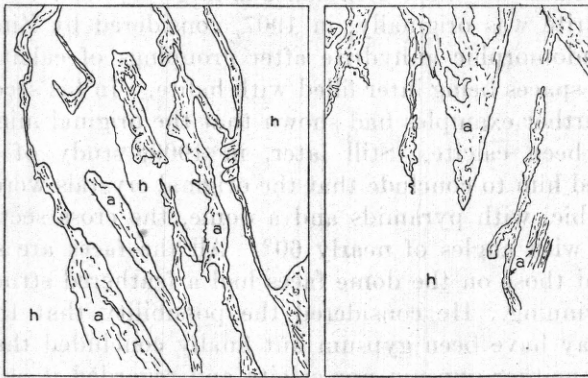
FIGURE 3.—Unusual forms of anhydrite as streaks in halite. a, Anhydrite; h, halite. One-half natural size. Government hole No. 2, at a depth of 837 feet 8 inches.

the secondary reaction and growth that accompanied the formation of certain other minerals. Some of the secondary crystals of anhydrite are perfectly euhedral, bounded by sharply developed crystal faces, and show no corrosion. Some are clear and free from any mineral inclusions; others contain abundant inclusions of specks and small masses of the surrounding mineral, especially of polyhalite. Other larger crystals of anhydrite are deeply corroded and attacked by the matrix. (See p. 19.)

A rather unusual form of association of anhydrite and halite is represented in several cores, especially in that from Government hole No. 2, where the specimen is composed largely of halite that contains more or less parallel as well as divergent streaks of anhydrite. (See fig. 3.) The individual streaks of anhydrite extend in a nearly vertical direction for many inches.

[9] Kling, Paul, Das Tachhydritvorkommen in dem Kalisalzlagerstätten der Mansfelder Mulde (Inaug. Diss.), Halle, 1913.
[10] Engel, Felix, Beitrag zur chemisch-petrographischen Kenntnis der Kalisalzlagerstätte von Salzdetfurth (Inaug. Diss.), Leipzig, 1913.

These structural forms greatly resemble those from Germany described by Zimmerman [11] and called by him pegmatite anhydrite. These intergrowths of anhydrite and halite, according to Zimmerman, consist of a groundmass of anhydrite with many acute cone-shaped forms over 10 centimeters (4 inches) long and partly hollow, which are now composed of anhydrite associated with many parallel bands of anhydrite. Cross sections show 6-sided figures as much as 4 centimeters (1½ inches) across. Much of the cone-shaped figure is now filled with halite. The shape and structure of the cones suggest the common scalenohedron of calcite, grown in skeletal form, with the systems of bands arranged in a rhombohedral skeletal form. The anhydrite masses are fine grained, and the spaces between the cones and bands are filled with halite in large crystals. This pegmatite anhydrite was originally, in 1907, considered by Zimmermann to be pseudomorphic anhydrite after groupings of calcite crystals, the empty spaces being later filled with halite. In his second study, in 1908, further examples had shown that the original mineral could not have been calcite. Still later, in 1909, study of additional material led him to conclude that the original crystals were probably orthorhombic, with pyramids and a dome, the cross sections being hexagonal with angles of nearly 60°. All the faces are striated or ribbed, and those on the dome faces had a feathered structure, suggesting twinning. He considered the possibility that the original mineral may have been gypsum but finally concluded that it could have been neither gypsum nor calcite and regarded it as unknown.

Zimmermann's description of the forms of pegmatite anhydrite shows that his material resembles closely that found in Texas and New Mexico. Similar forms with a hexagonal cross section were found in the core of Government hole No. 2 at a depth of 808 feet 6 inches to 809 feet 7 inches. Some of these hexagonal forms are now halite, and others are anhydrite. No conclusive evidence as to the original mineral can be offered, nor is it certain that such an occurrence truly represents a replacement of some earlier mineral. These intergrowths of anhydrite and halite may be original for these minerals.

Another unusual association is that of a fine-grained contorted anhydrite bordered by one or more layers of coarser crystals which project into the halite and develop a decidedly lacy appearance to the whole specimen. (See fig. 4.) It is rather characteristic to find anhydrite in much larger and more perfect crystals wherever it projects into halite.

Another type of intergrowth of these two minerals presents halite in a peculiar facies. Many of these intergrowths show hexagonal

---

[11] Zimmermann, E., Pegmatitanhydrite: Deutsche geol. Gesell. Zeitschr., Band 59, pp. 136-143, 1907- Deutsche geol. Gesell. Monatsber., 1908, pp. 70-71; 1909, pp. 10-16.

cross sections and seem to be related to those described under halite, for it is the halite and not the anhydrite that shows a definite structural form.

The anhydrite in portions of several cores consists of angular fragments of anhydrite which are cemented by fine-grained anhydrite. Some of these fragments are surrounded by thin seams of halite. In the core from Government hole No. 7 angular pieces of white anhydrite completely surrounded by a thin layer of halite were found in a gray magnesitic clay matrix, as shown in Plate 12, A. This occurrence is also mentioned under halite.

Some rare and unusual forms of anhydrite rock are illustrated in Plate 4. The brecciated variety shown in Plate 4, B, has many concentric lines, which do not appear in the common anhydrite rock shown in Plates 1, 2, and 3. Although this brecciated anhydrite rock was not studied further, it seems to resemble a type of occurrence described by Goldman [12] in his studies of salt-dome cap rock.

Specimens such as those shown in Plate 4, A and B, indicate that the anhydrite has been subjected to movement, but to judge solely by the small quantity of material of this sort in the anhydrite cores received and studied in Washington this is an unusual rather than a common feature of the whole deposit.

The general structural features of the reticulated specimen shown in Plate 4, C, suggest that both halite and polyhalite were introduced

FIGURE 4.—Lacelike intergrowths of halite (h) and anhydrite (a), from Government hole No. 2, at a depth of 950 feet 6 inches

into the anhydrite and magnesite and have replaced them, the halite preceding the polyhalite. The lower part of the specimen consists of massive polyhalite with two irregular areas of (residual ?) halite, one to the extreme left and the other to the extreme right. The reticulated mixture of halite, anhydrite, and magnesite shown in the upper portion of the illustration at first gives the impression of brecciation, which detailed observation fails to confirm.

Many of the thin sections studied show numerous crystals of anhydrite in various stages of alteration to polyhalite. Plate 5 shows three particularly good examples.

[12] Goldman, M. I., Petrography of salt-dome cap rock: Am. Assoc. Petroleum Geologists Bull., vol. 9, No 1, p. 51, 1925. (See figs. 11, 12, 15, and especially 20, A, B.)

In the different cores considerable evidence has been seen of the alteration of anhydrite to polyhalite, both in individual crystals, as shown in Plate 5, and in the massive fine-grained anhydrite rock. This alteration is so intimately connected with the genetic history of polyhalite that its description is deferred to the section on polyhalite.

No examples have been seen which showed conclusive evidence that a complete change of an anhydrite crystal to polyhalite has taken place, but the relations that are sketched in Figure 14 are very suggestive. The character of the fine-grained polyhalite now occupying the space formerly occupied by anhydrite, as shown in Plate 5, is not different from that of the rest of the polyhalite of the core and shows that evidence of the former existence of anhydrite in a completely changed crystal can not easily be recognized.

Some of the larger secondary crystals of anhydrite in polyhalite and halite were freed by dissolving the associated minerals in hot water and were then examined crystallographically. They are usually bounded by the three pinacoids, a (100), b (010), and c (001), the edges between a (100) and c (001) being truncated by narrow dome forms.

Optically the anhydrite shows normal properties. Most of the crystals in thin section show parallel extinction, but where the section has been cut so as to be oriented parallel to the pyramid form the extinction is necessarily inclined, even though anhydrite is orthorhombic. Anhydrite possesses three rectangular cleavages parallel to the three pinacoids a (100), b (010), and c (001). Crushed fragments that lie parallel to one of the cleavages will give parallel extinction. The mineral has a moderate birefringence, so that by means of its indices it can usually be readily identified. A very few of the larger, more nearly perfect crystals of anhydrite, probably secondary, show twinning lamellae on b (010) after r (101), but no twinning has been observed in any of the massive anhydrite. This lack of twinning in nearly all the anhydrite serves to distinguish it from the other minerals, particularly polyhalite, which is commonly complexly twinned. Polyhalite is the only other common saline mineral whose refractive indices and birefringence are near those of anhydrite. But all the indices of anhydrite are higher than 1.568, whereas all the indices of polyhalite are lower. Moreover, anhydrite is optically positive, whereas polyhalite is negative. The average refractive indices of anhydrite, as given in the literature and used in this report, are $\alpha = 1.570$, $\beta = 1.575$, $\gamma = 1.614$. An immersion oil of index 1.570 usually suffices to separate anhydrite from the other saline minerals.

BLOEDITE

Bloedite, $Na_2SO_4.MgSO_4.4H_2O$ (Na_2O, 18.6; MgO, 12.0; SO_3, 47.9; H_2O, 21.5 per cent), was not definitely identified. However, several

thin sections of halite show a very small quantity of a mineral scattered through it in a sort of skeletal form, which from its very low birefringence and low index is deemed to be bloedite. Comparison with known bloedite shows a very similar appearance, and though the mineral so observed can not be definitely determined, its reference to bloedite seems justifiable. It has not been found in polyhalite and seems to be restricted to the chloride group of minerals. The possible occurrence of vanthoffite in Midland County, Tex., is reported by Sellards and Schoch.[13]

CALCITE

Calcite, $CaCO_3$ (CaO, 56.0; CO_2, 44.0 per cent), has not been found in any of the cores from the potash field. However, it has been reported from several well cuttings in this field as fine-grained aggregates with halite and anhydrite and in one sample with glauberite. The exact locality or mode of occurrence of these samples is unknown.

CARNALLITE

Carnallite, $KCl.MgCl_2.6H_2O$ (K, 14.1, equivalent to K_2O, 17.0; Mg, 8.7; Cl, 38.2; H_2O, 39.0 per cent), has been found in cores from Government holes Nos. 1, 2, 12, 17, and 18, and in many of the private cores. It is massive and compact, showing no crystal faces. The individual crystal units, seen in crushed material under the microscope, are small, few of them exceeding a millimeter across. It occurs most abundantly as small specks and blebs, associated with halite and sylvite, but it also forms narrow seams of the pure mineral, some as much as 4 inches thick, in clay and in other parts of the cores. (See pl. 6, A.) It is widespread in Government hole No. 12, in which it is present as stains, specks, blebs, small irregular masses, and short seams through a vertical depth of 553 feet. Here it occurs commonly in the anhydrite and polyhalite, and colors them a reddish brown. It is also present, from 1,335 feet 1 inch to 1,336 feet 6 inches, as disseminated grains in a dark-brown clay with halite; from 1,347 feet 7 inches to 1,351 feet 7 inches it is disseminated through halite as stains, blebs, and veinlets, which color the whole specimen reddish; at 1,348 feet 2 inches anhydrite colored dark reddish brown by carnallite makes a sharp boundary with normal gray anhydrite free from any carnallite.

Some of the irregular masses of carnallite in the core from Government hole No. 12 have a decided vertical extension and in their shape and position resemble the vertical growths of halite in anhydrite, as illustrated in Plates 8, A, B, C, 9, and 10; and described on pages 32–35. These roughly vertical streaks suggest replacement of halite by carnallite, similar to the replacement of vertical halite growths by

[13] Sellards, E. H., and Schoch, E. P., Core drill tests for potash in Midland County, Tex.: Texas Univ. Bull. 2801, p. 166, 1928.

polyhalite described on pages 59–60. Such examples of the replacement of earlier minerals by polyhalite, as shown in Plates 29, 30, *A*, *B*, and 32, *C*, are very similar to parts of the core from Government hole No. 12, in which carnallite is the replacing mineral instead of polyhalite.

In some of the halite from Government hole No. 12 the carnallite forms roughly rectangular masses, as if it had filled in the rectangular cavities (negative crystals) occurring in the halite. Other masses of carnallite in the halite are most irregular in shape.

No definite evidence was seen that carnallite has replaced any of the other minerals, but its occurrence as irregular blebs and streaks in the anhydrite rock in Government hole No. 12 strongly suggests that it has replaced the anhydrite rock. These masses of carnallite in the anhydrite rock occur in much larger crystal units than those of anhydrite and contain numerous inclusions of smaller anhydrite crystals similar to the inclusions of anhydrite in a large polyhalite crystal that is illustrated in Plate 22, *A*, but direct evidence of replacement, such as that observed for many of the other minerals, was not recognized. The general character of the association of carnallite with the other minerals, coupled with its occurrence as small seams cutting through these other minerals, shows that it is of later formation. Carnallite apparently also partly replaces some of the masses and streaks of polyhalite in the anhydrite rock, but direct evidence of such a reaction was not seen. Apparently the development of carnallite in the anhydrite rock is accompanied by the formation of polyhalite, some of which as small crystals is included in the larger masses of carnallite along with included anhydrite.

In the cores from Government holes Nos. 1 and 2 the carnallite is almost colorless, at places with a pale-pink or purplish cast, whereas in that from Government hole No. 12 and in many of the private cores it is dark reddish brown. It is brittle and easily breaks into small pieces with the usual brilliant luster. Its taste is very bitter, and the broken pieces show no cleavage faces. The brilliant luster, bitter taste, and lack of cleavage serve as criteria for its field determination. The mineral readily deliquesces and dissolves in the adsorbed moisture. It is readily soluble in the drilling brine (sodium chloride and magnesium chloride), and much of the carnallite originally in the cores has thus been lost in the drilling operation. Plate 6, *A*, shows how readily the carnallite dissolved in drilling.

Optically carnallite can be readily identified, for it is the only compact massive mineral found in these cores with a strong birefringence [14] that has all of its indices lower than 1.50. Picromerite has a birefringence of only 0.015 and has not yet been identified in any of these

---

[14] According to E. S. Larsen (The microscopic determination of the nonopaque minerals: U. S. Geol. Survey Bull. 679, p. 161, 1921), weak birefringence is less than 0.010, moderate 0.010 to 0.024, strong 0.025 to .099, very strong 0.100 to 0.199, and extreme 0.200 and higher.

cores. Epsomite, with a strong birefringence (0.028) and low indices (all indices lower than a of carnallite), in these cores is always an efflorescence on kieserite or langbeinite and is never massive. Carnallite is optically positive, with a large axial angle, and the indices, as determined, are shown below.

Refractive indices of carnallite

Locality	a	β	γ	B	Determined by—
Government well No. 1, New Mexico	1.465	1.474	1.496	0.031	Schaller.
Spain	1.467	1.472	1.497	.030	Do.
Germany	1.467	1.475	1.494	.028	Busz.
Average	1.467	1.474	1.496		

Crushed fragments are irregular in shape without any cleavage. About half of the crushed fragments show no twinning; the others show sets of twinning lamellae, but here and there a piece is composed largely of fine polysynthetic twinning lamellae, like the plagioclase feldspars. A section normal to an optic axis showed two sets of such twinning lamellae making angles of about 36° with the position of extinction. Other pieces showed different and smaller angles.

A selected pure sample of carnallite from Government hole No. 1 (depth 933 feet 6 inches) was analyzed in the laboratory of the Geological Survey with the following result:

Analysis of carnallite

[J. J. Fahey, analyst]

	Analysis	Ratios
K	14.07	0.360 or 1.01 or 1.
Mg	8.80	0.362 or 1.01 or 1.
Cl	38.32	1.079 or 3.02 or 3.
H_2O	38.38	2.132 or 5.96 or 6.
Insoluble	.04	
Na	Trace.	
Ca, SO_3	None.	
	99.61	

The ratios give the well-established formula $KCl. MgCl_2. 6H_2O$.

Bromine was tested for by E. T. Erickson in over 200 sections of core. Only six samples from Government hole No. 1, all of which contained carnallite, definitely showed the presence of bromine. In all samples, however, the quantities present were less than 0.1 per cent. Tests for iodine showed that if present at all its quantity would be less than 0.005 per cent.

CELESTITE

Celestite, $SrSO_4$ (SrO, 56.4; SO_3, 43.6 per cent), has been found only once. A single crystal 1 millimeter (one twenty-fifth inch) long was identified in a cutting from the Eldridge well, Loving County, Tex., at a depth of 967 feet, associated with halite, anhydrite, and a little polyhalite. The imperfect crystal showed large faces of d (102) with narrow faces of the base c (001). Measured $d:d' = 78° 34'$ (calculated 78° 49'). On fusion before the blowpipe flame, the crystal readily gave the red flame of strontium.

CLAYS

No attempt was made to identify the particular mineral species present in the clays that are so abundant both as masses and as layers in the cores. The clays do not seem to present any unusual mineralogic features except that so far as tested they all contain magnesite in greater or less quantities. Every clay examined, though showing no effervescence with cold acid, effervesced more or less with hot acid. This constant association of magnesite with the clay is a striking feature.

Three differently colored varieties of clay are present—reddish brown, dull greenish, and white or light gray. The colored varieties are generally distinct from one another, though here and there one variety is present as small blebs in another. The varieties have similar relations to the other minerals present and may form distinct layers or occupy thin seams or be present as blebs and irregular masses.

The reddish-brown clay is more abundant than the others, and considerable thicknesses of it have been penetrated in the drilling. The greenish clay appears to be more abundant in the chloride group, but the white and gray variety is usually associated more directly with the anhydrite rock. The white or gray clay is much richer in magnesite than the other varieties and seems to grade in places into nearly pure massive magnesite.

When the greenish variety is separated from the associated salines by water solution and air dried, it appears lighter in color and more grayish. There is a rather constant association of the dull-greenish clay with the reddish-brown saline minerals, such as sylvite and polyhalite. Only relatively small quantities of the brown variety are present with the minerals of the chloride zone. Such a relation suggests that the ferric iron of the brownish clay has been leached out and later precipitated as small plates of hematite in the reddish potash minerals. The iron oxide content of two varieties of these clays was determined as follows:

Percentages of iron oxide in two clay varieties

[E. P. Henderson, analyst]

	Ferric oxide (Fe_2O_3)	Ferrous oxide (FeO)
Reddish-brown clay____	5. 15	0. 96
Greenish-gray clay_____	. 44	1. 14

Though there is no great difference in the content of ferrous oxide in the two clays, there is a marked difference in the content of ferric oxide and of total iron oxide.

Starting with these layers of clay and passing upward in the cores, a more or less regular sequence of minerals may be noticed. At the base is the clay, which gradually becomes richer in anhydrite until layers of nearly pure anhydrite (also containing magnesite) are found, as shown in Plate 3, *B*. Above this anhydrite and either with or without a sharp boundary occurs the polyhalite. Next comes a chloride zone, consisting essentially of halite with a little polyhalite (blebby salt), above which the halite is essentially free from polyhalite. In this chloride zone, if sylvite is present, the mineral combinations commonly become more complex, and the dull-greenish clay is much more abundant than the brownish variety.

The clays in individual mineral sequences differ somewhat in their mode of occurrence. Those in the sulphate zone generally occur in layers, ranging in thickness from 1 millimeter (one twenty-fifth inch) to about 5 centimeters (2 inches). To a much less extent the clay is present as finely disseminated material. In the mineral associations of the chloride group the reverse mode of occurrence is more noticeable, for in this group the clay is much more widely distributed as irregular masses and only rarely forms distinct thin layers. There are, of course, some layers of clay in the chloride group, and some of them are relatively thick, but such layers are not nearly as common as in the sulphate group.

Any clay uniformly distributed as an impurity through the halite would on recrystallization of the halite tend to become segregated into angular and irregularly shaped blebs or aggregates. Anhydrite and polyhalite, on the other hand, have almost no tendency to recrystallize into such coarse-grained material as the halite and other chlorides. Therefore any clay that is expelled from a recrystallizing mass of the sulphate minerals would be moved relatively only short distances, and therefore larger aggregates of clay would rarely form.

The clay encountered in a chloride zone is usually confined to spaces between the individual crystals of halite and does not penetrate the halite itself. On the other hand, if the halite contains

blebs of sylvite, carnallite, leonite, or langbeinite, the clay, though excluded from these blebs, is uniformly distributed throughout the halite.

DOLOMITE

Dolomite, $CaCO_3.MgCO_3$ (MgO, 21.8; CaO, 30.4; CO_2, 47.8 per cent), has not been positively recognized, although it is entirely possible that some of the very fine grained carbonate mineral in these cores is dolomite instead of magnesite. Most of the grains of the carbonate mineral have an ω index of 1.70, though a few grains seem to have an ω index nearer to 1.68 than to 1.70 (the index of magnesite), suggesting the presence of dolomite. If a little ferrous iron replaces part of the magnesium in dolomite, its ω index (1.68) is raised to practically that of magnesite (1.70), so that it is not possible by optical examination alone to prove definitely the absence of dolomite. The samples tested chemically showed very little calcium, owing probably to the admixed anhydrite.

EPSOMITE

Epsomite, $MgSO_4.7H_2O$ (MgO, 16.3; SO_3, 32.5; H_2O, 51.2 per cent), is rather widespread in its occurrence in these cores but only in very small quantity. So far as known, it is not an original native mineral of the salt deposit but has invariably formed, after the cores have been taken, as an efflorescence by the hydration of kieserite and to a lesser extent of langbeinite. Though this secondary efflorescence, developed in the laboratory, may occur on any of the kieserite it is especially prone to develop where the kieserite is associated with polyhalite. This efflorescence of magnesium sulphate is referred to as epsomite, though much of it is composed of lower hydrates than the one that has $7H_2O$. It develops very readily in Washington, the efflorescent growth shown in Plate 6, B, having formed in only a few months. The development of epsomite in the laboratory and in lesser quantity on the cores before they reached Washington was probably greatly accelerated by the action of the magnesium chloride drilling brine.

The swelling of the affected part of the core carries some of all the minerals there present into the efflorescence. This formation of epsomite has also been observed to a lesser degree where the kieserite and langbeinite are in halite. If the specimen is mainly anhydrite, with some kieserite present, there is very little tendency for this hydration to occur. It is very probable that other hydrates of magnesium are mixed with the epsomite, but their separation is practically impossible and their definite identification doubtful. In the magnesium efflorescence from the Eldridge well there were noted some irregular shaped prisms, biaxia', intricately twinned (like some

of the polyhalite), which had the approximate indices $\alpha = 1.475$ and $\gamma = 1.485$, with an estimated birefringence of 0.010 to 0.015. This may be the 5-hydrate, whose indices are $\alpha = 1.482$, $\gamma = 1.493$.

GLAUBERITE

Glauberite, $Na_2SO_4.CaSO_4$ (Na_2O, 22.3; CaO, 20.1; SO_3, 57.6 per cent), has been found in cores from Government hole No. 4, at a depth of 1,736 feet 1 inch; Government hole No. 6, between 639 and 640 feet; Government hole No. 7, at several places between 582 and 785 feet; and three private cores. An exceptionally thick layer of glauberite was found in the Mc-Ginn well between 864 feet and 865 feet 8 inches. This glauberite was colorless, but most of the glauberite found is reddish brown. The associated minerals occurring with glauberite are polyhalite, halite, anhydrite, clay, and magnesite. In Government core No. 7 a zone of glauberite from a depth of 691 feet 11 inches to 692 feet 2 inches has thin bands of anhydrite running through it.

Occurrences of glauberite in the cores are shown in Plate 7.

In State well No. 1, at a depth of 1,232 feet, white glauberite is directly associated with a reddish-brown variety. The white variety shows a decided tendency to crys-

FIGURE 5.—Explanation of minerals shown in Plate 7, A. The checked glauberite (g) in the upper left portion is brown. The solid black areas represent black glauberite. Other minerals are anhydrite (a), halite (h), and polyhalite (p)

tallize, and incomplete crystals, showing a large base, c (001), with faces of s (111) as much as half an inch across, are abundant. These crystal units are closely compacted together, so that only parts of a crystal show any number of freely developed crystal faces. One small fragment, an eighth of an inch across, showed faces of c and s with several intermediate very narrow positive pyramids. One of these, d (447), is new for glauberite. The forms and angles are as follows:

	Measured		Calculated	
	°	′	°	′
c (001) $\wedge$ s (111)	43	08	43	02
c (001) $\wedge$ δ (112)	27	59	27	57
c (001) $\wedge$ d (447)	30	30	30	45
c (001) $\wedge$ ϵ (445)	38	07	38	07

The new form d (447) is associated with δ (112) as narrow striae. A remeasurement of the angle $c \wedge d$ gave 30° 29′.

A second larger colorless and transparent crystal of glauberite, nearly a quarter of an inch long and one-sixteenth of an inch wide, incomplete and bounded in part by a cleavage face of c (001), showed on measurement 18 crystal forms, 6 of which are new.

The forms observed are as follows:

c (001)	k (335)	n ($\bar{1}$11)
a (100)	α (334)	l ($\bar{2}$21)
m (110)	ϵ (445)	x ($\bar{3}$31)
z ($\bar{3}$02)	s (111)	e ($\bar{3}$11)
h (118)	v ($\bar{1}$13)	q ($\bar{9}$56)
i (114)	u ($\bar{1}$12)	o ($\bar{4}$21)

Of these forms h(118), i(114), k(335), l($\bar{2}$21), o($\bar{4}$21), and q($\bar{9}$56) are new for glauberite.

The measured and calculated angles are given in part in the following table of interfacial angles:

Measured and calculated interfacial angles on glauberite from New Mexico

Angle	Measured	Calculated	Angle	Measured	Calculated
a (100) $\wedge$ m (110)	48 29	48 29	c (001) $\wedge$ s (111)	43 03	43 02
a (100) $\wedge$ c (001)	67 52	67 49	c (001) $\wedge$ v ($\bar{1}$13)	24 38	24 39
c (001) $\wedge$ m (110)	75 31	75 31	c (001) $\wedge$ u ($\bar{1}$12)	36 25	36 11
c (001) $\wedge$ z ($\bar{3}$02)	65 47	65 55	c (001) $\wedge$ n ($\bar{1}$11)	61 00	61 00
c (001) $\wedge$ h (118)	7 48	8 26	c (001) $\wedge$ l ($\bar{2}$21)	79 40	79 11
c (001) $\wedge$ i (114)	16 31	15 54	c (001) $\wedge$ x ($\bar{3}$31)	88 56	89 17
c (001) $\wedge$ k (335)	31 57	31 47	m ($\bar{1}$10) $\wedge$ e ($\bar{3}$11)	32 11	32 14
c (001) $\wedge$ a (334)	36 48	36 41	m ($\bar{1}$10) $\wedge$ o ($\bar{4}$21)	22 09	21 35
c (001) $\wedge$ ϵ (445)	38 41	38 07	e ($\bar{3}$11) $\wedge$ o ($\bar{4}$21)	10 02	10 39

The crystal fragment was also measured by the 2-circle method, chiefly for the determination of some very small pyramid faces. The most significant of these measurements for the identification of the rarer and the new forms are given in the following table:

Two-circle measurements of some of the rarer and new forms of glauberite from New Mexico

Forms	Measured		Calculated		Forms	Measured		Calculated	
	ϕ	ρ	ϕ	ρ		ϕ	ρ	ϕ	ρ
h (118)	75 39	28 07	76 10	28 15	e ($\bar{3}$11)	66 01	68 29	66 07	68 30
i (114)	67 11	34 53	67 59	34 25	q ($\bar{9}$56)	48 14	52 04	48 10	52 05
x ($\bar{3}$31)	36 56	75 27	36 59	75 22	o ($\bar{4}$21)	57 18	75 09	57 33	75 22

The forms c (001) and s (111) are by far the largest ones on the crystal fragment. Of intermediate or medium size are a (100),

m (110), n ($\bar{1}$11), and h (118). One face of e ($\bar{3}$11) is very small and triangular, whereas a second face of e forms a line face between a and s. A medium-sized striated face of h (118) lies close to c (001), and i (114) forms a set of broad line faces next to it. On this section of the crystal fragment, between c (001) and s (111), the two forms h (118) and i (114) are the only ones present.

The other forms, except the two new pyramids q ($\bar{9}$56) and o ($\bar{4}$21), are line faces.

It may be noted here that the angles for x ($\bar{3}$31) for glauberite given in Goldschmidt's Winkeltabellen as $\phi = 48° \ 29'$ and $\rho = 72° \ 07'$ are in error. The correct angles for x ($\bar{3}$31) are $\phi = 36° \ 59'$ and $\rho = 75° \ 28'$. The angles given by Goldschmidt are those for the form ($\bar{3}$21), which is not known in glauberite.

The single face of q ($\bar{9}$56) is very minute, lying between e ($\bar{3}$11) and n ($\bar{1}$11) but not zonal with these two forms. Neither is q in the zone e ($\bar{3}$11), a ($\bar{1}$00). The symbols ($\bar{9}$56) are close to the simpler ones ($\bar{9}$66) or ($\bar{3}$22), but the calculated angles are considerably different, and the form could be seen to be definitely not in this zone.

Calculated for ($\bar{9}$66) = ($\bar{3}$22)_____	$\phi = 42°$	56'	$\rho = 54°$ 32'
Calculated for ($\bar{9}$56)_____	$\phi = 48$	10	$\rho = 52$ 05
Measured_____	$\phi = 48$	14	$\rho = 52$ 04

The single face of o ($\bar{4}$21) makes a short line face between e ($\bar{3}$11) and m ($\bar{1}$10), lying in this zone.

On these two fragments 20 crystal forms were identified, 7 of which are new. It seems probable that this horizon would yield crystals of glauberite, showing an unusually rich combination of crystal forms.

Most of the glauberite of the cores, however, is massive and free from any regular crystal outlines. The mineral can be most easily distinguished from the others by its conchoidal fracture and its brittleness. It can not readily be detected by the appearance of the outside surface of the cores, but if the core is split open the properties mentioned make the glauberite mass rather conspicuous. Glauberite has been found in three colors. Reddish brown is the most abundant; next a colorless or white variety; and least common is a peculiar dark, almost black variety. The dark glauberite occurs along the boundaries of some of the thin reddish-brown seams. A thin section including this contact failed to show any appreciable difference between the two varieties, though in the hand specimen the contrast in color is very striking. Glauberite associated with polyhalite was also determined in several of the cuttings from "Texas salt wells," the exact location of which is not known.

Refractive indices of glauberite

Locality	α	β	γ	Determined by
Germany	1.515	1.532	1.536	
Government well No. 7	1.512	1.532	1.535	Henderson.
State well No. 1	1.513	1.533	1.534	Schaller.
New Mexico-Texas salt well	1.513	1.532	1.535	Do.
Average	1.513	1.532	1.535	

No definite evidence was seen that any of the glauberite has replaced the anhydrite rock, but in a section of core from State well No. 1 the arrangement of the included layers of magnesite was very suggestive of such a replacement. In a thin section of a specimen from a depth of 1,230 feet 9 inches, which consists essentially only of glauberite, the layers of magnesite have been concentrated into short streaks and straight bands, whose direction in part follows the outside boundaries of individual crystals of glauberite or some crystallographic direction of the glauberite, such as cleavage. (See fig. 6.) This arrangement is in strong contrast to the occurrence of magnesite in anhydrite rock (pls. 1, 2, 3) or in much of the polyhalite rock (pls. 24, 27, 29, 30, *B*) and to its appearance as shown in thin sections of anhydrite rock, where the magnesite is in nearly horizontal layers (pl. 17, *A*) or in isolated masses scattered irregularly through its host mineral (pl. 18, *A*). The nearly perpendicular arrangement of some of the layers, however, is similar to the same arrangement as seen in some polyhalite (pl. 17, *B*.)

FIGURE 6.—Changed position of layers of magnesite inclusions in glauberite, showing that the glauberite is not an original mineral

Of particular significance is the perpendicular arrangement of the short, disconnected straight layers of magnesite in Figure 6. The two groups of parallel layers of magnesite there appear in different glauberite crystals, differently oriented. Such a perpendicular arrangement of bands of magnesite was not observed in the anhydrite rock and only rarely in the massive polyhalite. The crystals of glauberite are many

times larger than any of the crystals of anhydrite or polyhalite. It is inferred that when banded anhydrite rock was being replaced by glauberite the growing crystals did not assimilate the magnesite but pushed it aside as they grew. The magnesite thus became concentrated along the boundaries of glauberite crystals or was pushed into positions that were oriented with reference to the glauberite, such as cleavage directions.

GYPSUM

Gypsum, $CaSO_4.2H_2O$ (CaO, 32.5; SO_3, 46.6; H_2O, 20.9 per cent), is very rare in the cores received in Washington. It is very abundant in the anhydrite rock above the top of the "salts" (halite and associated salines) but does not occur commonly with the water-soluble saline minerals. A small quantity of it in a red clay was found in the core from Government hole No. 2 at a depth of 809 feet 2 inches. It may possibly have been derived from the overlying beds and therefore may be out of place in the saline series. In the Martin Yates No. 1 well, however, at a depth of 755 feet 3 inches to 756 feet 3 inches, a 1-foot layer of brown, fine-grained, and dull and earthy-looking gypsum lies between anhydrite. A 2-foot layer of coarsely crystalline reddish-brown gypsum, in columnar prisms [15] about one-sixteenth inch thick and one-half to 1 inch long, was also found in another private core, associated with a little halite.

Gypsum is abundantly developed artificially when polyhalite or glauberite is treated with water. Such artificial gypsum is very likely to be present in well cuttings. The gypsum so developed from polyhalite is usually in distinct lath-shaped crystals. R. K. Bailey has noted that the gypsum so developed from glauberite is usually in white fibrous masses, without sharply defined individual crystal outlines.

HALITE

Halite, NaCl (Na, 39.4; Cl, 60.6 per cent), common rock salt, is the predominant mineral of the cores, of which it forms about 75 per cent. It is everywhere massive, compact, or cleavable, and shows no unusual mineralogic features. Nearly all of it is colorless or grayish white, and some of the cleavage pieces, as much as 2 inches across, are perfectly colorless and transparent. A very little of it is reddish brown, and this variety is usually associated with similarly colored sylvite. In several of the private cores specks of blue halite have been found, not over 1 millimeter thick, associated with reddish and colorless halite and reddish sylvite. The halite in parts of the cores

---

[15] All the gypsum observed in the sections of core sent to Washington is compact and fibrous, showing no individual crystal form, and is identical in character with the gypsum in the veins in anhydrite rock above the "salts," as shown by material from the shaft of the United States Potash Co. near Carlsbad, N. Mex., and by similar core material from beds above the "salts" in the Eldridge well. No unchanged individual gypsum crystals comparable in shape or size to the forms shown in Plates 8, 9, and 10, have been observed in any of the cores or material from the shaft of the United States Potash Co.

is colored pink of various shades by varying quantities of fine-grained disseminated polyhalite.

Negative crystals (cavities) of rectangular shape have frequently been observed, and some of these cavities are partly filled with a liquid. On several occasions, when a core of halite was broken open, it was found to be damp.

In many of the hand specimens it appears that halite may have replaced both anhydrite and polyhalite. There are rather thick layers or seams of halite that contain rounded masses of both anhydrite and polyhalite. These masses become smaller as their distance from the top or bottom of such a layer increases. However, the criteria that suggest this type of replacement are not very definite, and thin sections of such material have failed to show any conclusive genetic relation. The opposite relation, polyhalite replacing halite, is much more easily proved. (See pl. 23.)

Some masses of halite are so full of fine-grained disseminated anhydrite or polyhalite that they have little resemblance to halite, except for the cubical cleavage. The general relations found in the halite zone suggest that this zone has been recrystallized since its formation. The clay has been segregated into angular inclusions which are characteristic of the coarse crystalline halite or sylvinite layers. The dull-greenish or light-gray clay commonly occurs with the reddish sylvite. This association suggests that the clay has been leached by potash-bearing brines. (See p. 24.) The colorless sylvite is considered to be older than the reddish variety, because polished surfaces of cores display sylvite grains in which reddish borders surround colorless centers. (See pls. 37, B, 38.) Carnallite occurs in some layers of halite and is the only potash mineral present in some of them. Its color is usually reddish brown, whereas the halite adjoining the blebs of carnallite is colorless.

FIGURE 7.—Outlines presented by crystals of gypsum, bounded by the commonest of the simple terminal forms for comparison with halite in anhydrite-halite intergrowths. *a*, Terminal form *l* (111); *b*, terminal form *n* (Ī11); *c*, terminal form *e* (Ī03); *d*, twinned crystal, terminal form *l* (111); *e*, twinned crystal, terminal form *n* (Ī11); *f*, twinned crystal, terminal form *e* (Ī03); *g*, horizontal cross section of crystal of gypsum, showing derivation of hexagonal shape of halite as shown in Plate 8, *D*, *b* (010), *m* (110)

Intergrowths of halite and anhydrite, in which the halite has a form unusual for that mineral, have already been mentioned. (See p. 19.) They are shown in Plates 8, 9, and 10.

In shape these elongated, nearly vertical masses of halite strongly resemble crystals of gypsum, in both the simple and the apparently

twinned form, the latter suggesting the swallowtail type of twin gypsum crystals.

The most distinct and regular individuals were measured with reference to the angular values of their bounding lines.

The commonest simple terminal faces of gypsum crystals are l (111), the positive unit pyramid; n ($\bar{1}11$), the negative unit pyramid; and e ($\bar{1}03$), a negative dome. As viewed in sections parallel to the plane of symmetery, the clinopinacoid b (010), which is also the cleavage direction in gypsum, these common terminal faces would present the shapes shown in Figure 7, a, b, c. Many of the elongated masses of halite (pls. 8, C; 9) present shapes agreeing with these forms. The outlines presented by similar forms of gypsum; when twinned and viewed on the clinopinacoid, are shown in Figure 7, d, e, and f. Many of the masses of halite observed likewise agree in form with the outlines of twinned gypsum crystals.

Measurements of the angles of the terminal planes on the masses of halite in these cores have no absolute value, because the bounding lines are so short and irregular that accurate results can not be obtained. Moreover, there is no way of knowing the orientation of each particular mass of halite to the surface of the core. But the averages of the measurements obtained are compared below with the angles of gypsum crystals.

Average of measurements of angles on masses of halite in potash cores compared with the corresponding angles of crystals of gypsum

	Average measured	Gypsum	
	°	°	′
Elongation $\wedge$ l (111), fig. 7, a	50	52	25
Elongation $\wedge$ n ($\bar{1}11$), fig. 7, b	64	66	10
Elongation $\wedge$ e ($\bar{1}03$), fig. 7, c	91	87	49
$l \wedge l$, twin, fig. 7, d	111	104	50
$n \wedge n$, twin, fig. 7, e	129	132	19
$e \wedge e$, twin, fig. 7, f	Nearly 180.	175	38
Sections normal to elongation:			
$m \wedge m'''$, fig. 7, g	68	68	30
$b \wedge m$, fig. 7, g	54	55	45

In spite of the wide divergence shown by measurements of the edges of individual masses of halite the average is close enough to the angles for gypsum to suggest strongly that the shapes now shown by the halite are those of gypsum. The resemblances in form already noted further substantiate this suggestion.

Most of the sections of the masses of halite, at right angles to the elongation and parallel to the layers of magnesite in the anhydrite rock, show a very irregular outline, but some have a distinct 6-sided outline (pl. 8, D), and in a few the edges are straight enough to be measured under the microscope, and their angles agree very closely with the angles of gypsum in the prism zone. The shape of these

masses of halite obviously bears no relation to the crystal form of halite and must therefore be referred to another mineral. Several thin sections of these anhydrite-halite intergrowths have been carefully examined for residual traces of a preexisting mineral, but none could be seen. Gypsum would be a logical mineral to form in an anhydrite mass, and until more evidence is found the original mineral is considered to have been gypsum. These masses of halite break through and interrupt many of the layers of magnesite and are therefore considered to be later in formation. Very likely these crystals of gypsum grew in the anhydrite rock, banded with layers of magnesite, before consolidation and while it was still in a mushy condition. After the crystals of gypsum had formed, the anhydrite rock inclosing them became firm.

A rather remarkable feature is that much of the halite that has taken on the form of gypsum is uniformly oriented, as shown by the cleavage. (See pl. 8, D.) The original gypsum crystals were not uniformly oriented, though they approached a nearly vertical direction in their elongation. From this relation, together with the fact that no residual traces of gypsum or of other preexisting minerals are present in the halite, it is inferred that the gypsum was probably dissolved away, leaving crystal cavities which later became filled with halite. The halite, then, would be an infiltration pseudomorph after gypsum rather than a replacement pseudomorph. In thin section the boundaries between the halite and the anhydrite are most irregular and commonly contain much recrystallized anhydrite, in larger and better developed crystals. Some of the halite contains more or less included anhydrite. (See pl. 10.)

Unusually large and well-developed growths of halite of this character are present in the Yates No. 1 well, two sides of a section of core from which are shown in Plate 9, A and B. Several well-formed examples of the swallowtail type of twinning are present. Not only are the masses of halite unusually large and show the twinned character of the upper termination very well, but they also show the radiated character of the groups even better than is shown in Plate 8, B.

These masses of halite, unlike those shown in Plate 8, are bordered by a lacelike fringe of anhydrite, similar in character but slightly coarser than the lacelike anhydrite described on page 18 and illustrated in Figure 4. At places there is a very narrow seam of halite between the massive anhydrite rock and the fringe of coarser anhydrite, which is almost free of any anhydrite. This thin seam of halite shows up much better in A than in B, Plate 9.

The lacelike fringes of anhydrite bordering the masses of halite, thought to be pseudomorphous after crystals of gypsum, raise doubts as to whether all these pseudomorphs of halite after gypsum are infiltration pseudomorphs. Such occurrences as shown in Plate 9

are more suggestive of replacement pseudomorphs, the fringes of anhydrite being formed from the preexisting gypsum by the dehydrating action of the replacing sodium chloride.

A section of the core from Government hole No. 20 recently received, shown in Plate 10, is even more suggestive of a replacement rather than an infiltration pseudomorphic change of halite after gypsum.

The longest observed vertical growth of halite, simulating and probably pseudomorphous after gypsum, in the anhydrite rock, is $5\frac{1}{2}$ inches long and nearly an inch across. It is shown to the right in Plate 10. On the left of the specimen shown in Plate 10 is the end of the right arm of a swallowtail twin that measures 2 inches across horizontally and $5\frac{1}{4}$ inches long and is the largest example of this type of twinning structure seen in specimens from this field.

The banded character of the anhydrite rock forming the matrix of the halite masses is due to alternating variation in the quantity of halite present and is an additional example of banding due to such alternations of anhydrite and of halite, as has been shown in Plate 3, A. The nearly solid gray bands in Plate 10 are due to anhydrite; the mottled bands are due to a mixture of halite with varying quantities of included anhydrite.

These bands, where there are no vertical halite growths, are nearly horizontal, as can be seen at the very top of the specimen (pl. 10) and in the lower center. But they curve upward to a considerable degree on both sides of the long vertical halite growth and similarly around the right arm of the swallowtail twin shown on the left.

Considerable discontinuous portions of the solid gray bands consisting essentially of anhydrite are inclosed in the halite masses. It can readily be seen that these discontinuous portions in the halite are parts of the bands in the anyhdrite rock and show that the formation of the original mineral (probably gypsum), after which the halite is pseudomorphous, took place subsequently to the formation of the banded anhydrite rock but probably before it reached its present state of compactness.

Similar structures on a smaller scale are shown in the bottom of the specimen. The presence of the discontinuous portions of the bands of anhydrite rock in the halite, some of them apparently completely surrounded by the halite, does not favor the idea that the halite is an infiltration pseudomorph after gypsum, as previously suggested for the occurrences illustrated in Plate 8. It may well be, however, that both types of pseudomorphism—namely, infiltration and replacement—have occurred.

These anhydrite-halite intergrowths have a remarkable resemblance to graphic granite in the elongation of the inclosed mineral, the

six-sided cross section of the masses of halite, and the uniform orientation of the inclosed halite.

These masses of halite, upon the advent of the potash brines, became very susceptible to replacement by polyhalite, and in many of these cores this process is represented from beginning stages (pl. 29, *A*) to almost complete replacement (pl. 29, *B, C, D*).

The typical vertical section with a narrow layer of clay at the bottom followed by massive anhydrite rock with or without polyhalite above, as already described, is well illustrated by the following sections from three private wells. All three contain typical sections of anhydrite with the vertical growths of halite, as illustrated in Plates 8, 9, and 10, which uniformly lie just above the massive anhydrite. The section from the Blanchard No. 1 well is free from any polyhalite, and that from the Kelly No. 1 well contains only a little, but that from the Blanchard No. 2 well contains considerable.

Vertical sections from three private wells showing uniform position of anhydrite with vertical growths of halite

[Figures indicate thickness]

Minerals	Blanchard No. 1		Kelly No. 1		Blanchard No. 2	
	Ft.	*in.*	*Ft.*	*in.*	*Ft.*	*in.*
Halite	10+		(?)			
Halite with little disseminated polyhalite			(?)		8+	
Essentially polyhalite with little anhydrite			(?)		2	3
Anhydrite with vertical growths of halite which are largely replaced by polyhalite				7		
Anhydrite with vertical growths of halite	6	6	1	9	2	9
Anhydrite	1	6	5		3	10
Clay		3		3		4
Depth of bottom of clay	1,006	3	727		856	

The formation of these gypsum crystals, of which only the inherited form (pls. 8, 9, 10) is now left, must have been due to unusual causes. If it were mere hydration of the anhydrite then the gypsum crystals should have formed in the anhydrite immediately above the 3-inch basal layer of clay. But, as shown in the table above, there is in the Kelly No. 1 and Blanchard No. 2 wells about 5 feet of anhydrite practically free from these forms inherited from pre-existing crystals of gypsum.

Could these gypsum crystals have been derived from the decomposition of earlier polyhalite? Laboratory experiments have shown that polyhalite is decomposed by water; all the potassium and magnesium and part of the calcium going into solution, the remaining calcium crystallizing out as gypsum. If a body of polyhalite had been attacked by brines sufficiently dilute to decompose it a considerable quantity of crystals of gypsum would have accumulated, which by uniting and recrystallizing may have formed, in the anhydrite rock, the crystals whose outlines and shapes are now preserved by halite.

Definite evidence of the replacement of anhydrite by halite is shown in Plate 11, *A*, and of glauberite by halite in Plate 11, *B*.

In Plate 12, *A*, fragments of anhydrite are shown surrounded by halite in a highly magnesitic clay groundmass. The fragments of anhydrite are angular and resemble brecciated pieces deposited in a clay rich in magnesite. The surrounding halite may have been squeezed out of the clay by compaction and may thus have found its way around the fragments of anhydrite. Much of the anhydrite was attacked and partly replaced by halite, and nearly every one of the smaller blebs of halite, in the clay, contains either a residual speck of anhydrite, or, as seen in thin section, contains a small quantity of disseminated grains of anhydrite. But in a few blebs of halite no anhydrite can be seen. The halite may be a much later introduction; it may have permeated through the anhydrite-clay mixture and thus become deposited around the boundaries of the fragments of anhydrite.

Where the halite growths in anhydrite show a rough crystal outline the tendency for them to be in a vertical position is very pronounced. Distinct fracture fillings by halite are also clearly vertical. (See pl. 7, *B*.) On the other hand, where small masses of halite occur in either anhydrite or polyhalite, and where they show no suggestion of any crystal outline but have a lenslike shape they tend to lie horizontally, many of such lenslike masses extending an inch or two in length with a vertical thickness of an eighth to half an inch.

Small fibrous veins of halite are developed in some cores, especially where much clay is present. The fibrous character of the halite, much of which is pink or reddish, is rather unusual.

HEMATITE

Hematite, Fe_2O_3 (Fe, 69.9; O, 30.1 per cent), occurs as plates of microscopic size disseminated through many of these saline minerals. Most of these plates have a hexagonal outline, others are rounded or slightly elliptical, and a few are rodlike. The average maximum size of the platy crystals is about 0.005 millimeter; the rods average about 0.02 millimeter in length.

The hematite, other than that in the clays, is largely confined to the potassium minerals, and the rather constant association of this reddish-brown pigment with the potassium minerals in one of the most striking features of the deposit. Most of the polyhalite is colored, and the variations in color (pink, reddish brown, and brown) are due to varying quantities of hematite. Sylvite does not exhibit such a range of colors, but most of it is either reddish brown or colorless. Much of the carnallite, glauberite, leonite, and langbeinite is colored by hematite, but some of these minerals are as generally colored as either polyhalite or sylvite. Some of the halite is as deep reddish

brown as the sylvite, but most of the halite is free from color. Very little of the anhydrite is colored by hematite, and that only in the immediate vicinity of colored polyhalite.

Hematite did not form from the solutions which precipitated anhydrite and halite, but as the brines became richer in potassium they also apparently became enriched in iron. If the hematite is the result of bacteriologic action, then the potassium brines were a more favorable medium for bacterial growth than the brines that contain only very minor quantities of potassium.

KAINITE

Kainite, $KCl.MgSO_4.3H_2O$ (K, 15.7; MgO, 16.1; Cl, 14.3; SO_3, 32.1; H_2O, 21.8 per cent), has been identified in two Government cores and in nine private cores. In one Government core it occurs from a depth of 1,430 to 1,432 feet, and in another from a depth of 1,366 to 1,371 feet and 1,495 to 1,499 feet. It is massive, with a poorly developed fibrous fracture surface, and has a characteristic honey-yellow color with a rather dull or slightly greasy luster. In this section (pl. 12, B) it shows a columnar or coarse fibrous structure, similar to the appearance of a broken surface when examined by a hand lens.

FIGURE 8.—Kainite between sylvite and langbeinite

Optically it resembles carnallite, and its moderate birefringence (0.021) gives the crushed fragments brilliant interference colors, though it shows evidence of cleavage, which is lacking in carnallite. Crushed fragments show a conchoidal fracture with concentric ribs. The mineral is optically negative, with an axial angle ($2V$) of nearly 90°, as the bar shown on sections normal to an optic axis remains nearly straight. All its indices are higher than 1.490, which serves at once to separate it from carnallite. The refractive indices determined are as follows:

Refractive indices of kainite

Locality	a	β	γ	B	Determined by
Government No. 13, New Mexico	1.493	1.504	1.515	0.022	Schaller.
McNutt No. 1, New Mexico	1.492	1.505	1.517	.027	Henderson.
Stassfurt, Germany	1.495	1.505	1.515	.020	Schaller.
Do	1.494	1.505	1.516	.022	Larsen.
Do	1.495	1.506	1.520	.025	Busz.
Do	1.493	1.504	1.515	.022	Henderson.
Average	1.494	1.505	1.516	.022	

Repeated determinations of γ failed to yield an index as high as 1.520, as given by Busz, and this figure, quoted by Goergey, is, as stated by Larsen, not consistent, for from Busz's results the mineral would be positive, whereas it has been definitely observed many times, on sections normal to an optic axis, that the mineral is negative. Many pieces from the McNutt No. 1 well suggest most irregular penetration twins, the extinction of the two parts being about 40° apart.

An analysis of selected material, probably not quite pure, from the McNutt No. 1 well, made in the laboratory of the Geological Survey, gave the following results:

Analysis of kainite from Eddy County, N. Mex.

[J. J. Fahey, analyst]

	Analysis	Ratios	
K	13.30	0.340	0.93
Na	1.03	.024	
MgO	16.72	.415	1.06
Cl	13.51	.381	.98
SO₃	32.50	.406	1.04
H₂O	20.95	1.164	2.98
Insoluble	1.74		
	99.75		

Iron, aluminum, and calcium were absent in the water-soluble portion analyzed. The ratios indicate the well-established formula $KCl.MgSO_4.3H_2O$.

A thin section from the Gypsy No. 4 well at a depth of 933 feet 11 inches, shows a narrow band of kainite between sylvite and langbeinite, the columnar structure of the kainite being normal to its contact with the other two minerals, as shown in Figure 8. Its position strongly suggests that it may be a secondary mineral, a reaction product between sylvite and langbeinite, possible reactions being as follows:

$$\underset{\text{Sylvite}}{KCl} + \underset{\text{Langbeinite}}{K_2SO_4.2MgSO_4} + nH_2O = \underset{\text{Kainite}}{MgSO_4.KCl.3H_2O} +$$
$$\underset{\text{Picromerite}}{K_2SO_4.MgSO_4.6H_2O}$$

$$\underset{\text{Sylvite}}{2KCl} + \underset{\text{Langbeinite}}{K_2SO_4.2MgSO_4} + nH_2O = 2(\underset{\text{Kainite}}{MgSO_4.KCl.3H_2O}) + K_2SO_4$$
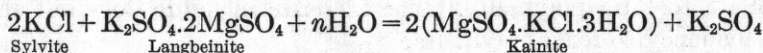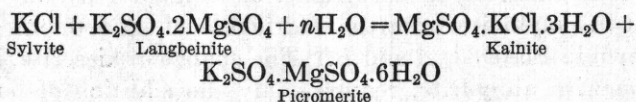
If the second reaction takes place, the excess of K_2SO_4 may search out calcium and magnesium sulphate to combine to form polyhalite, some of which is present in the slide. The first reaction would yield picromerite as well as kainite, but no picromerite has been observed in any of the cores, although careful search has been made for it.

Kainite also occurs as pseudomorphs after langbeinite (see p. 41) in Government core No. 13 at a depth of 1,700 feet 8 inches to 1,702 feet 4 inches.

KIESERITE

Kieserite, $MgSO_4.H_2O$ (MgO, 29.0; SO_3, 58.0; H_2O, 13.0 per cent), is rather widespread in its occurrence and is found in 20 of the cores examined, but nowhere in any quantity. The most abundant occurrence noted was in Government hole No. 1, where a seam about an inch thick lies at a depth of 1,177 feet. It is pure white, has a vitreous luster, and is associated with nearly all the saline minerals, chiefly with polyhalite, anhydrite, and halite. It forms compact granular fine-grained masses, the individual crystals of which are very small and generally rounded. Occurrences of kieserite in the cores are shown in Plate 33.

As seen in thin sections and in crushed fragments immersed in oil, kieserite is readily identified by its very high birefringence (0.065), which is much higher than that of any other mineral found in these cores except magnesite.

A characteristic structure of kieserite is its twinning, which may be simple, composed of two units, or complex or repeated, consisting of many individuals in twin position. (See pl. 13, *A*.) Twinning lamellae, both simple and multiple, are common. Several such twins, as observed under the microscope, are shown diagrammatically in Figure 9.
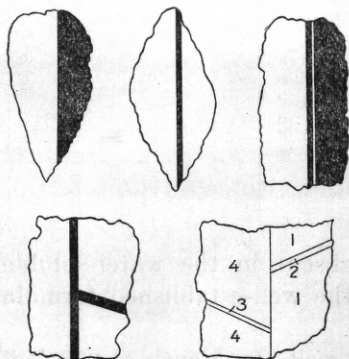
FIGURE 9.—Common twinning structure in kieserite crystals, as observed under the microscope

Kieserite has been partly replaced by leonite (see p. 45), and material from the Eldridge well presents evidence that kieserite has been partly replaced by fine-grained polyhalite (pl. 13, *B*), but in most of its occurrences definite evidence of its reactions with other minerals is lacking. The occurrence of isolated residual kieserite embedded in polyhalite from the Eldridge well, at a depth of 1,125 feet is shown in Plate 33, *A* and *B*. The change of kieserite, in direct association with anhydrite, requires only the addition of potassium sulphate to form polyhalite. The kieserite in halite does not show any tendency to form polyhalite.

Lueck [16] measured $2V = 55°$, noted occasional twinning after (111), and determined that the combined water is given off at 390°. He considers the fine-grained kieserite pseudomorphous after sylvite.

[16] Lueck, Hugo, Beitrag zur Kenntniss der älteren Salzgeberger (Inaug. Diss.), 32 pp., Leipzig, 1913.

Refractive indices of kieserite

Locality	α	β	γ	Determined by
Martin Yates No. 2 well, New Mexico	1.520	Not determined.	1.582	Henderson.
Hallstadt	1.523	1.535	1.586	Goergey.
Stassfurt	1.518	1.531	1.583	Lueck.
Average	1.520	1.533	1.584	

LANGBEINITE

Langbeinite, $K_2SO_4.2MgSO_4$ (K_2O, 22.7; MgO, 19.5; SO_3, 57.8 per cent), was observed in 11 cores, both in massive granular form (pl. 14, *A*, *B*) and in distinct tetrahedral crystals showing a triangular outline on the core surfaces (pl. 14, *C*, *D*). Some of the crystals are as large as those of any of the other minerals in this field, reaching a maximum size of 2 centimeters (three-quarters of an inch.) Langbeinite is associated with halite and sylvite and generally with a little kieserite. Some specimens, several feet in length, consist essentially of langbeinite and halite. In the McNutt No. 1 well at a depth of 1,430 feet to 1,431 feet 6 inches, where small masses of kainite are present, langbeinite forms perhaps three-quarters of the core for a vertical length of nearly 1½ feet, and in the Gypsy No. 4 well at a depth of 925 feet 10 inches to 930 feet 1 inch langbeinite forms two-thirds of the core. In Government hole No. 17 an 11-inch section from a depth of 2,523 feet 10 inches to 2,524 feet 9 inches contained 20.63 per cent of K_2O, indicating 90.9 per cent of langbeinite.

Langbeinite is not very soluble in the drilling brine but is attacked by it, yielding a dull-white coating or slight efflorescence, similar to that produced by kieserite. This coating on the outside surface of many halite cores indicates the presence of langbeinite. Langbeinite is much more slowly soluble in cold water than either halite or sylvite, and much of the langbeinite present can be recovered by quickly dissolving out the chloride minerals.

Some massive colorless varieties resemble granular quartz in their lack of color, transparency, and glassy luster. Most of the langbeinite, however, has a distinctive pink color. It is the "hardest looking" of the saline minerals and has a conchoidal or irregular fracture with no cleavage. The general appearance of the massive mineral is shown in Plate 14, *A* and *B*.

In the core from Government hole No. 13, at a depth of 1,700 feet 8 inches to 1,702 feet 4 inches, the tetrahedral crystals of langbeinite have been altered to kainite. The changed crystals are simple tetrahedra and consequently show a triangular outline on the surface of the specimen. Where they occur on the outside surface of the core

the drilling brine has dissolved the kainite to a depth of an eighth of an inch, the triangular depressions being rather striking, as langbeinite itself is not appreciably dissolved away by the drilling brine. The kainite of these pseudomorphs is fine grained, compact, and of a straw color and waxy luster. It does not show the characteristic fibrous or columnar structure so typical of most of the kainite. A few small residual masses of the glassy langbeinite are still embedded in the kainite. The altered crystals are comparable in size to those shown in Plate 14, C, being on the average almost half an inch across.

The core from Government hole No. 16 at a depth of 433 to 441 feet consists mostly of halite, with a little brown clay, a little polyhalite, and considerable white kieserite. Some of the kieserite aggregates have a distinct tetrahedral outline, not as sharp as those of kainite just described, but still sufficiently distinct to suggest that this kieserite is pseudomorphous after langbeinite.

Both these changes of langbeinite are chemically simple. The change to kieserite is simply a removal of the potassium sulphate:
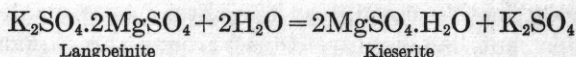
$$K_2SO_4.2MgSO_4 + 2H_2O = 2MgSO_4.H_2O + K_2SO_4$$
$$\text{Langbeinite} \qquad\qquad\qquad \text{Kieserite}$$

Although a careful search was made for arcanite (K_2SO_4) or aphthitalite ($(K,Na)_2SO_4$), none was found. The potassium sulphate, however, may have been fixed in the associated polyhalite.

The change of langbeinite to kainite is essentially an interchange of part of the sulphate radicle to the chloride radicle, with the addition of water. The change can be illustrated as follows:

Langbeinite_____ $K_2|SO_4|.2MgSO_4$

Kainite_____ $K_2|Cl_2|.2MgSO_4.6H_2O$
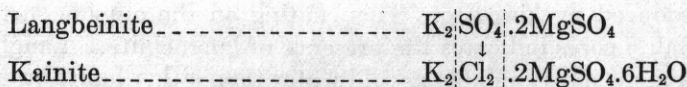
At another place in the core from a Government hole the relations suggest that langbeinite has replaced halite.

A specimen of core from the Blanchard No. 1 well contains several partly altered crystals of langbeinite, whose triangular outline shows that the crystals are simple tetrahedra. The centers of some of the crystals are still langbeinite, fresh and glassy, surrounded by borders of dull-white alteration products, which are described briefly below. (See pl. 14, C.) The largest observed tetrahedral crystal is shown in Plate 14, D. Similar tetrahedral crystals with triangular outline, from Germany, have been illustrated by Fulda.[17]

Optically langbeinite is isotropic, with a refractive index of 1.533, just a little below that of halite, from which it can also be distinguished, both in the hand specimen and under the microscope, by

---

[17] Fulda, Ernst, Das Kali, vol. 2, p. 67, fig. 20, 1928.

the absence of any cleavage. The absence of the salty taste of halite also helps to differentiate it, for langbeinite is practically tasteless. The refractive index is averaged from the following three determinations:

Refractive index of langbeinite

Locality	n	Determined by—
Eddy County, N. Mex.	1.532	Schaller.
Germany	1.533	Luedecks, quoted by Goergey.
Do.	1.535	Goergey.
Average	1.533	

In a thin section that contains langbeinite from one of the private cores the relations strongly suggest that this mineral is younger than sylvite and has replaced it. An elongated, rounded tongue of langbeinite is surrounded by·sylvite, the cleavages of which are similarly oriented on both sides of the tongue. A thin zone of red coloration follows the contact but is confined to the sylvite. Considerable polyhalite, some in relatively coarse crystals, is present.

Langbeinite from the McNutt well, carefully purified by the use of heavy solutions, has been analyzed in the laboratory of the Geological Survey with the following results:

Analysis of langbeinite

[J. J. Fahey, analyst]

	Analysis	Ratios	
K_2O	22.37	0.2371	1.02 or 1
Na_2O	.48	.0077	
MgO	19.15	.4749	1.98 or 2
SO_3	57.44	.7180	3.00 or 3
Loss on ignition	.25		
Insoluble in water	.05		
Cl, Ca	0		
	99.74		
Specific gravity	2.858		

The ratios correspond closely with the well-established formula $K_2SO_4.2MgSO_4$.

The white powdery alteration product, when examined microscopically, is seen to be a mixture of fine-grained material with a few distinct prismatic crystals, all of which have a mean index higher than 1.49 and lower than 1.52. None of these substances could be definitely determined optically. Epsomite and picromerite are excluded, but the material may represent a lower hydrate of magnesium sulphate, or a mixture of several such lower hydrates. Aphthitalite also may possibly be present. According to chemical tests, the mixture is composed largely of magnesium sulphate but contains a little potash.

Pseudomorphs of picromerite and epsomite after langbeinite have been described [18] from salt deposits in the Alps. The alteration products of langbeinite from the New Mexico and Texas potash fields have too high refractive indices to be referred to picromerite, all of whose refractive indices are lower than 1.48.

Minute six-sided crystals appear in some of the langbeinite. Their index is lower than that of langbeinite; they have a moderate birefringence and may be loeweite. Engle [19] mentions such inclusions of hexagonal crystals of loeweite in langbeinite (from Germany), and in some places these in turn contain small inclusions of langbeinite.

LEONITE

Leonite, $K_2O.MgO.2SO_3.4H_2O$ (K_2O, 25.7; MgO, 11.0; SO_3, 43.7; H_2O, 19.6 per cent), has been identified in the cores from seven private wells, in which it occurs with kainite, polyhalite, halite, sylvite, and possibly langbeinite, and in Government core No. 17. Its total quantity is very small, because it forms only small masses, seams, and specks intimately mixed with the other minerals. In the Joe Mitchell well at a depth of 1,368 feet pale-yellow leonite with a waxy luster
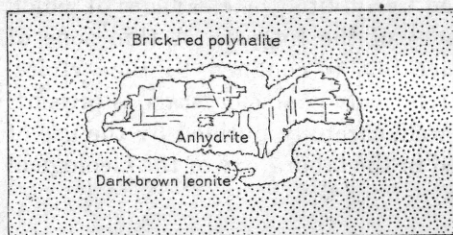
FIGURE 10.—Leonite forming a narrow seam between a large corroded crystal of anhydrite and massive polyhalite. 1¾ times natural size

is intimately mixed with kainite and associated with reddish sylvite and halite. Most of this core is composed of halite, but it contains also some magnesitic clay. In places leonite occurs in larger blebs, and the material for analysis was picked out by hand under the binocular from one of these blebs. The associated kainite could not be mechanically separated from the leonite, which it greatly resembles in appearance, but from the chemical analysis of the mixture of these two minerals, the quantities of the constituents necessary for the kainite could readily be deducted on account of its chlorine content.

In the Martin Yates No. 2 well at a depth of 843 feet dark-brown leonite together with a large crystal of anhydrite, for which it serves as coating, is embedded in massive brick-red polyhalite. (See fig. 10.) The crystal of anhydrite, one of the largest seen, measures 21 millimeters in length and is of irregular outline. Its coating of dark-brown leonite forms a border 1 millimeter wide which separates it from polyhalite.

[18] See abstract of literature in Hintze, Carl, Handbuch der Mineralogie, vol. 1, part 28, p. 3725, 1929.
[19] Engle, Felix, Beitrag zur chemisch-petrographischen Kenntniss der Kalisalzlagerstätte von Salzdet-furth (Inaug. Diss.), p. 35, Univ. Leipzig, 1913.

Such a relation suggests that the leonite is a secondary mineral, a reaction product of preexisting minerals. The large crystals of anhydrite are considered to be secondary and later than the much smaller ones that form the fine-grained anhydrite cores, illustrated in Plate 1. In the same specimen which contains the leonite just described there are radiating groups of other crystals of anhydrite 1 centimeter or more long. If these crystals have grown at the expense of polyhalite, then after the removal of calcium sulphate to form anhydrite the remaining potassium and magnesium sulphates could unite to form leonite:

$$2CaSO_4.K_2SO_4.MgSO_4.2H_2O + 2H_2O = 2CaSO_4 + K_2SO_4.MgSO_4.4H_2O$$

$$\text{Polyhalite} \qquad\qquad\qquad \text{Anyhdrite} \qquad \text{Leonite}$$
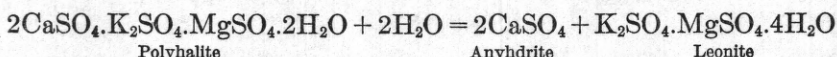
Such a reaction would be the reversal of that previously indicated by which anhydrite is attacked by potash and magnesium solutions to yield polyhalite. Many of the cores show these secondary large anhydrite crystals developed in polyhalite with no leonite, and in the same specimen in which occur the relations shown in Figure 10 there are small masses of similar dark-brown leonite in the massive polyhalite without any anhydrite. Several thin sections show that polyhalite replaces leonite and forms at its expense, according to the reaction

$$K_2SO_4.MgSO_4.4H_2O + 2CaSO_4 = 2CaSO_4.K_2SO_4.MgSO_4.2H_2O + 2H_2O$$

$$\text{Leonite} \qquad\qquad \text{Anhydrite} \qquad\qquad \text{Polyhalite}$$
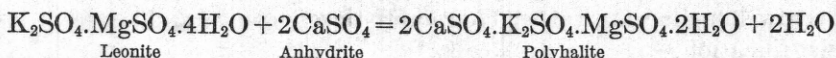
which is the reverse of the reaction shown above.

The alteration of leonite and its relation to other minerals is shown in Plate 15. The same thin section from which Plate 15, B, was taken, also shows in a similar way that kieserite has been replaced by leonite. There is here a good example of two steps of a mineral sequence, the new compound being chemically more complex than that from which it is derived.

$$MgSO_4.H_2O \rightarrow K_2SO_4.MgSO_4.4H_2O \rightarrow 2CaSO_4.K_2SO_4.MgSO_4.2H_2O$$

$$\text{Kieserite} \qquad\qquad \text{Leonite} \qquad\qquad\qquad \text{Polyhalite}$$
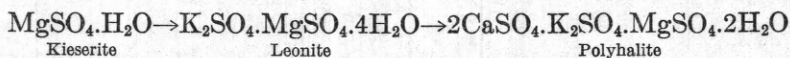
In another specimen leonite surrounds detached and partly isolated areas of polyhalite, all in halite, as shown in Plate 16, A. The leonite seems to have formed at the expense of the polyhalite, which is fine grained and not in coarser crystals as in Plate 15, A and B. A reversal of the reaction shown in Plate 15, A and B, may have taken place here. On the other hand, the polyhalite may have formed in the leonite and may have grown first in small detached areas. The relation of leonite to polyhalite, as illustrated in Plate 16, A, is not at all clear.

The leonite in the blebs ranges from colorless to pale yellow, but streaks of it in polyhalite are dark reddish brown. So far no definite crystals have been found. In all the occurrences noted it forms massive rounded blebs or irregular bodies. Leonite shows no cleavage and is slightly harder than halite. Absence of cleavage and greater hardness are properties of both leonite and langbeinite, but these two minerals can easily be distinguished under the microscope.

Refractive indices of leonite

Locality	α	β	γ	Sign	Determined by
Stassfurt	1.483	1.487	1.490	—	Goergey.
Do	1.478	1.481	1.486	+	Schaller.
Do	1.479	1.482	1.487	+	Henderson.
Martin Yates No. 1 well, New Mexico	1.481	1.483	1.487	+	Do.
Average of the last 3 determinations	1.479	1.482	1.487	--------	

Goergey's determinations are slightly higher than the others.

Leonite is optically positive and not negative, as given by Goergey. This fact was proved on material from Stassfurt as well as on that from New Mexico. The axial angle $2V$ is very close to 90°. Most of the leonite shows narrow twinning lamellae, generally with two sets of lamellae crossing each other at an angle of about 60°. These narrow lamellae are rather characteristic of leonite and serve in its identification.

A chemical analysis of a sample from the Joe Mitchell well that contained 25 per cent of admixed kainite is given below.

Analysis of leonite, with 25 per cent admixed kainite

[E. P. Henderson, analyst]

	Analysis	Deduction of kainite	Remainder	Calculated to 100 per cent	Ratios
K	a 3.97	3.97	--------	--------	
K_2O	18.95	--------	18.95	25.74	0.273 or 0.99 or 1
Na_2O	None.				
MgO	12.42	4.09	8.33	11.31	.281 or 1.01 or 1
SO_3	40.80	8.14	32.66	44.36	.554 or 2.00 or 2
H_2O	19.18	5.49	13.69	18.59	1.033 or 3.73 or 4
Cl	3.61	3.61	--------	--------	
	98.93	25.30	73.63	100.00	

a The percentage of potassium as calculated from the chlorine content was deducted from the total potassium determined to give the correct percentage of K_2O.

The ratios of the analysis, after the kainite is deducted, agree closely with the formula of leonite. The water content, however, is a little low, which probably accounts for the low summation of the analysis.

LUENEBURGITE

Lueneburgite, $3MgO.B_2O_3.P_2O_5.8H_2O$ (MgO, 25.4; B_2O_3, 14.6; P_2O_5, 29.8; H_2O, 30.2 per cent), is the only boron mineral thus far identified. This constitutes the second known occurrence of this rare mineral, which was first found in Germany. All the cores have been tested for boron, which is usually present merely in traces. Careful search for a definite boron mineral in those specimens that have a relatively high content of boron revealed it in only three of the private cores, and in these lueneburgite was definitely determined. The mineral has also been identified by F. C. Calkins in many of the well cuttings from this field. His identifications were based on the optical properties, verified by qualitative tests for borate and phosphate.

The lueneburgite in the three private cores occurs as very small white blebs, so fine grained that no definite structure or habit can be detected without the use of a microscope. It is probably widespread throughout the cores as minute specks but is only rarely concentrated in sufficient quantity to be definitely identified.

In the three private cores in which lueneburgite was definitely identified it was associated with halite, sylvite, and considerable clay. In the Gypsy No. 3 well at a depth of 811 feet 7 inches a single small bleb was identified in halite containing a few small masses of sylvite and inclusions of clay. In the Gypsy No. 4 well at a depth of 749 feet 3 inches a small mass of fine-grained white lueneburgite was embedded in brown clay, associated with much more magnesitic green clay containing halite and reddish-brown sylvite. In the Martin Yates No. 2 well at a depth of 948 feet a small bleb was embedded in halite, associated with considerable clay and reddish-brown sylvite. Small irregular blebs of polyhalite were also present.

The powdered material under the microscope resembles polyhalite to some extent but shows no cleavage or twinning. It is the absence of twinning that most readily distinguishes lueneburgite from polyhalite. Its refractive indices are lower than those of polyhalite.

Refractive indices of lueneburgite

Locality	α	β	γ	Determined by—
Gypsy No. 3 well, New Mexico	1.522	1.541	1.548	Henderson.
Germany	1.520	1.54	1.545	Larsen.
Average	1.521	1.541	1.547	

Chemical tests gave a ready reaction for phosphate, as well as for borate, with no sulphate or chloride. Magnesia was the only base present.

Chemical tests for boron were made by E. T. Erickson on more than a thousand samples from nearly all the cores. Of these, 74 samples, from 6 Government cores and 8 private cores, showed the presence of about 0.1 per cent B_2O_3. About a third of these samples were largely grayish or greenish clay mixed with the other saline minerals, about another third were chiefly anhydrite, a fifth were largely halite mixed with other minerals, and the remainder were polyhalite, sylvinite, and various mixtures. Three layers of brownish sandstone between the saline minerals also contained about 0.1 per cent of B_2O_3. Eleven samples of clay, with admixed polyhalite, halite, or sylvite, contained as much as 0.2 per cent of B_2O_3.

If the boron in these samples is to be ascribed to lueneburgite, then it may belong to the sulphate group (see pp. 9, 12) as well as to the chloride group. In the three private cores in which lueneburgite was definitely identified, however, the associated minerals are those of the chloride group.

MAGNESITE

Magnesite, $MgCO_3$ (MgO, 47.6; CO_2, 52.4 per cent), is found in minute particles throughout these cores. It occurs as scattered individual crystals or groups of crystals, as irregular bunches, streaks, and fine lines, as fairly uniform layers or bands reaching a maximum thickness of nearly an inch, and as pure-white masses of smaller size. The individual crystals are very minute, 0.001 millimeter or less in diameter, but form rosettes of crystals (suggestive of "iron roses," aggregates of hexagonal crystals of hematite) as much as 0.02 millimeter across. Some of the rosettes have a rounded trigonal or rhombic outline, and occasionally what appears to be a single crystal unit as much as 0.01 millimeter in diameter is found. Most of them, however, are very small. Their definite identification as magnesite was established on an aggregate (pl. 16, C) in anhydrite from the Eldridge well, for enough material could there be obtained to show chemically the absence of iron and calcium.

The individual crystals are so small and the aggregates so compact that the mineral appears almost opaque in thin sections. Under very high magnification, its high birefringence can be noted, and a determination of the ω index always gives a result very close to 1.70.

Several occurrences of magnesite are illustrated in Plates 16, 17, and 18.

In places magnesite forms aggregates or nests of nearly pure material reaching a diameter of slightly more than a centimeter (half an inch). The largest aggregate seen, shown in Plate 16, C, was found to consist of pure magnesite, only a trace of calcium, derived from a little admixed anhydrite, being detected in a chemical test. Usually such aggregates of magnesite are very much smaller, as shown in Plate 16, B and D.

The magnesite is very widespread in its occurrence. It was found in all the cores of the sulphate group and in many of those of the chloride group. All the anhydrite rock and polyhalite rock examined contains magnesite. This magnesite is all in very fine-grained particles and is rarely scattered promiscuously through the other minerals but is nearly everywhere in layers or bands, some of which are regular and straight, whereas others are very irregular and disconnected. Those in the anhydrite rock are by far the most regular and most nearly horizontal. Such layers of magnesite are illustrated in Plates 1, 2, 3, and 8, A, B. In many of the specimens that consist essentially of pure polyhalite, or of anhydrite and polyhalite, similar regular and nearly straight layers of magnesite are abundant, as shown in Plates 24, 27, 29, and 30, B. Nevertheless, much of the polyhalite has most irregular and crinkly layers of magnesite, many of which have their continuity broken, as illustrated in Plates 26, B, and 27, C.

The layers of magnesite in polyhalite in the McNutt No. 1 well show very strikingly in Plate 24 on account of their color contrast. Thin sections show that these layers of magnesite contain many long prisms of polyhalite, free from magnesite, and that the magnesite has arranged itself along the sides of the prisms of polyhalite. The relations strongly suggest that these prisms are later than the magnesite and that in their growth they have pushed it aside, in much the same way that the spherulites of polyhalite have pushed the magnesite aside in an occurrence described below (p. 52). Thin sections of the anhydrite rock show similar relations of prisms of anhydrite in the seams of magnesite. These prisms are larger than those in the matrix. All four of the samples of polyhalite shown in Plate 24 are nearly pure, and the percentages of K_2O present are very close to the theoretical values. Magnesite, which is practically the only impurity, is present to the extent of about 1 or 2 per cent.

The occurrence of magnesite is largely confined to anhydrite, polyhalite, and clay. Where magnesite is found with minerals other than these, it is generally inclosed in them. That magnesite was probably an early mineral to form is indicated by its constant association with the clays and the anhydrite. The presence of magnesite in polyhalite in the same mode of occurrence as in anhydrite suggests that it has suffered but little change during the process of replacement of the anhydrite by polyhalite.

The appearance of the layers of magnesite in thin sections is shown in Plates 17 and 18, which present four photomicrographs, two of anhydrite and two of polyhalite. Plate 17, A, shows several layers of magnesite in the anhydrite rock. Some of the thicker layers are more continuous than the thinner ones. A corresponding section of layers of magnesite in polyhalite is shown in Plate 17, B, where some

of the layers of magnesite are also fairly continuous but thinner, and the total quantity of magnesite present is much less than in the anhydrite.   Plate 18, A, displays an irregular aggregate of magnesite in anhydrite.   The corresponding type of occurrence of magnesite in polyhalite is shown in Plate 18, B, where, however, there is a greater local concentration of the particles of magnesite and a decrease in the total quantity of magnesite present.

The general similarity of the types of occurrence of the magnesite and of its relative quantity in anhydrite and in polyhalite favors the idea of the origin of the polyhalite by replacement of the anhydrite.

OPAL

Opal, $SiO_2.nH_2O$, has been identified in many samples of well cuttings from this field by F. C. Calkins.   The minute grains have a conchoidal fracture, are isotropic with an index of 1.45, and are insoluble in water.

The mineral has not been identified in any of the cores examined, though no special search for minute quantities of opal has been made.

POLYHALITE

GENERAL FEATURES

Polyhalite, $K_2SO_4.MgSO_4.2CaSO_4.2H_2O$ (K_2O, 15.6; MgO, 6.6; CaO, 18.6; SO_3, 53.2; H_2O, 6.0 per cent), is next to halite and anhydrite in abundance and is by far the most abundant potash-bearing mineral of the field.   Some beds of nearly pure polyhalite have a thickness of 8 feet, and beds a foot or more thick are numerous.   It has been found in all the potash core tests in the Permian basin of New Mexico and western Texas, both Government and private, and in cuttings from most of the wells drilled for oil in the same general region.   In addition to the beds of nearly pure polyhalite, it is present as disseminated small particles and larger blebs throughout most of the halite and much of the anhydrite sent in to Washington.

Practically all of it is massive and compact, and it has been found associated with all the other minerals mentioned in this report.   Very rarely large crystals of polyhalite have developed in halite.   (See pl. 30, C.)   Polyhalite exhibits a variety of color and texture.   The most common color is perhaps a dark brick red, but the mineral is also found in white, gray (light to dark), brown, orange, salmon, and various shades of red.   The varying texture also causes differences in color that are not perceptible to the naked eye but show clearly in a photograph.   (See pl. 24.)   The texture is usually very fine grained and gives an almost waxy appearance to the mineral.   Other specimens are coarser grained, granular, or, more rarely, composed of distinct crystals.   Much of the polyhalite in halite (pl. 25, especially

B and *C*) has a fuzzy or mossy appearance which is due in part to its being made up of coalescing spherulites, or rounded aggregates of minute fibers, whose structure is well shown where the polyhalite surrounds a regular cavity (negative crystal) in halite, as illustrated in Figure 15.

<center>FORMS</center>

Miscroscopic study of numerous thin sections has shown several different forms in which polyhalite occurs. These forms may, for convenience, be classed in four groups—fine grained, coarse grained, distinct euhedral crystals nearly all twinned, and fibrous. In many specimens of polyhalite two or more of these forms are intimately intermingled, whereas other specimens consist essentially of only one. These different forms are shown in photomicrographs in Plates 19 to 21.

The fine-grained polyhalite (pl. 19, *A*) resembles a mosaic of very minute irregular-shaped fragments and composes much of the material in the cores. Some of it is so fine that the individual grains are hardly recognizable under the microscope. In size of particles it grades imperceptibly into the coarse-grained forms. Some of the individual particles of the fine-grained material are equal in size in all directions, whereas others are short prismatic or short fibrous. Some specimens show many of the varieties mentioned intermingled in a confused mass. The fine-grained polyhalite may have embedded in it a considerable quantity of any or all the other forms mentioned, together with anhydrite and kieserite in varying amounts.

The coarse-grained polyhalite (pl. 19, *B*) is similar in structure but much coarser and generally contains imperfectly developed crystals scattered through it. It is commonly found in halite in varying quantities. The mixture of the two minerals, where the halite is in excess, forms what is known as "blebby salt." Some grains are equiangular; others are short or long prismatic. The crystals may show no regular boundaries, or they may be euhedral and form a compacted mass.

The distinct euhedral crystals of polyhalite are abundant and are found in all the cores examined. They appear in anhydrite, in the fine and coarse granular varietieis of polyhalite, and in halite. Commonly they are directly associated with rectangular crystals of anhydrite and with sharply angular or corroded crystals of kieserite. The crystals of polyhalite embedded in halite are as a rule sharply bounded by crystal faces, without corrosion (pl. 20, *B*). This condition prevails especially where the crystals are embedded in fine granular polyhalite and where halite is also present; the crystals projecting into halite along the edge of the mass are well formed. In places where the halite has been partly dissolved by the drilling brine, crystals of

polyhalite, several millimeters long and as much as a millimeter thick, project from the surface of the core.

Twinning is a very characteristic feature of polyhalite and shows itself in different ways. The relations between the mode of twinning and the crystal morphology have not been worked out, but Figure 11 shows the habit and mode of twinning often observed in thin sections of polyhalite.

A very full and complete description of the crystallography of polyhalite, with its twin structures, has been given by Goergey.[20] He states that polyhalite has a good cleavage parallel to a (100) and a separation, commonly into very thin sheets, after the twinning plane b (010). Two laws of twinning are represented—after b (010) and after c (001).

Some of the euhedral crystals appear to be corroded and attacked by the fine-grained variety, whereas other crystals similarly embedded in the fine-grained polyhalite have straight edges and show no corrosion. There is probably no conclusive age relation between the two varieties, but the sharply bounded crystals are much more abundant than the corroded ones and in general are considered to be the result of recrystallization and therefore later than the fine-grained matrix at whose expense they have grown.

The coarser-grained variety and the better-formed crystals contain much less coloring pigment than the compact fine-grained matrix, and in their recrystallization they seem to have discarded the pigment.

Though in general there seems to be somewhat less magnesite in fine-grained polyhalite rock than in anhydrite rock, yet considerable magnesite remains in nearly all specimens of polyhalite rock that were seen. The bands and layers of magnesite can be well seen in the specimens of compact polyhalite rock shown in Plate 24. In the spherulitic polyhalite (pl. 21, B) the fibers seem to have pushed the magnesite away from the center, concentrating it along the outer boundaries. Some of the narrow zones of polyhalite rock in anhydrite rock seem likewise to have crowded the magnesite to their borders, though this is not invariably so. The appearance of the magnesite in polyhalite, as well as in anhydrite, is shown in Plates 17 and 18. The euhedral crystals of polyhalite, however, are free from any magnesite (pl. 20, B) and rarely contain any inclusions. The anhydrite inclusions shown in Plate 22, A, are therefore exceptional. This freedom from inclusions suggests that the euhedral crystals are later than the fine and coarse grained varieties. The total evidence, however, is not consistently in one direction, and the age relation of the euhedral crystals to the other varieties must therefore be left in doubt.

[20] Goergey, Rudolph, Ueber die Krystallform des Polyhalits: Min. pet. Mitt., Band 33, pp. 38–102, 1914.
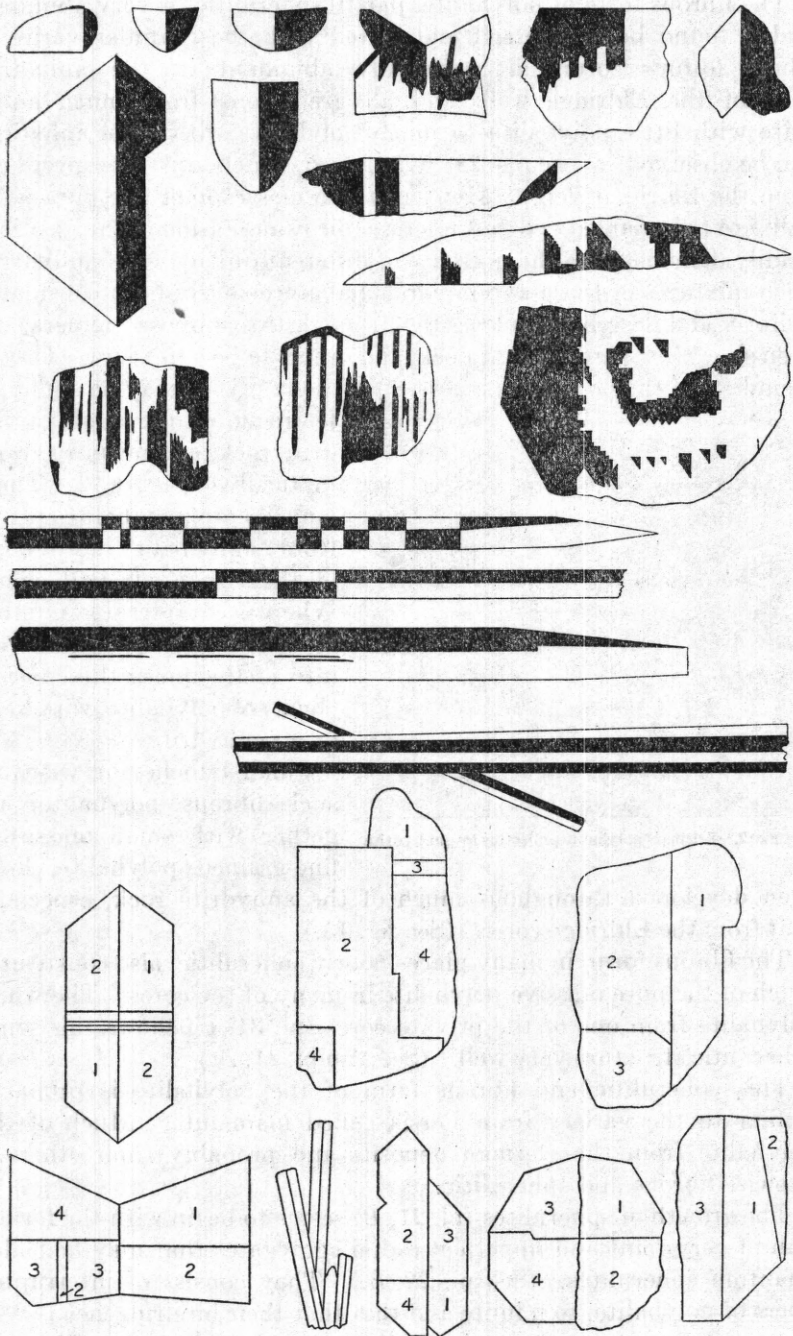
FIGURE 11.—Forms and twinning of polyhalite crystals as seen under the microscope with crossed nicols. The black areas represent the twinned portion in position of optical extinction. The numbered parts represent parts of the twinned crystals with similar optical orientation

The fibrous form of polyhalite, partly spherulitic, is very abundant and is found both by itself and mixed with the granular varieties. These fibrous forms are especially abundant in the anhydrite rock of the Eldridge well, and all gradations from much anhydrite with little polyhalite to much polyhalite with little anhydrite can be observed. (See pls. 28, B, 33, A, B, which illustrate specimens from the Eldridge well.) Many of these masses look like pure polyhalite to the unaided eye, but microscopic examination of thin sections readily demonstrates the presence of different quantities of anhydrite. Such mixtures of these two minerals have previously been considered uniform and described as krugite, although this supposed mineral has been shown by Van't Hoff, Lueck, and others to be a mixture. On the boundary of the polyhalite masses many long prisms may be seen pro-

FIGURE 12.—Prisms of polyhalite projecting into anhydrite

jecting into the granular anhydrite rock, as shown diagrammatically in Figure 12. These long fibers of polyhalite are free from anhydrite, and most of them show straight edges. Where a considerable number of these fibers have developed into a felted mass, this consists chiefly of polyhalite, with little or no anhydrite.

Small bunches or wisps of such fibrous polyhalite, together with small masses of fine-grained polyhalite, have been developed throughout much of the anhydrite rock, especially that from the Eldridge core. (See fig. 13.)

The fibrous form, in many places poorly spherulitic, also constitutes much of the pure massive polyhalite in many of the cores. The white polyhalite from one of the private cores (pl. 31, C) shows this semi-spherulitic structure very well. (See also pl. 21, A.)

This spherulitic and fibrous form of the polyhalite is probably similar to the variety from Persia called mamanite. Much of the polyhalite from the German deposits and probably from others is likewise fibrous and spherulitic.

The growth of spherulites (pl. 21, B) seems to begin with the formation of very faint and imperfect radial aggregates that may be called phantom spherulites. (See pl. 22, B.) They consist of interrupted fibers of polyhalite, so minute and thin that their birefringence is very low and they appear almost isotropic under crossed nicols. They are abundant in halite and can at places be recognized only by examination under crossed nicols. The isotropic halite is then black, and the feebly

refracting fibers of polyhalite have low gray interference colors. They are also abundant in glauberite but are even more difficult to recognize, on account of the low birefringence of glauberite. Their presence in strongly refracting anhydrite would be still more difficult to detect, but careful search has failed to show more than a very few spherulites of polyhalite in anhydrite. In their growth and development the individual fibers of the phantom spherulites seem to attain their complete length quickly, and subsequent growth, by further addition of the requisite brines, tends to increase the thickness of the fibers rather than their length.
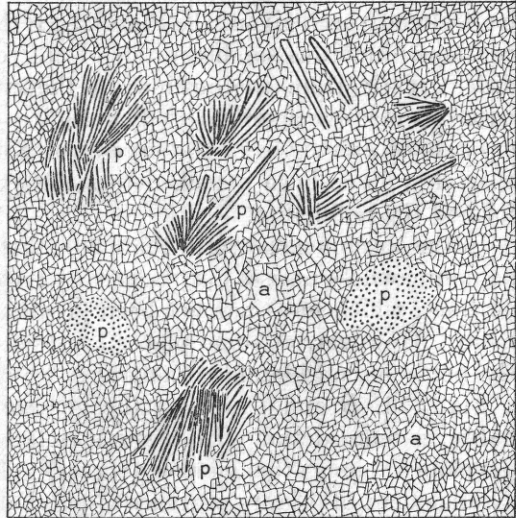
FIGURE 13.—Small wisps of fibers and isolated masses of fine-grained polyhalite (p) in anhydrite rock (a)

Some of the polyhalite of the mixture of the compact fibrous variety with the fine-grained variety contains groups or short streaks of fibers or prismatic crystals of polyhalite arranged in a manner to suggest
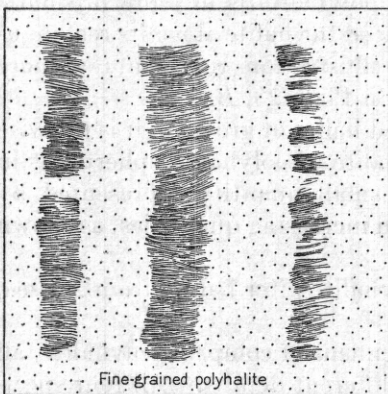
FIGURE 14.—Groups of prismatic crystals of polyhalite apparently formed from another preexisting mineral

formation from some other preexisting mineral. These groups commonly consist largely of thin twinned prismatic crystals, which extinguish as two or three units and thus, under crossed nicols, stand out strongly from the matrix. The individual prismatic crystals are thicker and show a higher birefringence than those that form the finer-grained matrix, and hence they also stand out from the matrix. (See fig. 14.)

Though the different forms of polyhalite have been classed in four groups, there are all gradations and mixtures between these groups. This is especially true of the polyhalite that occurs in salt, which, though in general coarsely granular, may grade into any or all of the other varieties.

The genetic relation of these four different forms of polyhalite to one another has not been deciphered. The relations as observed in nu-

merous thin sections present some evidence of sequence for some of the forms, but no consistent sequence has been recognized for all of them.

The genetic associations of polyhalite with other minerals are discussed under the heading of origin (p. 63). Some of these relations have already been given. In Plate 22, A, the large crystal of polyhalite contains numerous small crystals of anhydrite whose outlines do not differ greatly from the outlines of the crystals of anhydrite in the adjacent massive aggregate. The slightly more rounded shape of the crystals of anhydrite in the crystal of polyhalite suggests, however, that they have been attacked to some extent by the solutions that formed the polyhalite.

In the specimen shown in Plate 23, A, the polyhalite is encroaching on halite, whose masses may be readily recognized by their rectangular outlines, which have not yet been greatly modified by the encroachment. However, at some places crystals of polyhalite have invaded the halite in considerable quantities.

Plate 23, B and C, shows the genetic relations of polyhalite to halite in more detail. In B small isolated areas of polyhalite have developed along the cleavage cracks of halite. The rectangular arrangement of minute particles of polyhalite, following the cleavages of halite, is well shown. This mode of occurrence has been observed several times, and though it apparently does not produce any great quantity of polyhalite in halite, it does show a sequence between these minerals and demonstrates that polyhalite can replace halite. Plate 23, C, demonstrates a similar genetic history between polyhalite and halite and also sylvite, but here the polyhalite is in more prismatic form and has clearly entered and replaced the halite along its rectangular cleavage cracks. Possibly this illustration represents a more advanced stage of the process shown in Plate 23, B.

The fact that polyhalite has replaced halite or grown in it is likewise demonstrated by the growth in the halite of polyhalite spherulites in varying quantities, starting with a small quantity represented by phantom spherulites and continuing in increasing quantities, as shown in Plate 25.

Replacement pseudomorphs of polyhalite after halite, from Aussee, were long ago described by Blum.[21]

Plate 24 contains views of four specimens of compact polyhalite, all from the McNutt No. 1 well but at different depths. All four specimens consist essentially of polyhalite. Specimens A and C contain 15.40 per cent of K_2O, indicating 98.6 per cent of polyhalite; specimen B, 14.90 per cent, indicating 95.4 per cent of polyhalite; and specimen D, 13.75 per cent, indicating 88.0 per cent of polyhalite.

Other sections of core are likewise nearly pure polyhalite. Thus, an 11-inch section from Government hole No. 15 at a depth of 605 feet

---

[21] Blum, J. R., Die Pseudomorphosen des Mineralreichs, p. 223, 1843.

1 inch to 606 feet contained 15.32 per cent of K_2O, indicating 98.1 per cent of polyhalite; a 7-inch section from the Kelly No. 1 well at a depth of 1,115 feet to 1,115 feet 7 inches contained 15.27 per cent of K_2O, indicating 97.8 per cent of polyhalite; and a 6-inch section from the Gypsy No. 4 well at a depth of 500 feet 2 inches to 500 feet 8 inches contained 15.21 per cent of K_2O, indicating 97.4 per cent of polyhalite. A section of 3 feet 3 inches from Government hole No. 13 contained 15.10 per cent of K_2O, indicating 96.7 per cent of polyhalite. Several other sections of polyhalite cores contained over 15 per cent of K_2O.

All the specimens shown in Plate 24 are compact and massive and are dark brownish red.

The specimen shown in Plate 24, A, exhibits well the wavy bands of magnesite and also strikingly illustrates the many large coarse growths of polyhalite in the fine-grained matrix. Many of these growths can hardly be detected by the eye, but a slight difference in tint has enabled the camera to bring out strongly the variations in texture. These larger units, black in reproduction, are seen in thin section to be composed of an aggregate of fibers of polyhalite in nearly parallel position, as sketched in Figure 14. Attention may be called to the black figure in the lower left corner of Plate 24, A, which shows a twin structure similar to that furnished by some of the halite-anhydrite intergrowths described on pages 32-35 and illustrated in Plate 8 and Figure 7.

The specimen shown in Plate 24, B, to the unaided eye looks like a uniform dense fine-grained material with but faint suggestion of the presence of the numerous bands of magnesite.

Plate 24, C, shows more variation in the grain of the polyhalite and also clearly shows the bands of magnesite, here more even and horizontal than in B. In D the dark phases are almost absent, but the abundance of the layers of magnesite is again shown.

These four specimens illustrate the characteristic structural features of the massive polyhalite from these cores. Comparison with the structure of the cores of anhydrite (pls. 1, 2, 3) shows that similar bands of magnesite are present in both. These bands of magnesite and of magnesitic clay are likewise shown in other views of the polyhalite cores. (See pls. 27, 29.)

<div align="center">OCCURRENCE</div>

The modes of occurrence of polyhalite in these cores differ considerably. They may be listed under four headings—(1) minute wisps of fibers, masses, or crystals invisible to the unaided eye; (2) blebby, irregular-shaped small masses, easily detected on inspection; (3) bands or layers of nearly pure mineral; (4) mottled small spherulites of polyhalite, both separate and coalescing, scattered throughout the other minerals.

The minute wisps of fibers and minute areas of fine-grained material are scattered promiscuously through anhydrite or more rarely through halite. Such an occurrence in anhydrite from the Eldridge core has been mentioned and is illustrated in Figure 13.

The most striking and spectacular mode of occurrence of polyhalite is in horizontal beds or layers, which differ considerably in thickness and purity, but it is much more widespread in small masses or blebs distributed through halite. Great thicknesses of halite contain these blebs, and there is a continuous gradation in the relative quantity of the two minerals in different samples of the cores, from nearly pure halite to nearly pure polyhalite. The pink color of the polyhalite makes a very striking contrast with that of halite or of anhydrite.

FIGURE 15.—Polyhalite crystals projecting into a cavity (negative crystal) of halite

Plate 25 illustrates blebby polyhalite in halite, and an occurrence of polyhalite crystals projecting into a cavity (negative crystal) in halite is shown in Figure 15.

In the specimen shown in Plate 28, D, there are three layers of almost pure polyhalite in halite. These layers probably do not represent extensive horizontal layers but are more lenticular, as is clearly indicated by the second layer, which ends on the right side and is connected on the left side with the third layer. The back of this specimen shows that the second layer is not a band of solid polyhalite but a coalescence of many small blebs, which present a solid mass of nearly pure mineral at the plane of the section where the core was polished, as shown in the illustration.

A mode of occurrence of blebby polyhalite, somewhat similar to that illustrated in Plate 25, is shown in Plate 26, where the matrix is anhydrite instead of halite. It is evident that in the formation of polyhalite from anhydrite a considerable quantity of calcium sulphate recrystallizes into larger crystals of anhydrite. The bands of magnesite, though continuous, have locally become very irregular in their boundaries, many of the blebs of polyhalite projecting into them and displacing them. Probably some of the magnesite has entered into the reaction by which polyhalite is produced and has furnished

magnesium. Most of the blebs of polyhalite in anhydrite are not spherulitic in structure but are composed of areas of fine-grained material, of a mosaiclike pattern and of no definite shape. Some are almost angular in their outlines.

The banded form of occurrence of polyhalite is especially well developed in anhydrite, and good examples are shown in Plate 27. Some of the apparently continuous bands of polyhalite consist of a series of disconnected smaller masses that seem to have grown in the anhydrite, with an indefinite and hazy upper boundary. Some of the polyhalite breaks through a layer of anhydrite and extends across and joins the next upper layer of polyhalite.

FIGURE 16.—Structure of horizontal bands of polyhalite, made up of coalescing vertical growths, as shown in Plate 29, B, C, and D

The general appearance of the specimen and the relations of the two minerals, as seen on the polished specimen, strongly suggest that the polyhalite has formed in the anhydrite, the process having proceeded in general along parallel horizontal planes.

Some other modes of occurrence of polyhalite are shown in Plate 28.

Some of the layered polyhalite shows a strongly developed vertical growth structure, as illustrated in Plate 29. (See also figs. 16, 17.)

FIGURE 17.—Relation of polyhalite, anhydrite, and magnesite in Government hole No. 4 at a depth of 1,300 feet

The typical apparent twin structure shown by the vertical growths of halite (fig. 7), is well shown in the extreme upper portion of Plate 29, B. A similar structure of the polyhalite is shown in Plate 29, C, but no halite is present, and only a little anhydrite with thin layers of magnesite.

The structure and mineral relationships of a specimen with relatively undisturbed layers of magnesite, such as those shown in the lower part of Plate 29, C, and the upper part of Plate 29, D, are indicated diagrammatically in Figure 17. The specimen shown in D includes two layers of anhydrite that contain considerably less polyhalite than the other layers. The polyhalite seems to have grown upward from the layers of magnesite, which are rarely broken through unless the entire mass has become disrupted and the remaining parts of the layer of magnesite displaced, as shown in C (upper part). In some places the polyhalite grew upward to the next overlying magnesite seam, but mostly it did not quite reach that far, so the remaining anhydrite is still present.

This structure, as shown in Plate 29 and Figures 16 and 17, is indicative of polyhalite that has grown in or replaced vertical growths

of halite, which themselves were probably pseudomorphs after pre-existing crystals of gypsum. (See pls. 8–10.) The magnesite seams have been chemically little attacked by solutions that could change halite to polyhalite. In thin section the pronounced structure of the vertical growth of polyhalite, as seen in the specimens and well reproduced in Plate 29, is entirely lost, all the polyhalite being a fine-grained aggregate of a fibrous structure. The geometric forms shown, as, for example, the twin structure, do not belong to polyhalite but have been retained from a preexisting mineral by the growing polyhalite. The sequence thus shown may be expressed as

$$\text{Anhydrite} \rightarrow \text{gypsum} \rightarrow \text{halite} \rightarrow \text{polyhalite}$$

The association of anhydrite with clay is illustrated in Plate 3, B, where anhydrite with magnesite is above and clay with magnesite is below, and more or less anhydrite is scattered all through the clay. Similar relations are indicated in Plate 30, A. In Plate 30, B, the matrix consists of anhydrite, accompanied by typical layers of magnesite. Vertical growths of halite rest on the layers of magnesite and extend into the anhydrite, as shown in Plate 29, A. But here there are also present some horizontal layers of nearly pure polyhalite and also a combination of growths of polyhalite and halite, for one band clearly shows vertical growths of halite resting on polyhalite that contains considerable halite, the whole resting on a thin layer of magnesite and extending into anhydrite. Plate 30, C, illustrates some large crystals of polyhalite in halite, with associated anhydrite.

Much of the polyhalite, when polished, does not have a perfectly uniform structure, such as might be expected from the appearance of the broken surface. A banded structure, due to layers of magnesite, is most common. (See pls. 24, 27, 29.) Some of the polished surfaces of the massive polyhalite show a mottled appearance, which is due to several features. One of these is the inclusion of some other mineral, as, for example, anhydrite (pl. 31, A) or halite (pl. 31, C). Grains of magnesite scattered irregularly through the polyhalite, instead of in bands, also give a mottled effect. Small grains of kieserite are also here and there sufficiently abundant to contribute a mottling effect, which, however, rarely shows until the particles of kieserite begin to hydrate, taking on more water and efflorescing to a higher hydrate. The anhydrite of the mottled specimen shown in. Plate 31, A, is seen in thin section to be largely corroded and replaced by polyhalite. A magnified view of part of a thin section of this specimen is given in Plate 5, which illustrates the genetic relation between anhydrite and polyhalite.

As the large crystals of anhydrite shown in Plate 5 to have been attacked and partly replaced by polyhalite belong to the secondary

or recrystallized type, it would seem that in the replacement of the anhydrite by solutions yielding polyhalite there are a number of stages in the mineral changes. The fine-grained anhydrite rock when changed to a similar fine-grained polyhalite rock develops larger secondary crystals of anhydrite that are probably due to the presence of a considerable excess of calcium sulphate. The changes of these larger secondary crystals of anhydrite to polyhalite would then belong to a later stage of the transformation, when additional brines would tend to attack these, too, and change them into polyhalite.

The specimen of white polyhalite shown in Plate 31, C, which owes its mottling effect to the presence of halite, was analyzed and found to contain 15.1 per cent of K_2O, which indicates a polyhalite content for the entire specimen of nearly 97 per cent, the remaining 3 per cent being essentially halite, with a very little magnesite. Other pieces of white polyhalite contain more halite; some show practically none. Such a specimen has a rather even-grained appearance, with almost no mottling.

Another feature that gives a mottling effect to the polyhalite is the difference in size of grain of the polyhalite itself and not the presence of another mineral. This is well shown in Plate 31, B and D. Whether such a mottling is due to crystals of anhydrite or of polyhalite can usually be determined by close examination of the shape of the crystals with a hand lens, for the anhydrite crystals, even when considerably corroded, still show a general rectangular outline (fig. 2), whereas the polyhalite crystals usually have pointed terminations and seldom show any rectangular outline. Treatment of the polished surface with a moist cloth or brief immersion in water dulls the polyhalite but does not affect the anhydrite. The crystals of polyhalite, however, are much more resistant to this dulling effect by water than the fine-grained matrix, whose bright polish can be very easily destroyed by moisture.

Polyhalite immersed in water quickly becomes coated with a thin film of gypsum, which, when the specimen dries, becomes white. Immersion of half a minute often suffices, and in about 10 minutes a good coating of white gypsum will be deposited. This procedure affords a means of detecting polyhalite that occurs in blebs, mixed with the other minerals, and is otherwise difficult to identify readily. (See pl. 32, A, B.) Such a development of gypsum also brings out clearly the structure of the whole specimen. (See pl. 33, A, B.)

A coarse granular structure is afforded by the mixture of polyhalite, anhydrite, kieserite, and halite. Each of these may occur as relatively large masses of pure mineral, but each generally contains abundant inclusions of one or more of the associated minerals. Such an agglomeration is illustrated in Plate 32, C. All the minerals mentioned are present in quantity. Anhydrite seems to be the most

abundant, but considerable magnesite is also present. The elongated vertical areas of polyhalite and the segregation of halite and kieserite into masses which are not horizontal suggest that the mineral complex is largely secondary, the result of various reactions and changes. Somewhat similar composite structures are shown in Plate 33, *C* and *D*.

The associations and genetic relation of polyhalite to anhydrite and kieserite are illustrated in Plate 33. The intimate mixture in different proportions of polyhalite and anhydrite, which gives rise to what was formerly considered a distinct mineral, krugite, is well shown in *A* and *B*. The larger, well-developed prismatic crystals of anhydrite are considered to be of secondary formation and to have recrystallized during the formation of polyhalite from the fine-grained anhydrite rock. The kieserite has been attacked and partly replaced by polyhalite, as shown in Plate 13, *B*.

Two additional phases of the intimate mixture of polyhalite, halite, anhydrite, and kieserite, as they appear in parts of the core, are shown in Plate 33, *C* and *D*. Some of the nearly vertical masses of polyhalite suggest the previously described vertical growths of polyhalite after halite, though their form is so irregular that their origin can not be determined with certainty.

In many of the sections of core that seem when viewed by the unaided eye to consist essentially of polyhalite both halite and anhydrite are present in greatly varying quantities. The polyhalite is fine grained and compact, and the minute disseminated particles of halite and of anhydrite are not readily visible.

Determinations of chlorine as well as of K_2O were made on some sections of several of the cores, which apparently consisted essentially only of polyhalite. As a microscopic examination of these sections of core showed the presence of only polyhalite, halite, and anhydrite, with very minor quantities of clay and magnesite the chemical determinations can be interpreted mineralogically by calculating all the K_2O to polyhalite and all the Cl to halite. On this basis the percentages of polyhalite, halite, and anhydrite for these sections of cores are as follows, the anhydrite, obtained by difference, including the very minor quantities of clay and magnesite. The sections are arranged with increasing percentages of polyhalite.

Percentages of polyhalite, halite, and anhydrite in certain sections of some of the cores

Core	Depth of section of core		Thickness	Polyhalite	Halite	Anhydrite
	Top	Bottom				
	Ft. in.	Ft. in.	Ft. in.	Per cent	Per cent	Per cent
Government No. 13	1,099 4	1,101 6	2 2	64.2	8.6	27.2
Blanchard No. 2	1,194 2	1,195 5	1 3	66.7	10.4	22.9
Kelly No. 1	1,092 5	1,096 1	3 8	67.3	1.5	31.2
Blanchard No. 2	1,269 5	1,271 0	1 7	69.7	13.9	16.4
Government No. 3	1,459 10	1,461 1	1 3	72.1	22.4	5.5
Government No. 4	1,304 0	1,305 2	1 2	74.4	1.0	24.6
Government No. 13	1,880 2	1,881 6	1 4	75.0	21.6	3.4
Government No. 11	1,518 4	1,519 6	1 2	75.3	2.5	22.8
Government No. 13	1,189 4	1,192 2	2 10	75.5	17.6	6.9
Government No. 3	916 0	918 0	2 0	75.8	12.0	12.2

Percentages of polyhalite, halite, and anhydrite in certain sections of some of the cores—Continued

Core	Depth of section of core		Thickness	Polyhalite	Halite	Anhydrite
	Top	Bottom				
	Ft. in.	Ft. in.	Ft. in.	Per cent	Per cent	Per cent
Government No. 11	1,555 9	1,557 1	1 4	76.6	16.9	6.5
Do	1,315 10	1,316 10	1 0	77.8	12.7	9.5
Do	1,587 2	1,587 11	0 9	77.9	2.7	19.4
Blanchard No. 2	1,307 2	1,312 2	5 0	77.9	14.7	7.4
Government No. 4	1,943 4	1,945 0	1 8	78.5	13.5	8.0
Government No. 3	1,062 0	1,062 4	0 4	80.1	12.5	7.3
Kelly No. 1	869 0	871 3	2 3	81.3	7.1	11.5
Do	504 1	505 3	1 2	82.3	17.7	0
Do	529 2	530 7	1 5	82.3	13.8	3.9
Government No. 3	1,169 10	1,170 6	0 8	82.9	17.0	.1
Blanchard No. 2	1,010 10	1,011 4	0 6	83.0	9.4	7.6
Government No. 13	2,095 6	2,097 0	1 6	84.1	.8	15.1
Do	828 6	830 7	2 1	85.6	6.7	7.7
Kelly No. 1	1,242 2	1,245 4	3 2	85.8	4.1	10.1
Blanchard No. 2	833 5	835 0	1 7	85.9	2.6	11.5
Government No. 11	1,979 4	1,981 0	1 8	85.9	6.2	7.9
Government No. 3	868 1	871 3	3 2	86.5	6.6	6.9
Government No. 4	1,311 7	1,312 8	1 1	86.5	5.9	7.6
Do	1,558 0	1,559 2	1 2	87.0	1.0	12.0
Kelly No. 1	1,245 4	1,251 3	5 11	87.2	10.7	2.1
Blanchard No. 2	947 3	947 11	0 8	87.8	12.0	.2
Government No. 3	1,035 3	1,036 3	1 0	89.1	1.7	9.2
Government No. 11	1,660 4	1,661 8	1 4	90.4	1.5	8.1
Government No. 13	1,805 8	1,807 3	1 7	90.4	5.6	4.0
Government No. 11	2,059 3	2,060 0	0 9	91.2	4.7	4.1
Government No. 3	951 8	952 5	0 9	91.3	2.1	6.6
Do	1,315 6	1,316 6	1 0	91.7	3.1	5.2
Do	1,012 3	1,014 3	2 0	95.0	1.5	3.5
Government No. 4	1,937 5	1,939 6	2 1	95.5	.8	3.7
Government No. 13	1,604 7	1,605 3	0 8	96.5	3.0	.5
Kelly No. 1	1,115 0	1,115 7	0 7	97.9	1.0	1.1

The wide variation in the percentages of halite and of anhydrite, in parts of the cores consisting essentially of polyhalite, is well shown.

Comparison of groups of sections of core having nearly the same polyhalite content shows a similar wide variation in the percentages of halite and of anhydrite:

Polyhalite	Halite	Anhydrite
67.3	1.5	31.2
69.7	13.9	16.4
72.1	22.4	5.5
74.4	1.0	24.6
75.0	21.6	3.4
75.3	2.5	22.8
82.9	17.0	.1
83.0	9.4	7.6
84.1	.8	15.1
87.0	1.0	12.0
87.2	10.7	2.1

ORIGIN

This investigation has indicated that much of the polyhalite is of secondary origin, having been derived from preexisting minerals by the action of natural brines or solutions. In some specimens evidence

of such action is lacking; in others it is clearly and abundantly present. However, the possibility of a direct precipitation of polyhalite from a brine can not be denied. The evidence so far obtained indicates that the greater quantity of polyhalite was formed by the replacement of anhydrite. But all these investigations of mineral relationships were necessarily confined to a study of cores only a few inches across. Consequently, the lack of knowledge of geologic structure and relations is a serious handicap in the interpretation of the origin and mutual genetic relations of these minerals. There is also a lack of quantitative chemical information as to the character of the brines and the various solubility and concentration relationships existing in them.

The cores show that much of the polyhalite occurs in horizontal layers. Such a structure could result from a direct chemical precipitation as well as by a replacement of anhydrite resulting from the action of a supernatant brine. A bed of white polyhalite of so characteristic an appearance as to be of use as a geologic marker was encountered in several adjacent private wells at the same general horizon, so that it seems to be a continuous bed of considerable lateral extent. Such an occurrence is suggestive of direct precipitation.

The first mineral to form in any quantity by the concentration of the brines was anhydrite. The concentration of magnesium and potassium in the remaining brine was continually increased, and it is possible that the calcium sulphate supplied by inflowing waters furnished the necessary constituent to form polyhalite directly from solution.

The brines doubtless varied greatly in their chemical composition at different times, and the physical conditions of temperature, pressure, and concentration likewise varied, so that at certain places conditions may have been reached that would cause the precipitation of polyhalite directly from the brines.

In a number of the cores, moreover, the boundary line between the massive anhydrite rock and the massive polyhalite rock seems to be so straight and even that in the absence of any recognizable replacement effects it seems possible that some of the sharply defined contacts of the two minerals are the result of direct precipitation of polyhalite from the brines.

The polyhalite at the sharply defined straight contacts is not different in character from that several inches above the contact. The polyhalite that has formed by the replacement of anhydrite rock varies so much in form, crystal habit, and grain size that these factors are of no value as criteria of its origin. Moreover, it would be reasonable to expect slight replacement effects at the contact with the anhydrite, if any quantity of polyhalite were precipitated thereon directly from a supernatant brine.

Some of the disseminated polyhalite in halite called "blebby salt" (pl. 25) might be considered an example of contemporaneous precipitation of these two minerals, though the replacement of halite by polyhalite is well established. (See pl. 23.) The more or less spherulitic character of this polyhalite (see pl. 22, *B*), however, is characteristic of replacement effects.

Evidence was observed in many thin sections that anhydrite crystals have been corroded by polyhalite, or perhaps, to speak more accurately, by solutions that have attacked and dissolved anhydrite and have yielded polyhalite. Many of the crystals of anhydrite are irregularly corroded; others have been separated into several parts, which still retain their parallel position. Such corroded and partly replaced anhydrite crystals are shown in Plate 5. It is considered possible, too, that the bands of parallel fibers of polyhalite, embedded in the fine-grained matrix, as described and illustrated above (p. 55, fig. 14), represent a similar phenomenon carried to completion. The crystals shown in Plate 5 are larger than most of the crystals of anhydrite in the massive anhydrite cores and probably represent a second or later generation, formed when the main mass of smaller crystals of anhydrite was replaced by polyhalite, the large excess of calcium sulphate present recrystallizing in part into these large crystals of anhydrite. A continuance of this replacing action or perhaps the advent of additional and new brines accomplished the results shown in Plate 5. The formation of polyhalite from other minerals, such as glauberite, kieserite, and leonite, has been described and illustrated.

Van't Hoff, who formed polyhalite experimentally, has proved that brines containing magnesium and potassium can yield polyhalite by action on anhydrite. He states [22] that a solution corresponding to $1,000 \ H_2O + 9.7 \ K_2SO_4 + 45.3 MgSO_4$, at 83°, has a great facility for changing anhydrite and other calcium salts, such as gypsum and syngenite, into polyhalite. He also indicates the possibility that anhydrite may be changed to polyhalite by chloride solutions.[23] The reaction is given as $MgCl_2 + 2KCl + 6CaSO_4 = Ca_4MgK_2 \ (SO_4)_6 + 2CaCl_2$. The polyhalite is called krugite, as given by the old (incorrect) formula. However, as krugite is simply a mechanical mixture of polyhalite and anhydrite, the reaction can now be stated in simpler and more accurate form as $MgCl_2 + 2KCl + 4CaSO_4 + 2H_2O = Ca_2MgK_2(SO_4)_4 . 2H_2O + 2CaCl_2$. Mineralogically, this can be stated in the form carnallite + sylvite + 4 anhydrite + water = polyhalite + 2CaCl_2 or again as 2 carnallite + 4 anhydrite + water = polyhalite + $2CaCl_2 + MgCl_2$.

---

[22] Van't Hoff, J. H., Untersuchungen über der Bildung der ozeanischer Salzablagerungen, p. 280, Leipzig, 1912.
[23] Idem, pp. 322-323.

Polyhalite has also been made by Basch [24] by treating syngenite and epsomite with a solution that contained 1,000 H_2O, 6.5 Na_2Cl_2, 7.5 K_2Cl_2, 52 $MgCl_2$, and 16.5 $MgSO_4$. In 24 hours at 56° the syngenite was converted to polyhalite. It was also prepared indirectly from gypsum by dissolving 48 grams of K_2SO_4 in 500 grams of H_2O and adding 8 grams of gypsum. By shaking occasionally a pulpy mass of syngenite was formed in 20 minutes. To this was added 60 grams of $MgSO_4.7H_2O$ and 333 grams of $MgCl_2.6H_2O$. The mass was then heated to 56° until 40 grams of water had evaporated. By keeping the material at 56° for some time, the syngenite was changed to polyhalite.

That anhydrite changes to polyhalite in the German occurrences has been noted by several writers. Lueck,[25] for example, gives a good illustration of the change of anhydrite to polyhalite.

The earliest samples of potash minerals from the New Mexico and Texas field received by the Geological Survey were well cuttings obtained in drilling for oil. Numerous microscopic observations made on these well cuttings suggested a secondary origin for the polyhalite. These observations have led to the conclusion that the polyhalite was formed by the reaction of a potassium-bearing solution on anhydrite. At some places the crystals of anhydrite seem to have been directly replaced by polyhalite; in specimens from other localities the polyhalite seems to be a reaction product of a solution and anhydrite. The salts in the solution have acted as a partial solvent of the anhydrite, and the crystals of polyhalite have grown in the resultant mixture of solution and solid anhydrite without actual metasomatic replacement of the anhydrite. The differences in modes of occurrence of these two minerals suggest that there is a definite difference in their ages and that polyhalite is invariably the younger.

A replacement origin for at least some of the polyhalite in well cuttings from Texas was also suggested by the fact that, when examined microscopically, the polyhalite was seen to have a fine-grained mosaic structure in which no definite crystal outline belonging either to polyhalite or to any other recognizable mineral could be detected. In part the structure resembled that of cryptocrystalline quartz. The individual crystal units with homogeneous extinction in polarized light were very minute and were angular in shape but without uniformity or regularity. At places, too, aggregates of fibers and prisms, both parallel and radiating, could be recognized. The characteristic mosaic structure of most of the crushed fragments in itself is suggestive of replacement phenomena. Later observations on cores have shown that the mosaic structure and the fibrous and prismatic forms of polyhalite are likewise common and abundant.

---

[24] Basch, E. E., Die Künstliche Darstellung und die Bildungs-Verhältnisse des Polyhalites (Inaug. Diss.)' 25 pp., Berlin, 1901. See also Akad. Wiss. Berlin Sitzungsber., 1900, pp. 1084–1085.

[25] Lueck, Hugo, Beitrag zur Kenntnis der älteren Salzgeberger, (Inaug. Diss.), fig. 26, Leipzig, 1913.

It was noticed occasionally that crushed fragments of polyhalite from well cuttings had an approximately rectangular shape. Each one of these rectangular pieces was a mosaic of very small masses of irregular-shaped polyhalite grains. The hand specimen showed no indication of being fractured or jointed by any system of fracture planes, and the rectangular pieces were too small and too few to owe their origin to any structure in the hand specimen as a whole. On the other hand, their occurrence was very suggestive of an inherited cleavage, not abundantly or perfectly developed, yet sufficiently so to demand special attention.

The above-outlined suggestion of a derivation of much of the poly-halite from anhydrite has been amply verified by the study of the much more abundant core material. Many thin sections that contain polyhalite, anhydrite, and other minerals show relations which point strongly to such a sequence of formation. As illustrated in many of the accompanying plates, the relations of the minerals present suggest that polyhalite has replaced anhydrite and other minerals. The concave outline of the contact of polyhalite rock against anhydrite rock and the irregularly distributed anhydrite that still remains in the polyhalite rock strongly favor such a conclusion. Illustrations of polyhalite that has replaced other minerals and partly formed at their expense are given as follows: After anhydrite in Plate 5, after glauberite in Plate 7, C, after halite in Plate 23, after kieserite in Plate 13, B, after leonite in Plate 15, and after sylvite in Plate 23, D. The formation of polyhalite in anhydrite rock by its growth as small blebs and spherulites is shown in Plate 26, and similar occurrences in halite rock in Plates 25 and 29.

The abundant and widespread occurrence of polyhalite in the halite rock—the so-called blebby salt—affords an example of the formation of polyhalite in which no element of an earlier mineral enters into the composition of the polyhalite. The mode of occurrence of polyhalite in the halite rock suggests, however, that it did not form by direct precipitation from and in a brine but by replacement of the halite rock through circulating solutions, even though neither the sodium nor the chlorine of the halite entered into the composition of the resultant polyhalite.

The first mineral formed, anhydrite, was stable in the dilute brines from which it was precipitated. However, as the concentration of the brines was increased largely through evaporation of the water, the anhydrite was no longer inert toward these supernatant brines, which were richer in magnesium and potassium. The greater concentration of magnesium and potassium salts in the brines caused them to react with the already formed anhydrite and possibly other minerals, to form polyhalite. Such a reaction may explain the relative scarcity of minerals like kieserite.

The entire sequence of mineral changes as described in this paper therefore represents one continuous process.

In general the relations observed at the contact surface of two minerals, where the possibility of replacement is considered, do not lead to any decisive conclusion as to origin. In many specimens the evidence for or against replacement is neutral, but other similar contact surfaces of the same pair of minerals will throw considerable light on the direction of mineral changes. Thus it is with the anhydrite-polyhalite contact surfaces. So many of these surfaces show evidence of the replacement of the anhydrite rock by polyhalite rock that the few examples in which such evidence is lacking may justifiably be regarded as having had a similar history, especially as they do not show any features that decisively suggest direct precipitation from a brine.

In none of these specimens that show the contact between the two minerals was any difference in character noted between the upper and lower contact surfaces. Generally the polyhalite rock is in horizontal layers in the anhydrite rock, and both the upper and lower surfaces show similar effects.

These comments on contact relations refer to a mass replacement of the anhydrite rock and not to the replacement of single individual crystals or crystal units, such as has been described for anhydrite crystals (pl. 5), for glauberite crystals or individual crystal units (pl. 7, C), for halite (pl. 23), for kieserite (pl. 13, B), and for leonite (pl. 15). For convenience of description, however, the massive anhydrite rock will be here referred to as anhydrite and the massive polyhalite rock as polyhalite. The replacement has not taken place metasomatically crystal by crystal but in mass, so that locally, at any one place, a considerable mass of the anhydrite has been replaced by polyhalite. No single crystal or crystal unit of anhydrite has been completely replaced by polyhalite in the sense of a pseudomorph. The polyhalite that has replaced anhydrite exhibits its own crystallographic and structural features. In this section rock replacement rather than mineral replacement is the essential idea, even though the replacing rock and the rock replaced are each composed of but a single mineral.

The particular features of these boundary lines or contact surfaces (as seen in thin sections) that have a bearing on the problem of genesis are as follows: (1) Convex surfaces of polyhalite against anhydrite, (2) irregular, interpenetrating contacts, (3) residua of anhydrite in polyhalite, (4) small scattered masses of polyhalite in anhydrite, (5) development of large secondary euhedral crystals of anhydrite in the polyhalite, (6) continuation of magnesite bands in the anhydrite into the polyhalite. These features are sketched diagrammatically in Figure 18.

1. Convex surfaces of polyhalite against anhydrite are well shown in Plates 34, 35, and 36 and diagrammatically in Figure 18. The masses of polyhalite are slightly intruded into the anhydrite. Even where the convexity does not appear clearly (it is exhibited very well in pl. 35, *B* (a photomicrograph of part of the contact of the specimen illustrated in pl. 34) and in pl. 36, *A*) and the contact surface is rather irregular, as shown in Plate 36, *B*, there still may be seen a few masses of the polyhalite with a convex surface against the anhydrite, as on the left in Plate 36, *B*. In some thin sections there are shown long, thin tongues of anhydrite (fig. 18) between two adjacent convex areas of polyhalite that are very thin and yet are longer than the width of some of the single rounded convex masses of polyhalite.

In some specimens the polyhalite is bounded by a layer of magnesite; in other specimens, however, the polyhalite is in direct contact with the anhydrite with no intervening layer of magnesite. In a few places where a thin seam of halite lies between the polyhalite and the anhydrite, the halite is bordered by a thick layer of magnesite, as if the incoming halite, unable to assimilate the magnesite chemically, pushed it aside.

Such convex surfaces of masses of polyhalite against anhydrite are very common and abundant where the two minerals are not in distinct layers, as illustrated in Plate 34, and where the polyhalite has grown in the anhydrite without forming definite layers, as is shown in Plate 35, *A*.

The polyhalite shows two features which have a direct bearing on the problem of sequence of formation but whose interpretation is difficult. Much of it is uniformly colored, but some specimens show two colors or, to speak more accurately, two different tints of the same color. This is shown by the specimen illustrated in Plate 34. Most of the polyhalite is the typical dark reddish brown variety (almost black in the view), but all through it a light, almost salmon-colored variety appears in irregular-shaped masses and stringers. This light-colored variety also forms a very narrow seam, not more than a millimeter thick, at the contact with the anhydrite. In the massive polyhalite there are areas of the dark variety surrounded by the light-colored variety. The difference in color is simply a difference in the abundance of the coloring pigment (hematite), but it probably represents two generations of polyhalite. It is believed that the dark variety was the first to form, the masses of polyhalite developing irregularly in the anhydrite (see for comparison pl. 28, *B*), and that a later generation of light-colored polyhalite then completed the replacement process and enlarged the masses of the dark polyhalite.

The anhydrite above the polyhalite (pl. 34) is not gray like the normal anhydrite but has a very pale salmon color that is due to the

presence of a small quantity of hematite dust irregularly scattered through it. This hematite dust seems to be concentrated in the magnesite and to a much smaller extent in the halite, which is present in very small amounts. Some of the similar reddish-brown streaks in the polyhalite seem to be due to a gradual replacement of magnesite by hematite, possibly through an intermediate sideritic stage. The salmon-colored anhydrite also contains a few crystals of polyhalite which are colorless. In one thin section a crystal of polyhalite, 5 millimeters long, lies in the anhydrite nearly parallel to the contact and but 1 or 2 millimeters away from it.

It is to be noted also that the fibrous variety of polyhalite tends to have its fibers arranged approximately parallel to the surface of
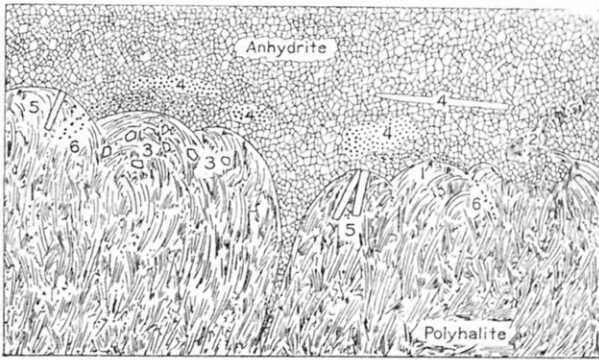
FIGURE 18.—Relations between anhydrite rock and polyhalite rock at their contact. The figures refer to the numbered features of the contact, as stated on page 68

contact with the anhydrite, as shown diagrammatically in Figure 18, a composite sketch.

In some of the contacts there is a narrow seam of halite between the two minerals, but in others no halite is present. Such halite usually contains many inclusions of anhydrite, which in part have recrystallized into more nearly perfect and slightly larger euhedral crystals. Locally along the halite-polyhalite contact secondary euhedral crystals of polyhalite fringe the massive material and project into the halite.

In some of this halite the layers of included magnesite follow the cleavage direction of the halite and are in part in perpendicular position to other layers of magnesite, like those in glauberite as sketched in Figure 6. Such a rearrangement of the included magnesite shows the halite to be the result of a later crystallization.

The tendency of polyhalite to develop in rounded masses in anhydrite, with a convex surface against the anhydrite, is well shown in Plate 35, A. Some of these masses have a broken layer of magnesite

around their boundary next to the anhydrite, as if, in the change of anhydrite to polyhalite, the new mineral had not been able to assimilate or to include the magnesite but pushed it aside in its growth, like the spherulites of polyhalite described on page 52.

In Plate 36, *A*, a wide vein of polyhalite is represented as entering anhydrite and as built up of coalescing rounded masses of polyhalite with the convex boundary against the anydrite.

2. The irregular, interpenetrating contacts of polyhalite and anhydrite are illustrated in Plate 36. Many of the contacts in this specimen display very well the irregular interpenetrating type of contact that results from the replacement of anhydrite by polyhalite.

3. Residua of anhydrite in polyhalite are shown in many of the contacts, either as isolated crystals or groups of crystals that form small masses of anhydrite rock, or as larger groups of such masses. (See pl. 36, *A*, *B*.) Some thin sections of these contacts, however, show no residua of anhydrite in the polyhalite, and such occurrences may suggest direct precipitation of the polyhalite from the brines. But no such residua would be present if the replacement process went to completeness, and many examples of other mineral occurrences could be cited in which from other evidence replacement is believed to have occurred without leaving any visible residua of the replaced mineral or rock.

4. Small scattered masses and individual crystals of polyhalite are present in the anhydrite away from the contact and without direct connection with the main body of polyhalite. Some of these scattered masses of polyhalite in anhydrite have their outlines partly determined by bands of magnesite. Such advance formations of a replacing mineral are a common feature of replacement deposits.

5. The development of secondary euhedral crystals of anhydrite in massive polyhalite shows that some chemical reaction has taken place whereby a part of the anhydrite has recrystallized into larger crystals.

6. The continuation of the magnesite bands from the anhydrite into the polyhalite is rarely seen, but a few examples were observed, as sketched in Figure 18.

The chemical reaction by which the anhydrite is changed to polyhalite is not known. Anhydrite is much more insoluble than polyhalite, but some conditions must have occurred which permitted the change to take place fairly readily. It seems reasonable to postulate that the calcium sulphate in the polyhalite was supplied by the anhydrite, but a large part of the anhydrite must have been removed and carried away, because the change to polyhalite occurred without observed change of volume. The replacement may have proceeded in similar fashion to that followed by other pairs of minerals for which no satisfactory explanation is available, though the evidence clearly

shows that it has taken place. A few suggestions, however, may be made as to possible conditions.

The anhydrite may have been changed to some other form of calcium sulphate, such as ·the hemihydrate or "soluble hydrate," or gypsum, which had only a transitory existence, being immediately thereafter further changed to polyhalite. Perhaps the brines of unknown composition reacting on the anhydrite could have caused such a change. Anhydrite was changed to compact gypsum, without change of volume, in the zeolite region of New Jersey, particularly at Paterson. Some of the gypsum was then changed to thaumasite, again without change of volume, so that the derivation of polyhalite from anhydrite, through some transitory form, is not excluded.

It is also possible and seems more probable that the change occurred in the chloride brine, the solubility of the anhydrite being caused by such a reaction as $CaSO_4 + MgCl_2 = CaCl_2 + MgSO_4$, yielding only soluble products, which would then react with a reversal of change, forming either polyhalite, if the other constituents of polyhalite were present and conditions of equilibrium correct, or secondary anhydrite.

OPTICAL PROPERTIES

The polyhalite from the Texas and New Mexico field exhibits optical properties similar to those of the mineral from Germany. The individual crystals are complexly twinned, in many specimens polysynthetically (like plagioclase feldspar), as well described by Goergey.[26] The prevalent forms of well-developed crystals as seen in thin sections are illustrated diagrammatically in Figure 11. The refractive indices agree with those obtained by Goergey from material from Ischl.

Refractive indices of polyhalite

Locality	α	β	γ	Determined by
Ischl	1.548	1.562	1.567	Goergey.
Eddy County, N. Mex	1.546	1.558	1.567	Henderson.
Do	1.548	1.561	1.567	Schaller.
Average	1.547	1.560	1.567	

Larsen[27] has noted that the best cleavage on the polyhalite from the Texas and New Mexico field shows twinning with extinction $Z' \wedge$ composition plane $= 28°$. Other cleavage shows two sets of twinning at about 90° with extinction X' to composition plane of commoner twin $= 28°$.

[26] Goergey, R., Ueber die Krystallform des Polyhalits: Min. pet. Mitt., Band. 33, pp. 48–102, 1915.
[27] Larsen, E. S., The microscopic determination of the nonopaque minerals, 2d ed.: U. S. Geol. Survey Bull. ——— (in preparation).

The chemistry of the polyhalite from the Texas and New Mexico field has been studied by George Steiger, of the Geological Survey. His results are as follows:

Two samples obtained from cuttings from the McDowell well, Glasscock County, Tex., were completely analyzed. Sample 1 was a rather coarsely crystalline brick-red variety, and sample 2 was a fine-grained compact salmon-colored variety. Both were remarkably pure, agreeing closely with the theoretical composition.

Analyses of polyhalite from Texas

[Analyst, George Steiger]

	1	2	Theoretical
Insoluble	0.27	0.39	
CaO	18.75	18.54	18.63
MgO	6.48	6.16	6.68
Na$_2$O	None.	.20	
K$_2$O	15.66	15.37	15.61
H$_2$O	6.07	6.50	5.96
SO$_3$	52.40	52.60	53.12
Cl	None.	None.	
	99.63	99.76	100.00

The water loss on sample 1 was as follows: Up to 125°, 0.05 per cent; at 150°, 0.05 per cent more; and at 180°, another 0.05 per cent; at a low red heat, 5.92 per cent; total, 6.07 per cent. Sample 2 lost 0.05 per cent at 130°, an additional 0.08 per cent at 250°, and 6.37 per cent at a low red heat; total, 6.50 per cent. A third sample, not analyzed, from the Means well (near the Eldridge well), in the northern part of Loving County, Tex., lost 0.40 per cent up to 280° with a total loss at a low red heat of 6.06 per cent. These determinations verify the results found by Lueck [28] that the water content of polyhalite is retained until a temperature of 340° is reached, when both molecules of water are given off.

PYRITE

Pyrite, FeS$_2$ (Fe, 46.6; S, 53.4 per cent) seems to be neither abundant nor widespread in these cores. Minute quantities have been observed in only two cores. A small mass was found in polyhalite from Government hole No. 13 at a depth of 1,281 feet 3 inches, and minute crystals were embedded in anhydrite from the Gypsy No. 4 well, at unknown depth.

---

[28] Lueck, Hugo, Beitrag zur Kenntnis der älteren Salzgeberger (Inaug. Diss.), p. 5, Leipzig, 1913.

QUARTZ

Quartz, SiO_2, is not common in these cores, but it has been detected in several. The largest crystals observed are about 2 millimeters in length and came from a depth of about 1,200 feet in one of the private wells. It occurs as imperfect crystals about 1 millimeter thick and readily recognized by the unaided eye embedded in polyhalite from the Gypsy No. 3 well at depths of 1,167 to 1,168 feet and 1,181 feet 11 inches to 1,183 feet 3 inches. Minute doubly terminated crystals were obtained from polyhalite from Government hole No. 8 at a depth of 595 feet 6 inches, when all the saline minerals were dissolved in acid. The quantity of quartz crystals present was about 0.04 per cent of the total core. In Government hole No. 12, at a depth of 1,368 feet 7 inches to 1,369 feet 2 inches, small quartz crystals were embedded in carnallite.

The mineral is probably more abundant than here recorded, having escaped detection, as no special search was made for it.

SYLVITE

Sylvite, KCl (K, 52.4 corresponding to 63.2 K_2O; Cl, 47.6 per cent), has been found in all but 2 of the 22 private wells drilled in Eddy County, N. Mex. It is present in the cores from Government holes Nos. 1, 2, 12, 13, 17, and 18.

It is characteristically of a reddish or reddish-brown color but may be either colorless or milky white. The color, however, can not be used as a criterion for distinguishing sylvite from halite, for some halite has the same color. Some of the sylvite from these cores has a peculiar milky-white or chalcedonic appearance, which was not observed in any of the halite. The sharper taste of sylvite, more biting than the salty taste of halite, usually differentiates it. The violet color it imparts to the flame quickly and definitely separates it from halite, which gives a strong yellow. Another distinguishing test lies in the fact that sylvite is not as brittle as halite. If a small piece of halite is gently pressed between two pieces of glass, it will crush into a fine powder, whereas a piece of sylvite similarly treated will not break into a powder but will flatten out like wax. F. C. Calkins has noted that pieces of sylvite when placed in water will crackle, whereas halite does not.

Sylvite has a cubical cleavage like that of halite. The surest way of identifying it is by optical examination, for it is isotropic with an index of refraction of 1.490, considerably lower than that of halite (1.544). Therefore any index oil with a refractive index between 1.50 and 1.53 serves as a medium for separating sylvite and halite. There is also a decided tendency for the reddish-brown pigment (hematite) to permeate all the sylvite, whereas in much of the halite

the pigment is in bands and streaks. Specimens of what appeared to be reddish-brown halite were seen to contain many colorless masses when examined microscopically.

Sylvite does not form large beds of pure material but is invariably mixed with halite and especially with small quantities of clay. Mixtures of halite and sylvite are known as sylvinite. (See pl. 37, in which the darker mineral is sylvite.)

The sections of core richest in sylvite show a potash content indicating the presence of about 50 per cent of sylvite. The richest section analyzed, from the Blanchard No. 2 well, showed 3 feet with a K_2O content of 34.80 per cent, indicating 55 per cent of sylvite. This 3-foot bed is a portion of a larger bed 11 feet 9 inches thick, at a depth of 921 feet 4 inches to 933 feet 1 inch, which averages 25.87 per cent of K_2O, the equivalent of 40.9 per cent of sylvite.

Sylvite occurs in blebs or thin layers with halite in zones that are nearly free from both anhydrite and polyhalite. Where it has formed in zones of halite that contain clay, the clay is invariably confined to the halite. In many places the clay makes up a large percentage of the sylvite-bearing portions of the core, and the sylvite inclusions become very irregular, yet little or no clay is found inclosed in the sylvite itself. In such associations small veinlets or rounded masses of polyhalite are locally found, generally in the clay.

The association of polyhalite and sylvite was noted particularly in several of the private cores from Eddy County, N. Mex. The thin seams of sylvite have the appearance of having replaced the polyhalite.

There seem to be two separate generations of sylvite. One is colorless and the other is reddish brown, but it can not be said that all sylvite that possesses a similar color is of the same generation. The evidence, however, indicates that the colorless variety is the older of the two. There is more reddish sylvite than colorless, and where the two occur together the larger blebs of the colorless variety are in many specimens surrounded by the reddish sylvite. No bleb with a reddish center and a white outer edge has yet been found. Therefore it appears that when the second generation of sylvite was introduced the solutions were rich in iron, because this generation of sylvite is very uniformly reddish. These solutions had some effect upon the earlier, colorless sylvite, because its outer edges have a reddish fringe.

The large quantities of clay associated with sylvite suggest the possibility that the solutions carrying sylvite have followed more or less irregular clay beds. It may be that the iron present in these sylvite solutions was leached from the clay, because the sylvite associated with the clay is generally reddish, and the large colorless masses of sylvite occur in parts of the core that contain little or no clay.

The suggestion that the reddish and the white sylvite represent two generations is based on the character of the sylvite in the cores received in Washington.   In many of these cores all the sylvite is reddish or reddish brown, with no indication that it has ever been white or colorless.   In a very few sections of core, however, the reddish sylvite forms only a narrow zone separating the milky-white sylvite from the surrounding halite and also penetrating cracks and cleavage planes in the white sylvite, as shown in Plate 38.   Such a relation confirms the previous statement that the reddish sylvite is later than the white, but it also suggests a process by which, if continued long enough, all the white sylvite could be changed to reddish sylvite.   The process of coloration consists of the introduction of hematite, either with or without the introduction of additional sylvite.

IDENTIFICATION OF THE MINERALS

GENERAL FEATURES

The following outline is presented for the purpose of enabling anyone interested to identify readily the various saline minerals found in the saline deposit of Texas and New Mexico.   Two methods are given, serving two purposes.   The first one is intended to enable a person not familiar with mineralogy to identify the minerals by their appearance and general properties.   The second method is based on optical determinations and requires a petrographic microscope with the necessary accessories, a set of immersion oils, and a knowledge of the methods of petrographic manipulation and study.   The first method is very general and is qualitative, no quantitative determinations being made; the second method is strictly quantitative and is based on the determination of the refractive indices of the minerals. In the qualitative method the determinations are made on what are generally called the physical properties, such as color, taste, and cleavage.   These properties are so well known that they need no definition.   The observer needs only to be cautious that the mineral investigated must be a single substance and not a mixture, for obviously a mixture has different properties from those of any one of its constituents.

In addition to the minerals already found in this field, there are added others found in European localities, any of which may occur in this field.   The list of minerals considered, arranged alphabetically, is as follows:

Aphthitalite (glaserite), $(K, Na)_2SO_4$.
Anhydrite, $CaSO_4$.
Ascharite, $Mg_2B_2O_5.H_2O$ (?).
Astrakanite.   See Bloedite.
Bischofite, $MgCl_2.6H_2O$.
Bloedite (astrakanite, simonyite, warthite), $MgSO_4.Na_2SO_4.4H_2O$.

Boracite, $5MgO.MgCl_2.7B_2O_3$.
Carnallite, $MgCl_2.KCl.6H_2O$.
Celestite, $SrSO_4$.
Chlorocalcite.   See Hydrophilite.
Douglasite, $FeCl_2.2KCl.2H_2O$.
Epsomite (reichardite), $MgSO_4.7H_2O$.
Glaserite.   See Aphthitalite.

Glauber salt. See Mirabilite.
Glauberite, $CaSO_4.Na_2SO_4$.
Gypsum, $CaSO_4.2H_2O$.
Halite (rock salt, salt), $NaCl$.
Heintzite. See Kaliborite.
Hematite, Fe_2O_3.
Hintzeite. See Kaliborite.
Hydrophilite (chlorocalcite), $CaCl_2.$
H_2O (?).
Kainite, $MgSO_4.KCl.3H_2O$.
Kaliastrakanite. See Leonite.
Kalibloedite. See Leonite.
Kaliborite (heintzite, hintzeite), $K_2O.$
$4MgO.11B_2O_3.18H_2O$.
Kaluszite. See Syngenite.
Kieserite, $MgSO_4.H_2O$.
Koenenite, $Al_2O_3.3MgO.2$ or 3 $MgCl_2.$
6 or 8 H_2O.
Langbeinite, $2MgSO_4.K_2SO_4$.
Leonite (kaliastrakanite, kalibloedite),
$MgSO_4.K_2SO_4.4H_2O$.
Loeweite, $MgSO_4.Na_2SO_4.2\frac{1}{2}H_2O$.
Lueneburgite, $3MgO.B_2O_3.P_2O_5.8H_2O$.
Magnesite, $MgCO_3$.

Mirabilite (Glauber salt), $Na_2SO_4.$
$10H_2O$.
Picromerite (schoenite), $MgSO_4.K_2SO_4.$
$6H_2O$.
Pinnoite, $MgB_2O_4.3H_2O$.
Polyhalite, $2CaSO_4.MgSO_4.K_2SO_4.$
$2H_2O$.
Reichardite. See Epsomite.
Rinneite, $FeCl_3.3KCl.NaCl$.
Rock salt. See Halite.
Salt. See Halite.
Schoenite. See Picromerite.
Simonyite. See Bloedite.
Sulphoborite, $H_4Mg_6(BO_3)_4.(SO_4)_2.$
$7H_2O$.
Sylvite, KCl.
Syngenite (kaluszite), $CaSO_4.K_2SO_4.$
H_2O.
Tachhydrite, $2MgCl_2.CaCl_2.12H_2O$.
Thenardite, Na_2SO_4.
Vanthoffite, $MgSO_4.3Na_2SO_4$.
Warthite. See Bloedite.
Zirklerite, $2(Al_2O_3.H_2O).9(Fe, Mg, Ca)$
$Cl_2.2H_2O$.

The following minerals have been omitted from this list because their individuality is questionable and their optical constants are not known: Almerinaite, $KCl.NaCl.MgCl_2.H_2O$ (?); chlorothionite, $K_2SO_4.CaCl_2$ (?).

In addition to these minerals of the salt deposits, there are a few nonsaline accessory minerals which have been reported from some of the European deposits. These are quartz, magnetite (in black carnallite), pyrite, sulphur, and possibly rutile.

The following terms have been used a great deal in the descriptions of saline mineral associations in European localities, especially in Germany:

Abraumsalt is a mixture of carnallite, sylvite, and kieserite.
Haupsalz is a mixture of kieserite, halite, and carnallite.
Hartsalz is a mixture of kieserite, sylvite, and halite.
Thanite is a mixture of halite and kainite.
Sylvinite is a mixture of halite and sylvite.

Other terms have been proposed, such as carnallitite (carnallite and halite) and kainitite (kainite and halite). Two or more mineral names have also been run together into one word for such a mixture. Krugite is a mixture of polyhalite and anhydrite.

QUALITATIVE METHOD

Color.—All the minerals listed, if free from any impurities, should be colorless in clear crystals or white or gray in compact massive form. However, it is very common for several of them to be strik-

ingly colored by impurities—for example, both the polyhalite and the sylvite from the Texas and New Mexico field are generally reddish brown, owing to the inclosed impurities (finely disseminated iron oxide). Thus color in itself is no absolute criterion. Bloedite, for example, has been found at different localities in the world in yellow, red, and green varieties; kainite in yellow, red, and blue varieties; and even halite in yellow, red, and blue varieties as well as white or colorless. But even if color is not a diagnostic property of positive value it can be used with discretion, and therefore the colors shown by the saline minerals of the Texas and New Mexico field are here listed.

Red to reddish brown: Polyhalite, sylvite, halite, glauberite, carnallite, gypsum. Pink or pale purplish: Polyhalite, carnallite, langbeinite. Blue: Halite. White, colorless, or gray: Anhydrite, halite, sylvite, polyhalite, kieserite, magnesite, langbeinite, glauberite. Yellowish: Kainite, leonite, polyhalite.

The reddish-brown color is due to a small quantity of iron oxide (hematite) scattered through the mineral. In many specimens the small six-sided plates of hematite could be clearly recognized under the microscope. In some specimens of halite the coloring matter remains behind as a thin skin if the halite is dissolved in water. The source of the coloring matter (iron) is probably in the clay. In many specimens the masses that show much red sylvite contain gray or greenish clay which originally may have been red but may since have been reduced and changed in color by solutions.

Taste.—Many of these minerals have a decided taste, as indicated below:

Tasteless	Slightly salty or bitter	Salty	Bitter	Stinging bitter
Anhydrite. Gypsum. Kieserite. Langbeinite. Magnesite. Polyhalite.	Glauberite. Leonite. Epsomite.	Halite.	Kainite.	Bloedite. Carnallite. Sylvite.

Solubility in water.—The minerals listed below as soluble will readily go into clear solution in water. Those listed as attacked do not go into clear solution but are decomposed by water, generally showing accompanying phenomena.

Soluble	Attacked	Insoluble
Bloedite. Carnallite. Epsomite. Halite. Kainite. Langbeinite (slow). Leonite. Sylvite.	Glauberite (becomes white). Polyhalite (becomes white, being coated with gypsum crystals).	Anhydrite. Gypsum. Kieserite. Magnesite.

Effect of exposure to air.—On exposure to air epsomite and mirabilite fall to a white powder; bischofite and carnallite attract moisture and become wet, though in a region of low humidity, like the Texas-New Mexico area, this effect may hardly show; kieserite and langbeinite slowly develop an efflorescence.

Cleavage.—The following minerals show good cleavage:

Anhydrite: Three rectangular cleavages.
Glauberite: One good cleavage.
Gypsum: One excellent cleavage.
Halite and sylvite: Cleave into cubes.

OPTICAL METHOD

The optical method requires apparatus and experience but is by far the best method for the definite and quick determination of the minerals. Those desirous of studying this method should refer to a report by Larsen,[29] and those wishing to follow up the optical examination of the saline minerals to a paper by Goergey.[30]

The method of identifying these saline minerals is based on the refractive indices and other optical properties. These indices can be measured readily and accurately under the microscope by the oil immersion method. The indices for the saline minerals, both those listed in this report and those found in other saline fields, are given in Plate 39. The indices are indicated by short vertical lines—one for isotropic minerals, two for uniaxial minerals (ω and ϵ), and three for biaxial minerals (α, β, and γ).

The horizontal line joining the vertical lines that represent the indices gives the birefringence or double refraction. The minerals are arranged according to an increasing value of the middle index β, or the mean index $\frac{(2\omega + \epsilon)}{3}$ for uniaxial minerals. The position of β relative to α and γ gives considerable additional information. If β is closer to α, the mineral is positive; if closer to γ, the mineral is negative. The position of β relative to both α and γ also gives a good indication of the size of the optic axial interference angle (which is, of course, only a direct function of the refraction indices). For uniaxial minerals, the sign is placed after the horizontal line joining (ω and ϵ).

For the preliminary placement of an unknown mineral to be determined by this optical method, the lines representing indices in units of 0.01 are good division lines. On the left side of Plate 39 the same minerals are arranged according to increasing birefringence. The determinations of the indices used on Plate 39 are taken in part from

---

[29] Larsen, E. S., The microscopic determination of the nonopaque minerals: U. S. Geol. Survey Bull. 679, 1921. (Second edition in preparation.)

[30] Goergey, R., Zur Kenntniss der Minerale der Salzlagerstätten: Min. pet. Mitt., Band 29, pp. 192–210, 1910.

the literature, chiefly from Goergey and Larsen, averaged with determinations made in the laboratory of the United States Geological Survey. Many of the determinations of the other minerals were checked.

Anhydrite.—The following refractive indices of anhydrite are given in the literature:

α	β	γ
1. 5696	1. 5755	1. 6136
1. 5693	1. 5752	1. 6130
1. 5700	1. 5757	1. 6138
1. 5698	1. 5753	1. 6137
1. 5695	1. 5757	1. 6135
		1. 6135
		1. 6139
Av. 1. 570	1. 575	1. 614

Aphthitalite.—As aphthitalite varies in the ratio of K and Na, its refractive indices also vary.

ω	ϵ	Determined by
1. 487	1. 492	Washington and Merwin.[a]
1. 490	1. 496	Do.
1. 490	1. 500	Quoted by Goergey.
1. 491	1. 499	Quoted by Goergey; used by Larsen.
1. 493	1. 501	Determined by Goergey.
Av. 1. 490	1. 498	

[a] Am. Mineralogist, vol. 6, p. 122, 1921.

Ascharite.—Larsen gives $\alpha = 1.53$, $\beta = \gamma = 1.55$. If ascharite is identical with szaibelyite (same as camsellite)[31] the indices should be about $\epsilon = 1.58$ and $\omega = 1.65$, and the supposed ascharite on which Larsen made his determination is another mineral. The values 1.53 and 1.55, given by Larsen, are provisionally accepted. Attempts to prepare ascharite artificially (following Van't Hoff's directions) from artificial pinnoite were not successful.

Bischofite.—

α	β	γ	Determined by
1. 495	1. 507	1. 528	Goergey.
1. 492	1. 506	1. 519	Henderson (Stassfurt).
Av. 1. 494	1. 507	1. 524	

Bloedite.—Examination of several samples of bloedite showed that all indices were below 1.485, and Goergey's figures are considered to be a little high.

	α	β	γ	Determined by
Ischl (?)	1. 486	1. 488	1. 489	Goergey.
Estancia Valley, N. Mex.	1. 481	1. 483	1. 484	Henderson.
Stassfurt	1. 481		1. 484	Henderson.
Average	1. 481	1. 483	1. 484	

[31] Schaller, W. T., Am. Mineralogist, vol. 13, p. 230 (footnote), 1928.

Carnallite.—The averages given in this paper—namely $\alpha = 1.467$, $\beta = 1.474$, $\gamma = 1.496$—are used.

Epsomite.—

α	β	γ
1.4324	1.4553	1.4612
1.4325	1.4554	1.4608
1.4319	1.4549	1.4602
1.4321	1.4553	1.4608
1.4326	1.4554	1.4609
Av. 1.432	1.455	1.461

Glauberite.—The averages, $\alpha = 1.513$, $\beta = 1.532$, $\gamma = 1.535$, are used.

Hydrophilite.—The refractive indices are those given by Slawson.[32]

Kainite.—The averages given in this paper—$\alpha = 1.494$, $\beta = 1.505$, $\gamma = 1.516$—are used.

Kieserite.—The averages given in this paper—$\alpha = 1.520$, $\beta = 1.533$, $\gamma = 1.584$—are used.

Langbeinite.—The average 1.533 is used.

Leonite.—The averages $\alpha = 1.479$, $\beta = 1.482$, $\gamma = 1.487$ are used.

Lueneburgite.—The averages $\alpha = 1.521$, $\beta = 1.541$, $\gamma = 1.547$ are used.

Mirabilite.—

	α	β	γ	Determined by
Artificial	1.396	1.410	[a] 1.419	Rosizky, quoted by Goergey.
Artificial	1.393		1.397	Schaller.
Recrystallized, California	1.391	1.394	1.396	Do.
	1.394	1.396	1.398	Larsen.
Average, omitting the first determination	1.393	1.395	1.397	

[a] Calculated.

Repeated determinations on artificial mirabilite showed that the indices given by Rosizky can not be correct. The substance has a very low birefringence, like bloedite. The highest index, γ, is always below 1.40.

Pinnoite.—Determinations on artificial pinnoite (by Schaller) gave $\omega = 1.562$, $\epsilon = 1.574$, agreeing with the determinations on the natural mineral ($\omega = 1.565$, $\epsilon = 1.575$).

Polyhalite.—The averages $\alpha = 1.547$, $\beta = 1.560$, $\gamma = 1.567$ are used.

Thenardite.—

	α	β	γ	Determined by—
Spain	1.471	1.477	1.485	Goergey.
California	1.471	1.477	1.484	Do.
Do	1.464	1.474	1.485	Larsen.
Estancia Valley, N. Mex	1.465	1.475	1.485	Schaller.
Nevada	1.466	1.473	1.482	Henderson.
Average	1.465	1.474	1.484	

[32] Slawson, C. B., Note on hydrophilite: Am. Mineralogist, vol. 14, p. 160, 1929.

According to their optical properties, the minerals may also be arranged in groups, as follows:

Isotropic: Sylvite, langbeinite, halite.

Weak birefringence (less than 0.010): Rinneite, bloedite, mirabilite, vanthoffite, leonite, aphthitalite, tachhydrite, celestite.

Moderate birefringence (from 0.010 to 0.024): Gypsum, pinnoite, boracite, douglasite, hydrophilite, picromerite, sulphoborite, syngenite, thenardite, loewite, ascharite, polyhalite, kainite, glauberite.

Strong birefringence (higher than 0.024): Lueneburgite, epsomite, carnallite, bischofite, anhydrite, kaliborite, kieserite, magnesite.

Twinning is also a characteristic feature of some of the minerals, as observed under the microscope.

Commonly twinned, but not markedly polysynthetically: Gypsum, kieserite, leonite, polyhalite. Polysynthetically twinned: Carnallite, kainite, leonite, polyhalite.

PLATES

PLATE 1

BANDED ANHYDRITE ROCK

A. Common form of anhydrite rock banded with thin, fairly regular, nearly horizontal layers of magnesite (light gray). From Government hole No. 4, depth unknown. A little polyhalite is present in the extreme upper part.

B. Similar banded anhydrite rock with much thicker layers of magnesite (light gray) which are not as continuous nor as regular as those in *A.* From Government hole No. 1, at a depth of 1,287 feet 4 inches to 1,287 feet 6 inches. On the lower left are irregular patches of magnesite, and toward the bottom the layers tend to form eyes or lenses. The dark patches in the upper portion (due to an organic stain) are unusual.

C. Similar banded anhydrite rock with the thin layers of magnesite (dark) very crinkly. From the Eldridge well at a depth of about 1,165 feet. The distribution of the magnesite through the anhydrite is shown much enlarged in Plate 17, *A.* Microscopic observation shows that the bands, instead of being continuous solid layers, are more or less dense aggregates of magnesite crystals or groups of crystals.

D. Similar banded anhydrite rock with thin layers of magnesite (light gray) at the top, a thick layer at the lower middle, and interrupted layers at the lower part. From Government hole No. 6, depth unknown. At the top and bottom are zones of nearly vertical halite (dark) which in places have disrupted the horizontal continuity of the layers of magnesite. Small isolated areas of halite (dark) are also shown in different parts of the specimen.

The specimens here illustrated give a conception of the texture and structure of the anhydrite rock. In *A, B,* and *C* anhydrite and magnesite are practically the only minerals present. *D* contains also a little halite, which was introduced later; and its effect on the structure of the preexistent rock is shown by the partial disruption of the layers of magnesite.

84

BANDED ANHYDRITE ROCK

PLATE 2

UNUSUALLY WELL BANDED ANHYDRITE ROCK
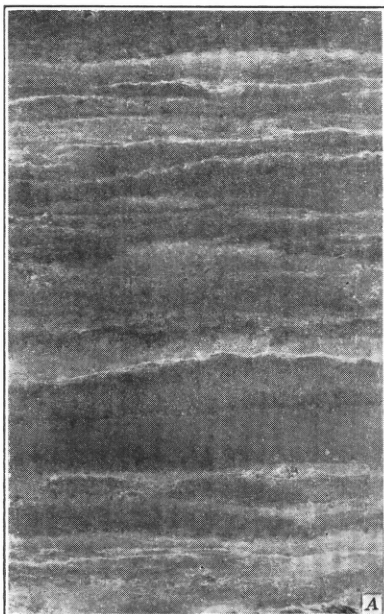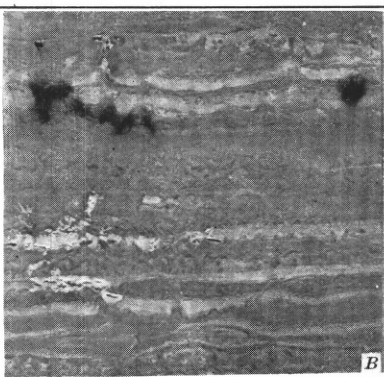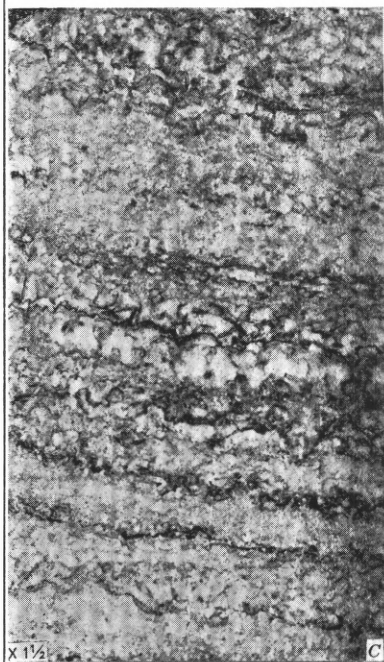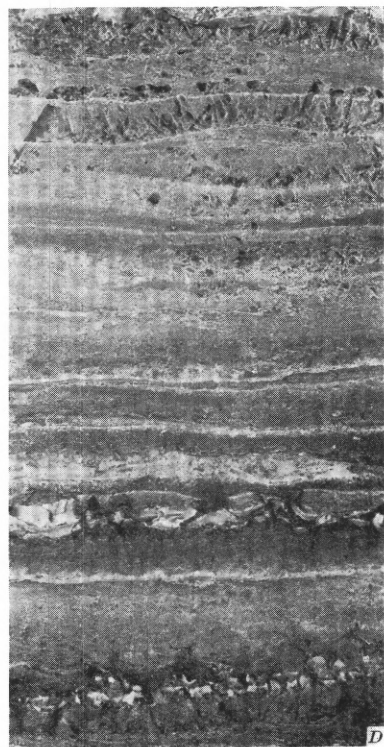
A. Anhydrite rock, unusually well banded. From Government hole No. 11 at a depth of 1,428 feet 4 inches to 1,428 feet 8 inches. The nearly white layers are magnesite, some of which swell and pinch and approach a lens-like structure, whereas others are fairly straight and continuous. In the upper portion are small aggregates of halite containing a little reddish-brown polyhalite.

B. Similar banded anhydrite rock from the same well as *A* at a depth of 1,428 feet 8 inches to 1,429 feet. The apparently bent layers in the upper portion are probably part of a small lens-like group of bands. The layers of magnesite in the upper portion are much thinner and more crowded than the much thicker layers at the bottom of the specimen. The irregular vertical distribution of the layers of magnesite is well shown.

C. The bands are unusually crinkled. From Government hole No. 13, at a depth of 1,532 feet 1 inch to 5 inches. The bands are even more crinkled than in the specimen shown in Plate 1, *C.* Such a crinkled specimen may represent the original rock, which when more or less replaced by polyhalite and other minerals would yield specimens with a crinkly appearance, as shown in Plates 26, *B*, and 27, *C.*

In these specimens the banded character of the anhydrite rock is more strikingly shown than in Plate 1, but such an occurrence is unusual in the cores thus far studied.

85
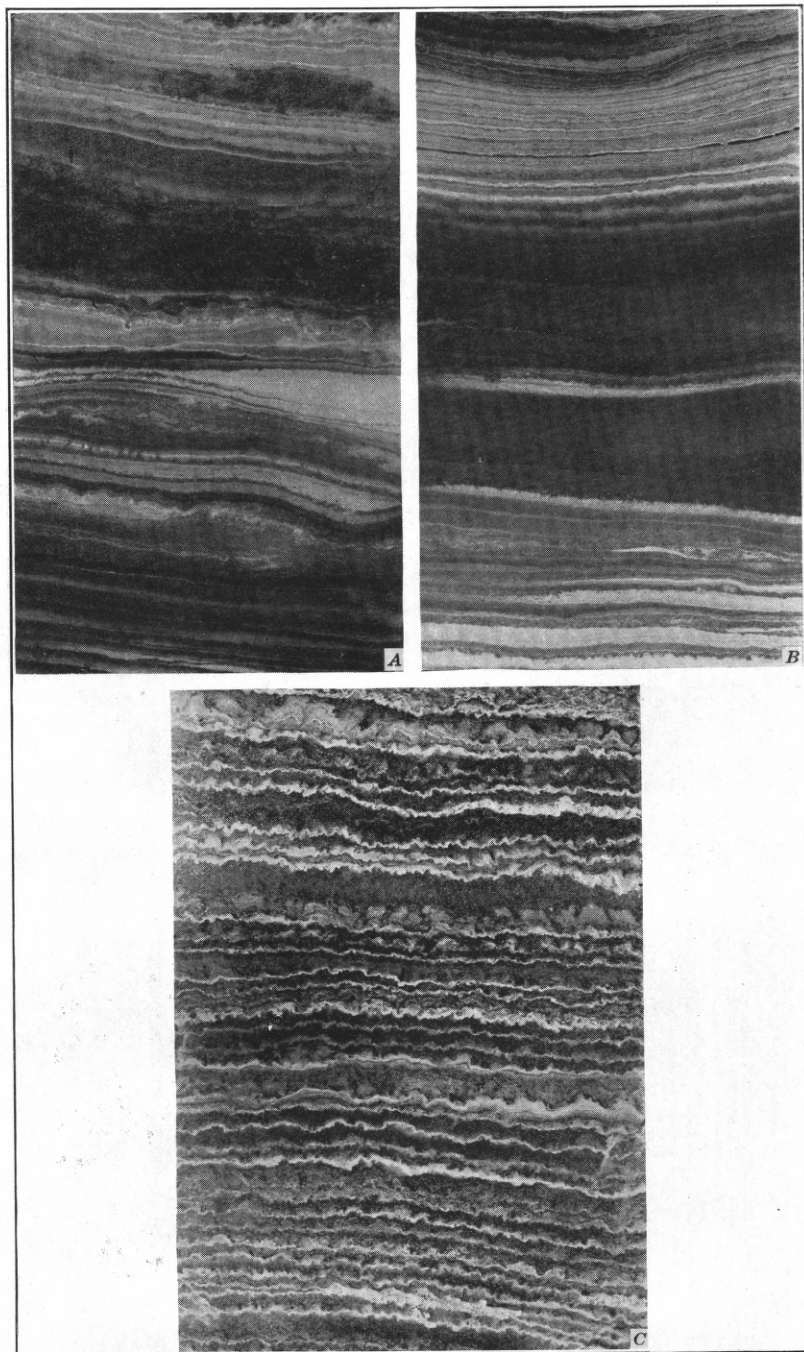
UNUSUALLY WELL BANDED ANHYDRITE ROCK

PLATE 3

ANHYDRITE ROCK WITH OTHER MINERALS

A. Alternating layers of anhydrite and halite, the latter partly dissolved by the drilling solution. From Eldridge well at a depth of about 1,172 feet. Outside of core shows how ordinary water used as a drilling brine solution has dissolved the halite. The anhydrite layers contain a little halite, and the halite layers also contain anhydrite, which is left as thin irregular ridges; neither layer consists entirely of a single mineral. There is also much isolated halite in the anhydrite between two layers of halite. Magnesite and prismatic casts of an unknown mineral are present in some of the layers but are too small to show in the illustration.

B. Anhydrite rock with magnesitic clay. From Government hole No. 2 at a depth of 886 feet 8 inches to 887 feet. The clay is highly magnesitic and grades into the anhydrite above, becoming gradually less in amount. There is enough of the magnesitic clay in the lower portion of the specimen to color it a light gray. The anhydrite in the upper portion (dark) has an unusual reddish tint, due to a little disseminated polyhalite, which is also present to a much smaller degree in the magnesitic clay. The irregular and contorted layers of magnesite are well shown in the middle. The top of the specimen is essentially free from clay but clearly shows the bands of magnesite, much more irregular in their form than those illustrated in Plate 1.

C. Anhydrite rock with magnesitic clay (c), layers of magnesite (m) in anhydrite above the magnesitic clay, glauberite (g), and polyhalite (p). From Government hole No. 6 at a depth of 639 feet 4 inches to 639 feet 8 inches. The lower part of the specimen shows the anhydrite banded with thick regular layers of magnesite (m) similar to those shown in Plate 1, *B*, but in the middle and upper parts, where glauberite and polyhalite are present, these bands are irregular and discontinuous. In the center of the specimen there is a 1-inch layer (g) with considerable disseminated glauberite, above which the anhydrite contains similarly disseminated polyhalite and halite. All the minerals present are fine grained and disseminated, so that the specimen as a whole does not show any appreciable area consisting of a single mineral.

86

ANHYDRITE ROCK WITH OTHER MINERALS

PLATE 4
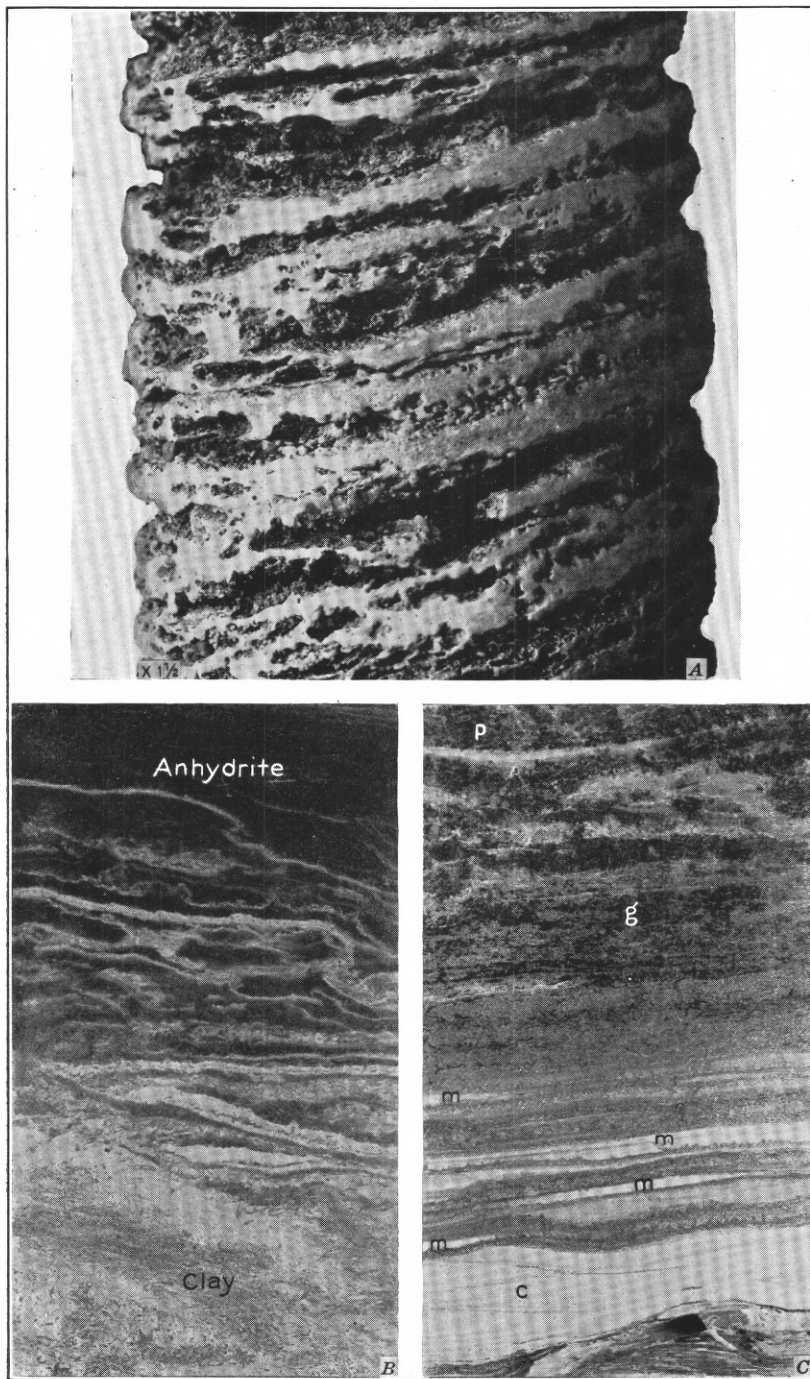
ANHYDRITE ROCK IN UNUSUAL FORMS

A. Folded layers of anhydrite (a). From Government hole No. 7 at a depth of 583 feet 10 inches to 584 feet 2 inches. The uppermost layer is bent nearly 90°. This layer is free from halite (h), which bounds it above and below. Other layers also show considerable folding and contortion. The lower half of the specimen is essentially anhydrite (a), free from halite except for small isolated areas (black). The white areas and narrow bands in the anhydrite are magnesite (m). At the extreme top of the specimen is a little polyhalite.

B. Brecciated anhydrite from Government hole No. 7 at a depth of 686 feet 2 inches to 686 feet 6 inches. Two varieties are present—a white brecciated variety and a fine-grained gray variety. The white variety is embedded in the gray or in halite. The white variety shows fine concentric lines not present in the other. The dark areas in the photograph represent halite.

C. An unusual network of thin layers of magnesite (white) in anhydrite from Government hole No. 7, depth unknown. A little polyhalite (mottled gray) and halite (black) is scattered throughout the specimen. The reticulated area contains much halite filled with many irregular, in places almost threadlike, lines of anhydrite. In the lower part polyhalite (p) is almost predominant, very little of the magnesite and anhydrite remaining. If the polyhalite was formed at the expense of the anhydrite a considerable quantity of the magnesite has likewise been attacked and changed.

87

ANHYDRITE ROCK IN UNUSUAL FORMS

PLATE 5
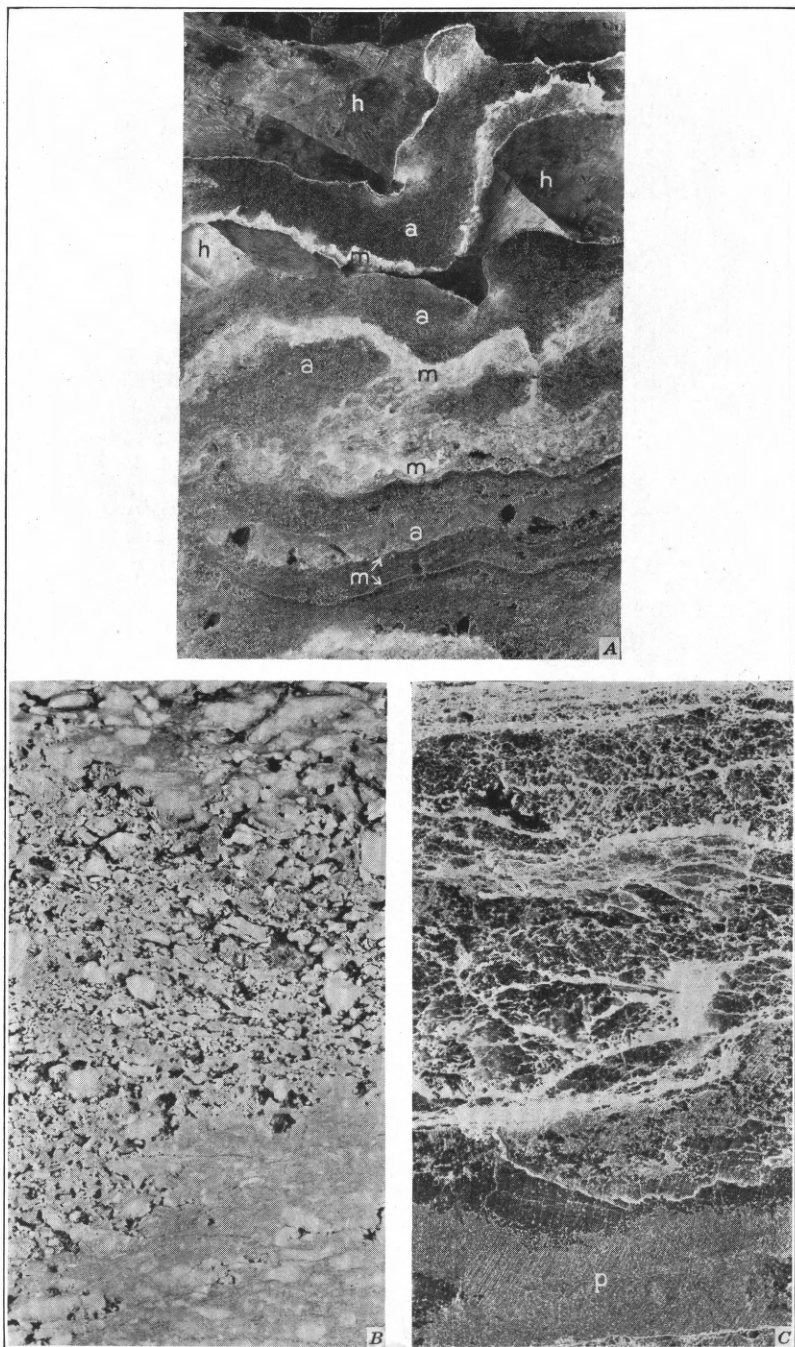
ANHYDRITE CRYSTALS PARTLY CHANGED TO POLYHALITE

A. Photomicrograph of a crystal of anhydrite (a). From the McNutt No. 1 well at a depth of 795 feet 7 inches. The crystal, shown black because it is in extinction position, has been eaten into on all sides by the fine-grained polyhalite (p) and in its center has been replaced to a large extent by a group of coarser crystals of polyhalite. At least 12 isolated and distinct areas of anhydrite, all in parallel position, can easily be recognized under the microscope. In the upper right corner is a nearly square crystal of anhydrite (shown light) which has been very little attacked. Such an association of largely replaced anhydrite crystals with others that show very little attack is not rare.

B. Photomicrograph of a crystal of anhydrite (a) attacked and partly replaced by fine-grained polyhalite (p). From Government hole No. 1, at a depth of 876 feet 7 inches. About half of the entire crystal is shown. It is in extinction position and therefore shows black. The remainder of the crystal is a continuous extension of the lower portion shown in the photograph. The entire crystal has been broken down by the attacking solution into four major pieces, all of which remain in parallel position.

C. Photomicrograph of a single anhydrite crystal (a) attacked and partly replaced by coarse-grained polyhalite (p). From the State No. 1 well at a depth of 1,359 feet 8 inches. The straight edges of many of the indentations in the outline of the crystal are due to the fact that the replacing polyhalite occurs in large crystals instead of being fine-grained, as in *A* and *B*. To the left, the anhydrite crystal has been completely severed by the invading polyhalite. The dark spots are due to magnesite.

88

ANHYDRITE CRYSTALS PARTLY CHANGED TO POLYHALITE

PLATE 6
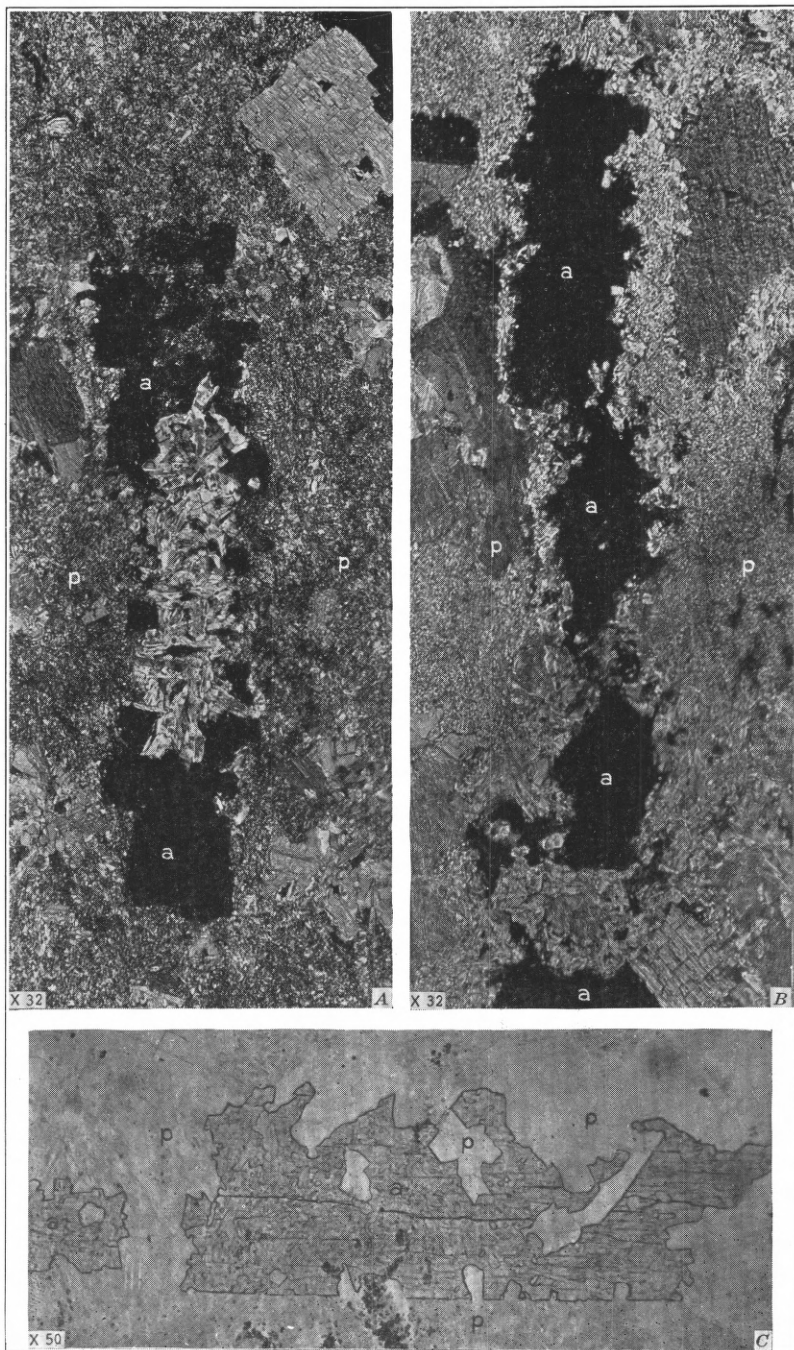
CARNALLITE AND EFFLORESCENCE OF EPSOMITE

A. Layer of carnallite nearly 2 inches thick in a mixture of clay, halite, and anhydrite. From Government hole No. 1 at a depth of 1,074 feet 4 inches to 1,074 feet 8 inches. About half of the carnallite has been dissolved by the drilling brine. Such layers of carnallite consist of the massive mineral in an almost pure form.

B. Efflorescence of epsomite on a piece of core from the McNutt No. 1 well at a depth of 798 feet 3 inches, consisting of fine-grained polyhalite through which are scattered many small crystals of kieserite (like those shown in pl. 13, A) and a few crystals of anhydrite. Most of the efflorescence shown developed on the core after it had been received in the Washington laboratory. Kieserite is especially prone to effloresce if associated with polyhalite, and the efflorescence carries with it, mechanically, small particles of the core, so that much of the efflorescence shown consists of polyhalite.

89
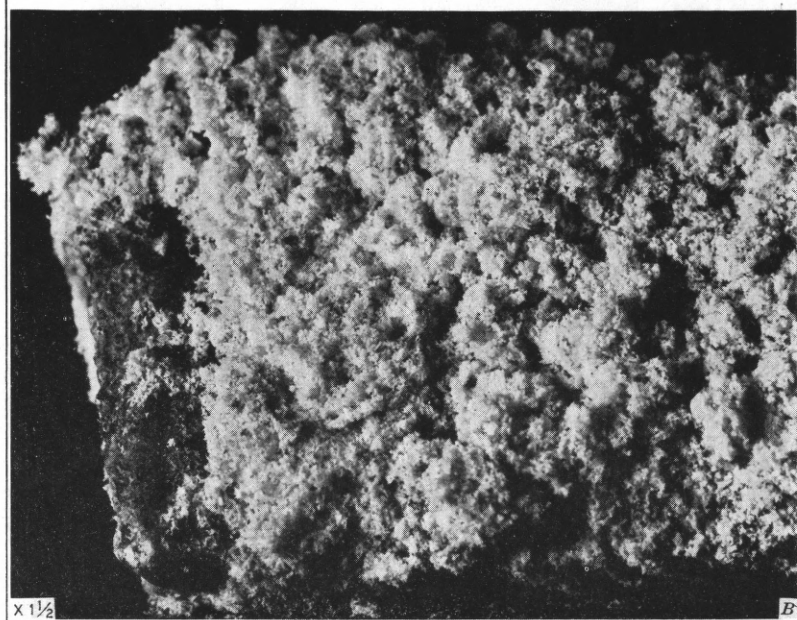
A, CARNALLITE; *B*, EFFLORESCENCE OF EPSOMITE

PLATE 7

GLAUBERITE

A. Glauberite, brown and black, with anhydrite and polyhalite, from Government hole No. 7 at a depth of 694 feet to 694 feet 4 inches. The minerals present are explained in Figure 5. The black color of part of the glauberite is most unusual. A narrow border of halite separates the glauberite (g) from the fine-grained polyhalite (p) in the upper center part. Nearly all of this halite contains crystals of polyhalite. The glauberite has a checked appearance not shown by the glauberite illustrated in *B*. The long secondary crystals of anhydrite (a) shown in the lower center are in polyhalite. The massive anhydrite rock (a) in the lower portion shows several of the thin beds of magnesite. This mineral is present in the glauberite-halite-polyhalite aggregate of the upper portion of the specimen, but here it is no longer in thin bands but has been crowded into relatively thick aggregates. A thin section of this specimen, partly shown in C, clearly demonstrates that this glauberite has been replaced in part by a mixture of halite and polyhalite.

B. Glauberite (g) above anhydrite (a) with a vertical seam of halite (h) containing a little polyhalite. From Government hole No. 7 at a depth of 691 feet 9 inches to 692 feet 1 inch. The two upper light-colored horizontal layers in the glauberite are anhydrite (a), but the third whiter layer is magnesite (m). That massive anhydrite in the lower part is more resistant to the replacing action of solutions than glauberite is well shown by the abrupt thinning of the halite seam. This lower layer of compact anhydrite contains considerable magnesite.

C. Photomicrograph of a thin section from the specimen shown in *A*, illustrating the partial replacement of glauberite (marked **X**) by a mixture of halite and polyhalite. Halite alone likewise seems to have attacked and replaced some of the glauberite. Residual areas of glauberite (gray) are scattered through the mixture of halite (black) and polyhalite (gray). They are parallel to one another and to the larger mass of glauberite at the bottom of the photograph. This larger mass of glauberite also shows faintly the development of phantom spherulites of polyhalite.

90
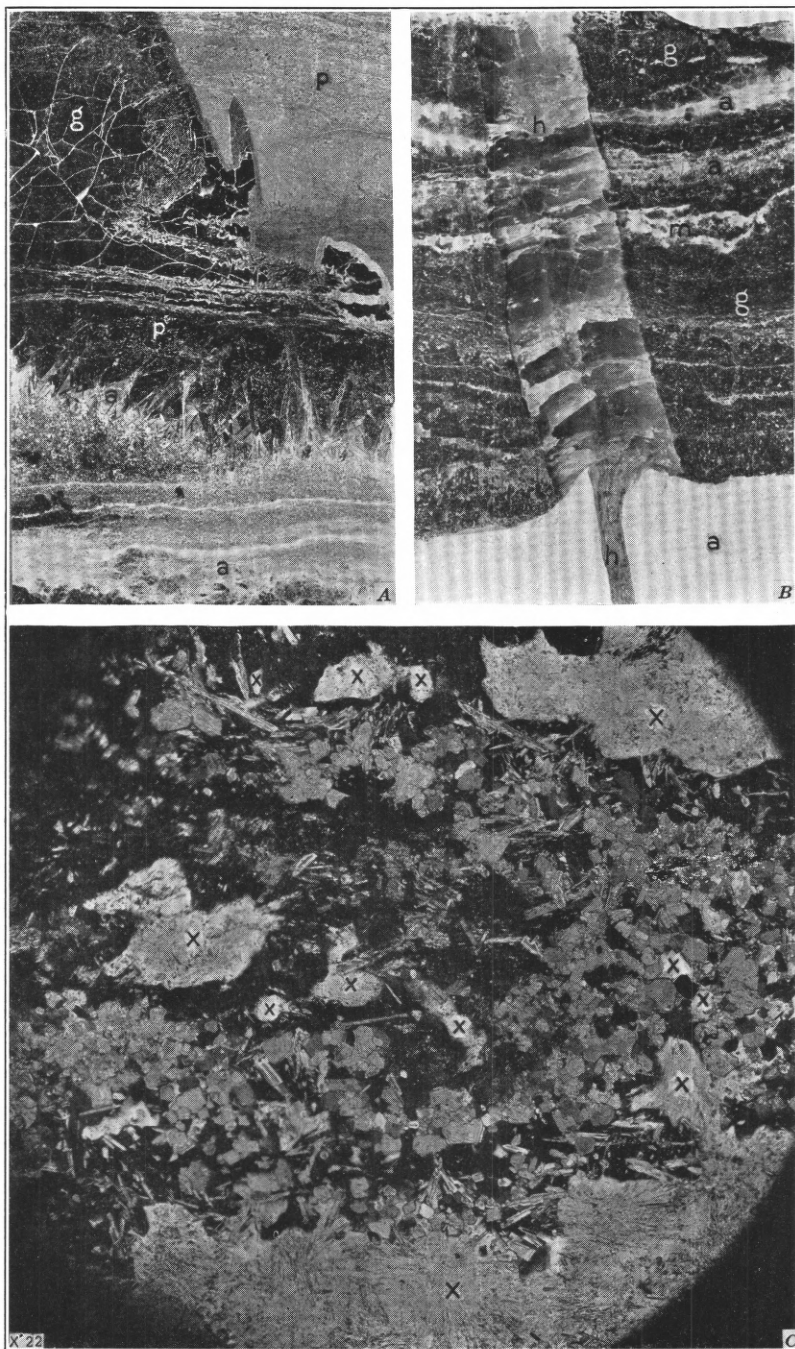
GLAUBERITE

PLATE 8

HALITE AND ANHYDRITE

A. Intergrowth of halite with banded anhydrite rock. From Government hole No. 7 at a depth of 582 feet 4 inches to 582 feet 8 inches. The masses of halite (dark) have irregular shapes, contrasting in this respect with the halite shown in *B*, but they show a pronounced tendency to be elongated in a nearly vertical direction.

B. Similar intergrowths, with more angular outlines of the masses of halite and a definite radiated structure. From Government hole No. 6 at a depth of 636 feet to 636 feet 4 inches. The regular shapes of many of the masses of halite suggest crystal forms, which are believed to represent the forms of preexisting crystals of gypsum. (See fig. 7.) Many of the radiating groups rest on a layer of magnesite, and some of the individual cry·tals break through such layers.

C. A group of the halite forms showing the "swallowtail" variety of twinned forms, closely resembling the similar twins of gypsum shown in Figure 7. From Government hole No. 6 at a depth of 636 feet 8 inches. Outside surface of core specimen. (See also pl. 9.)

D. View of the halite forms, at right angles to their elongation, showing their six-sided shape and uniformity of orientation, as indicated by cleavage. From Government hole No. 6 at a depth of 636 feet 6 inches.

91
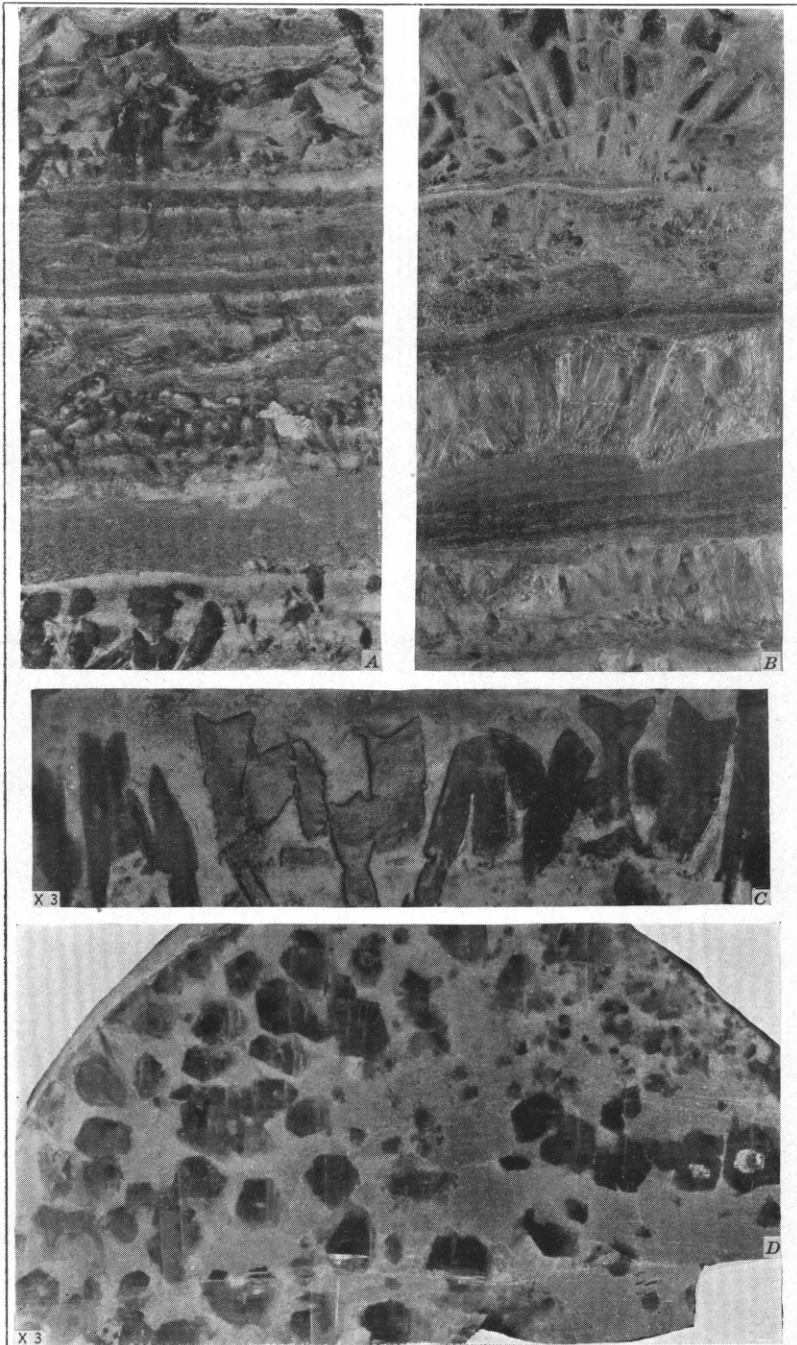
HALITE AND ANHYDRITE

PLATE 9

RADIATING GROUPS OF HALITE IN ANHYDRITE

A and *B* show the two sides of the section of core. From the Yates No. 1 well at a depth of 1,187 feet 3 inches to 1,187 feet 10 inches. The masses of halite (black) show an unusually large and well-developed form which is interpreted as being pseudomorphic after gypsum, as described in the text. The swallowtail type of twinning is the same as that shown in Plate 8, *C*, but on a much larger scale.

The core shows two groups (*A* and *B*) of radiating masses of halite, with several very well developed examples of the swallowtail type of twinning at the upper terminations. The masses of halite, unlike those shown in Plate 8, are bordered by a lacelike fringe of anhydrite much coarser than that forming the anhydrite rock. At places there is a thin seam of halite, almost free of anhydrite, between the massive anhydrite rock and the fringes of anhydrite in the halite.

The halite in the specimens is colored brownish by a little disseminated polyhalite, which is developed in considerable quantity in the upper part of the specimen in both the halite and the anhydrite rock.

92
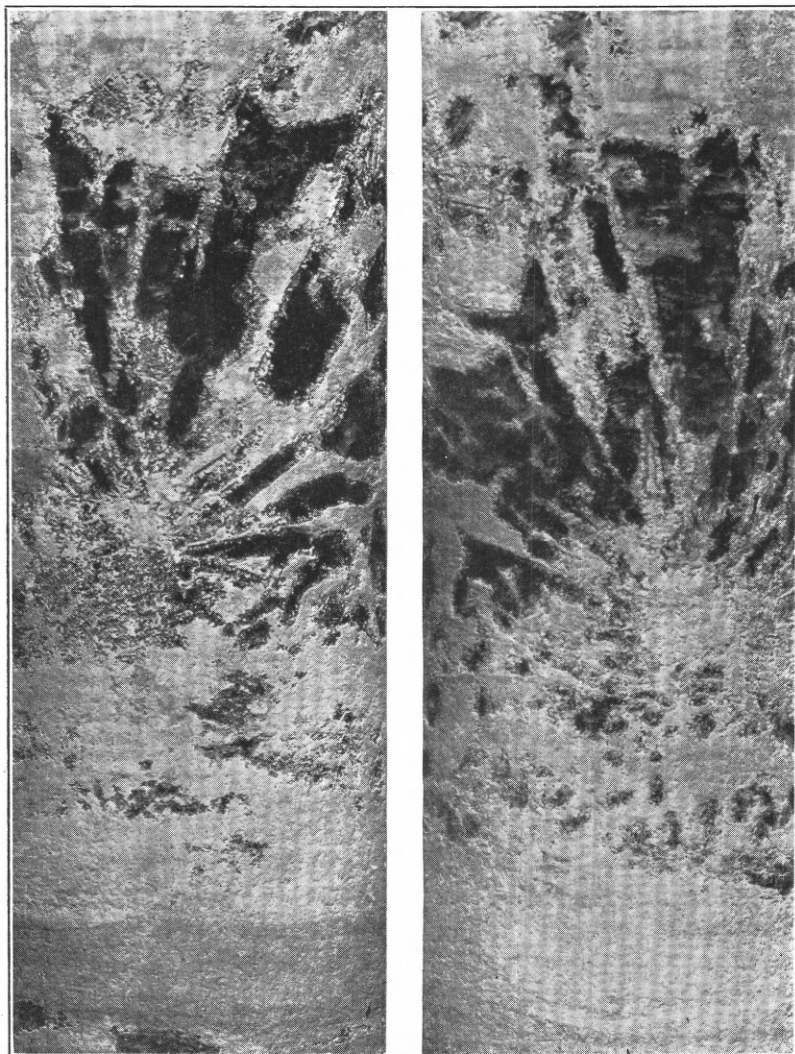
A   B

RADIATING GROUPS OF HALITE IN ANHYDRITE

PLATE 10

LONGEST OBSERVED VERTICAL GROWTH OF HALITE

Probably pseudomorphous after gypsum, in anhydrite rock, showing evidence of order of formation of anhydrite, gypsum, and halite. From Government hole No. 20 at a depth of 1,381 feet to 1,381 feet 7 inches.

The long mass of halite (black) to the right is 5½ inches long and is the longest observed example of these vertical growths of halite in the anhydrite rock. The shorter mass to the left is the right arm of a swallowtail twin extending 2 inches across horizontally.

The banded character of the anhydrite rock forming the matrix of the halite mass is due to alternating layers of anhydrite and halite with some included anhydrite. These bands are essentially horizontal where there are no vertical halite masses, as can be seen at the very top of the specimen and in the lower center. They have, however, been considerably curved upward on both sides of the vertical growths of halite, which also contain discontinuous portions of these same bands. The original continuity of these discontinuous portions of the bands with the similar nearly horizontal bands of the anhydrite rock can readily be traced. This structure indicates that the original mineral (after which the halite is pseudomorphous) grew after the formation of the banded anhydrite rock but probably before it was compacted into its present state.

93
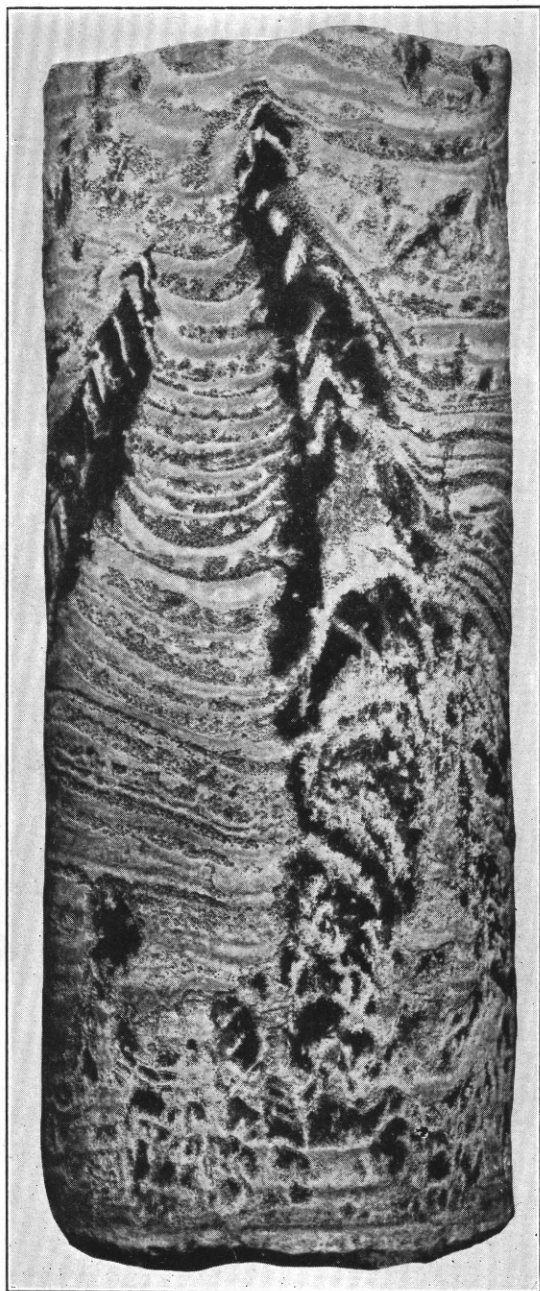
LONGEST OBSERVED VERTICAL GROWTH OF HALITE

PLATE 11

HALITE REPLACING ANHYDRITE AND GLAUBERITE

A. Photomicrograph of halite (h) replacing anhydrite (a) crystal. From State well No. 1 at a depth of 1,359 feet 8 inches. (Same slide used for pl. 5, *C*.) As halite is isotropic it appears black. Most of the halite in the thin section contains considerable polyhalite, but the halite that has replaced the earlier anhydrite contains very little polyhalite.

B. Photomicrograph of halite (h) replacing glauberite (g). From State well No. 1 at a depth of 1,221 feet. The lozenge-shaped black area is now halite, which, however, contains many inclusions of rounded and embayed residua of glauberite (g) that are nearly all similarly oriented and extinguish together. The lozengelike shape of the halite may be a transverse section inherited from a former crystal of glauberite bounded by faces of the unit pyramid *s* (111), whose angle is 63° 42'. The matrix of the black area is anhydrite rock and the prismatic crystal embedded in the halite is polyhalite (p).

94

HALITE REPLACING ANHYDRITE AND GLAUBERITE

PLATE 12
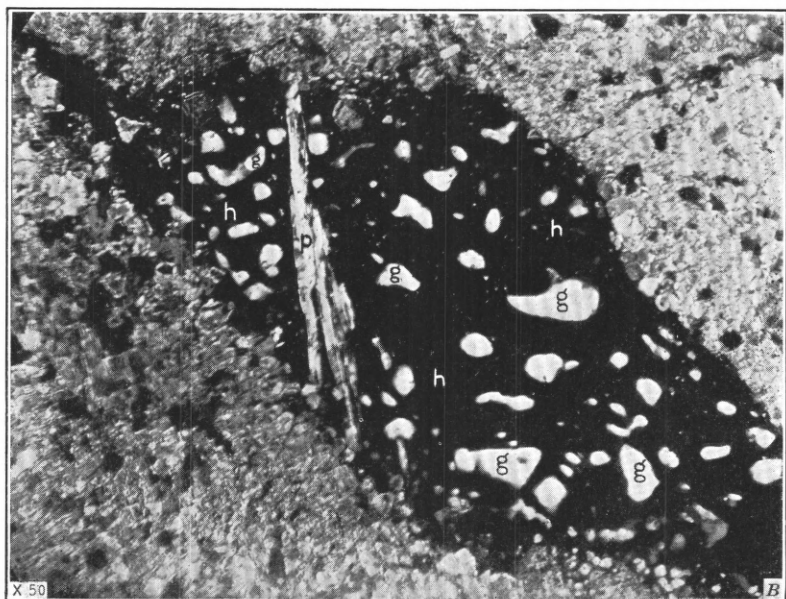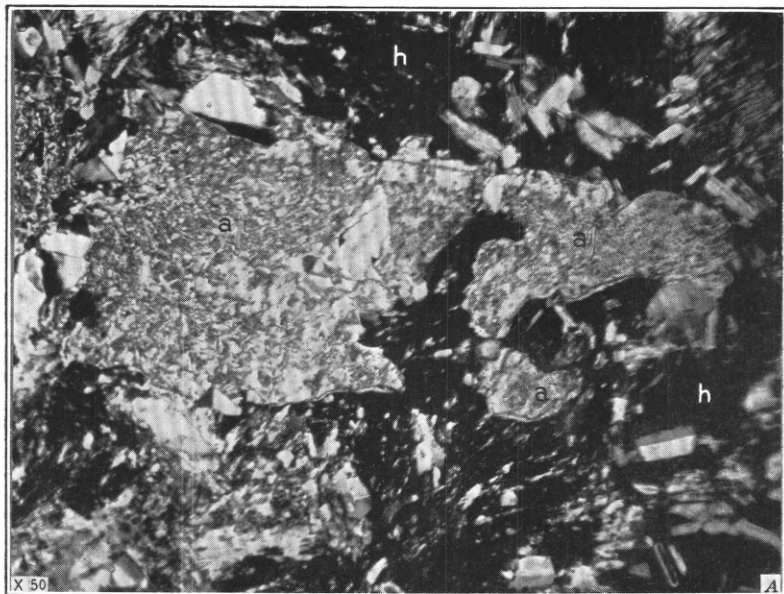
HALITE AND KAINITE

A. Halite surrounding fragments of anhydrite. From Government hole No. 7 at a depth of 840 feet. Every fragment of anhydrite (a), even the smallest, has a narrow rim of halite (h) (black). In some of the very small areas of halite that appear as solid black dots, especially in the upper right portion, no anhydrite centers can be seen. Examination of a thin section clearly shows that the halite has attacked and replaced the anhydrite, microscopic fragments of such residual anhydrite being seen in the halite. The matrix is magnesitic clay.

B. Photomicrograph of kainite. From the McNutt No. 1 well at a depth of 1,267 feet 6 inches. Under crossed nicols, showing characteristic fibrous structure.
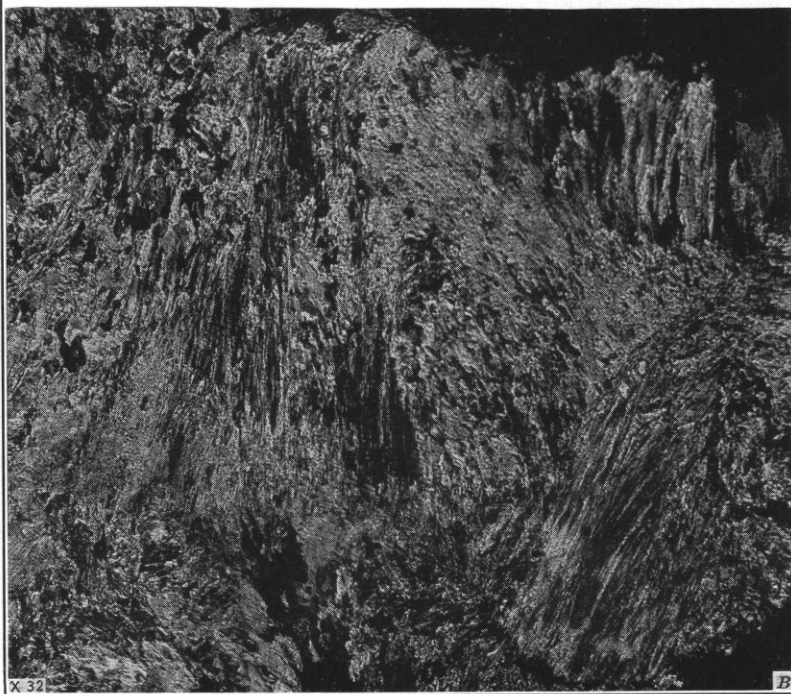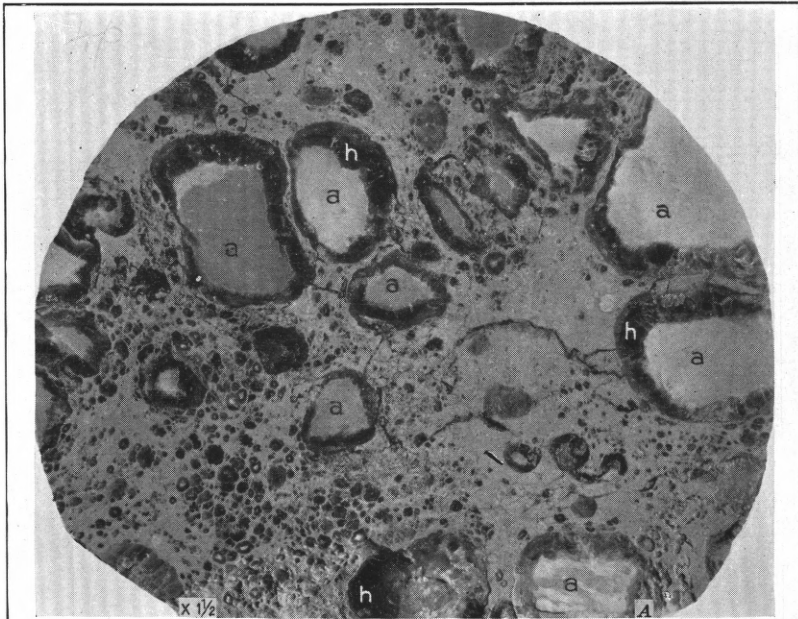
HALITE AND KAINITE

PLATE 13

KIESERITE

A. Groupings of twinned crystals of kieserite from the McNutt No. 1 well at a depth of 883 feet 4 inches. Nicols crossed. Photomicrograph showing appearance of twinned crystals of kieserite, especially as complex groupings in a fine-grained matrix of polyhalite. The ragged edges of the kieserite crystals suggest corrosion.

B. Crystal of kieserite partly replaced by polyhalite. From the Eldridge well at a depth of 1,125 feet. Photomicrograph showing attack upon a crystal of kieserite (k) by fine-grained polyhalite (p). The crystal of kieserite is in extinction position and appears black.

96
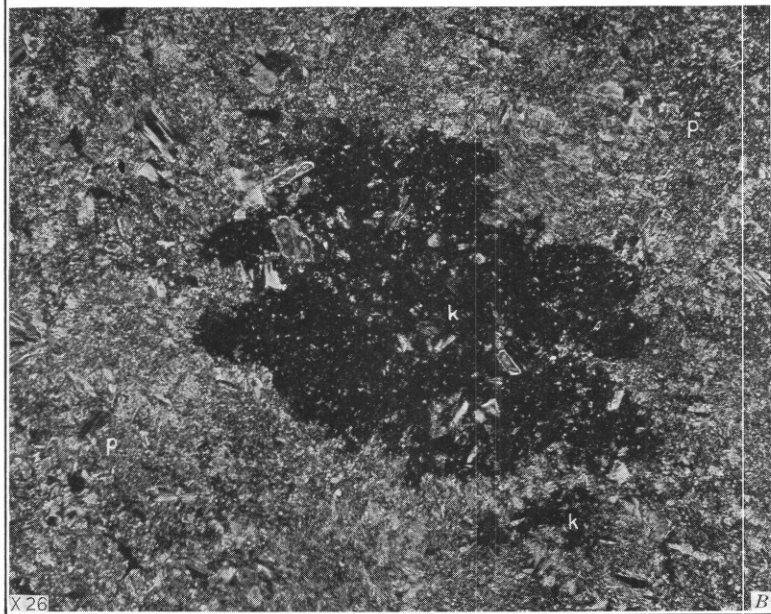
KIESERITE

PLATE 14

LANGBEINITE

A. Massive langbeinite (l) surrounding halite (h). From McNutt No. 1 well at a depth of 1,430 feet. The halite adjoining the langbeinite is reddish-brown (black in the photograph), but the halite in the center is colorless and transparent.

B. Massive langbeinite (l). From same source as *A.* The dark areas are reddish-brown halite (h). The quartzlike granular structure of the langbeinite is well shown in the upper portion.

C. Tetrahedral crystals of langbeinite. From Blanchard No. 1 well at a depth of 1,034 feet 2 inches to 1,034 feet 6 inches. These crystals are largely altered to a white powdery material and occur in a mixture of halite and sylvite with a considerable quantity of dull-greenish clay. The centers of the crystals still show original langbeinite, surrounded by its powdery white alteration.

D. Largest observed single tetrahedral crystal of langbeinite found. From the Gypsy No. 4 well at a depth of 850 feet 3 inches. The tetrahedral shape of the crystal is very well shown. It also is partly altered to a white powdery substance.

97

LANGBEINITE

PLATE 15
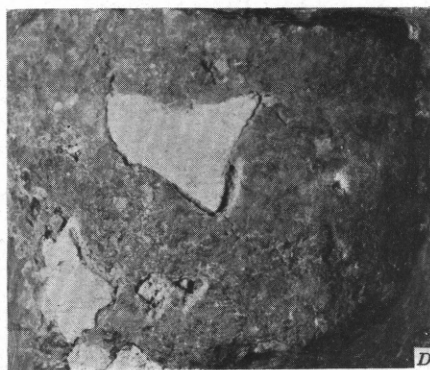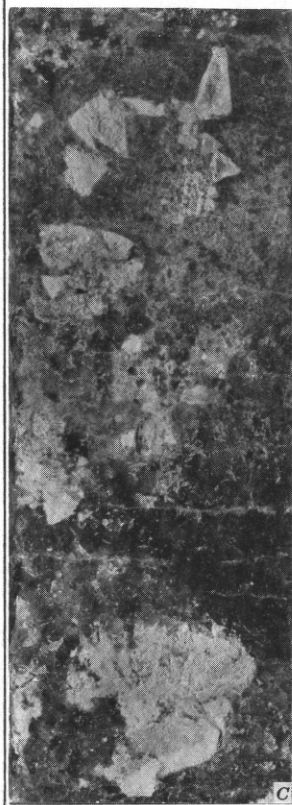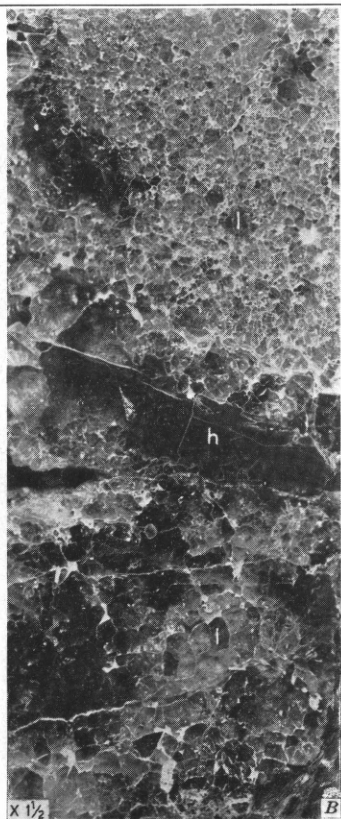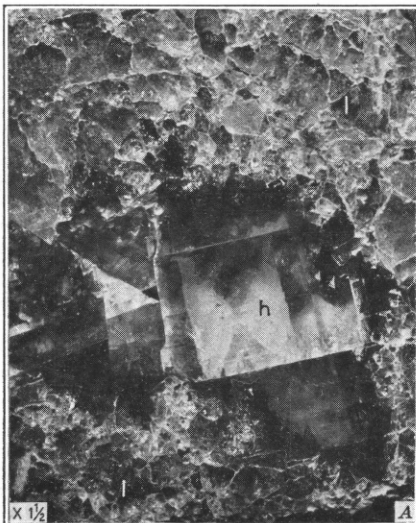
LEONITE

A. Photomicrograph of a crystal of leonite attacked and partly replaced by polyhalite. From Ballard No. 1 well at a depth of 641 feet. The boundary of the leonite crystal is very ragged and indented, and the resulting embayments have been filled with fine-grained polyhalite. Both the crystal of leonite and the fine-grained polyhalite contain larger more or less euhedral crystals of polyhalite, suggesting two stages in the replacement reaction which has furnished polyhalite. A few indistinct parallel twinning lamellae occur in the leonite.

B. Photomicrograph of a crystal of leonite, partly replaced by polyhalite. From the same thin section as that shown in *A*. The boundary line of the crystal is more irregular than in *A*, and the polyhalite has replaced the leonite to a greater extent, so that several isolated and detached areas of leonite, all in parallel orientation to the larger mass, are now completely surrounded by polyhalite. The leonite, as in *A*, contains numerous crystals of polyhalite scattered through it. It is shown black, in extinction position, to illustrate more clearly its relation to the polyhalite.

98

LEONITE

PLATE 16
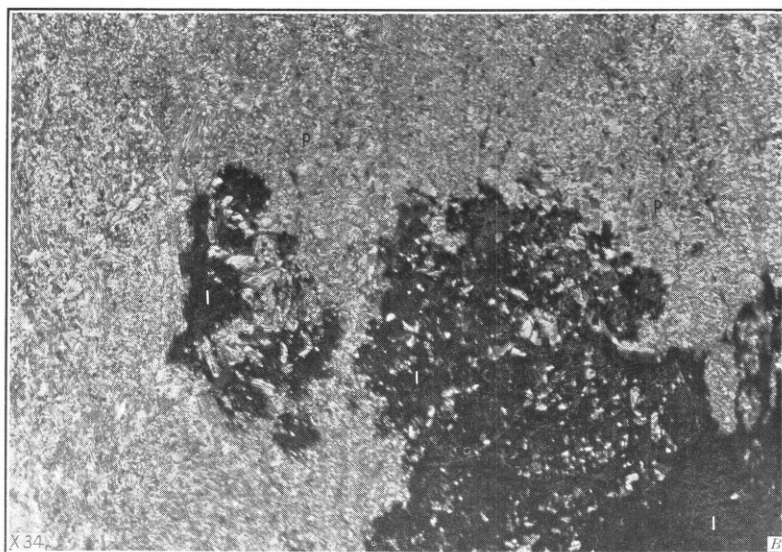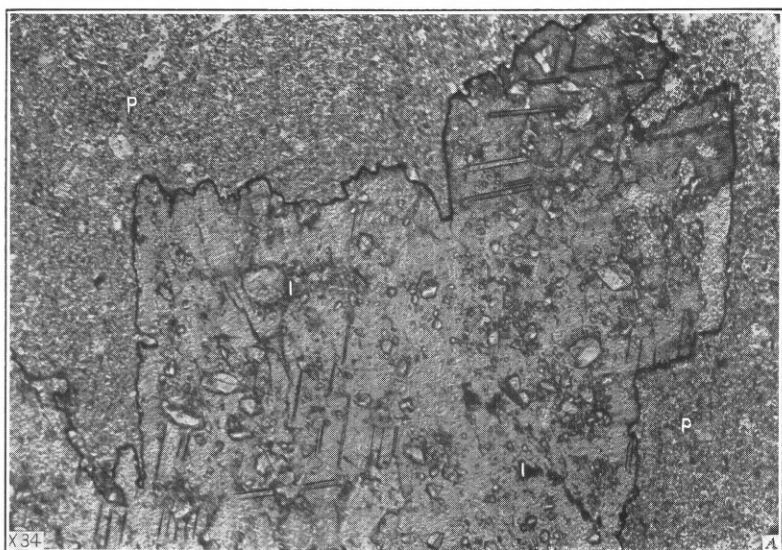
LEONITE AND MAGNESITE

A. Photomicrograph of leonite surrounding detached and partly isolated areas of polyhalite, all in halite. From Joe Mitchell well at a depth of 1,312 feet. The leonite (l) is gray, the polyhalite (p) is dark, and the halite (h) is the lightest in color. The relations of leonite and polyhalite in this section are not at all clear. The leonite seems to have formed at the expense of the polyhalite, though it is possible that the polyhalite has grown in and at the expense of the leonite.

B. Small mass of fine-grained magnesite in anhydrite rock. From Eldridge well at a depth of about 1,172 feet. Such aggregates are more abundant in the Eldridge core than in any of the others and occur either isolated, as shown here, or in horizontal layers scattered through the anhydrite, as shown in *D*.

C. Largest observed mass of fine-grained magnesite in anhydrite rock. From Eldridge well at a depth of about 1,172 feet. Material gouged out of this mass was tested chemically and found to be calcium-free magnesium carbonate. Cold hydrochloric acid has no effect on the magnesite, but it quickly dissolves in hot acid, with brisk efflorescence, and leaves no residue. The shape of the mass with its small short veinlets projecting into the anhydrite shows that it was formed in place. A few smaller detached areas of anhydrite (dark) are present in the large magnesite mass.

D. Horizontal layer of smaller masses of magnesite in anhydrite rock. From Eldridge well at a depth below 1,168 feet. These masses occur much more commonly in groups in horizontal layers than isolated. All this magnesite is exceedingly fine grained.

99
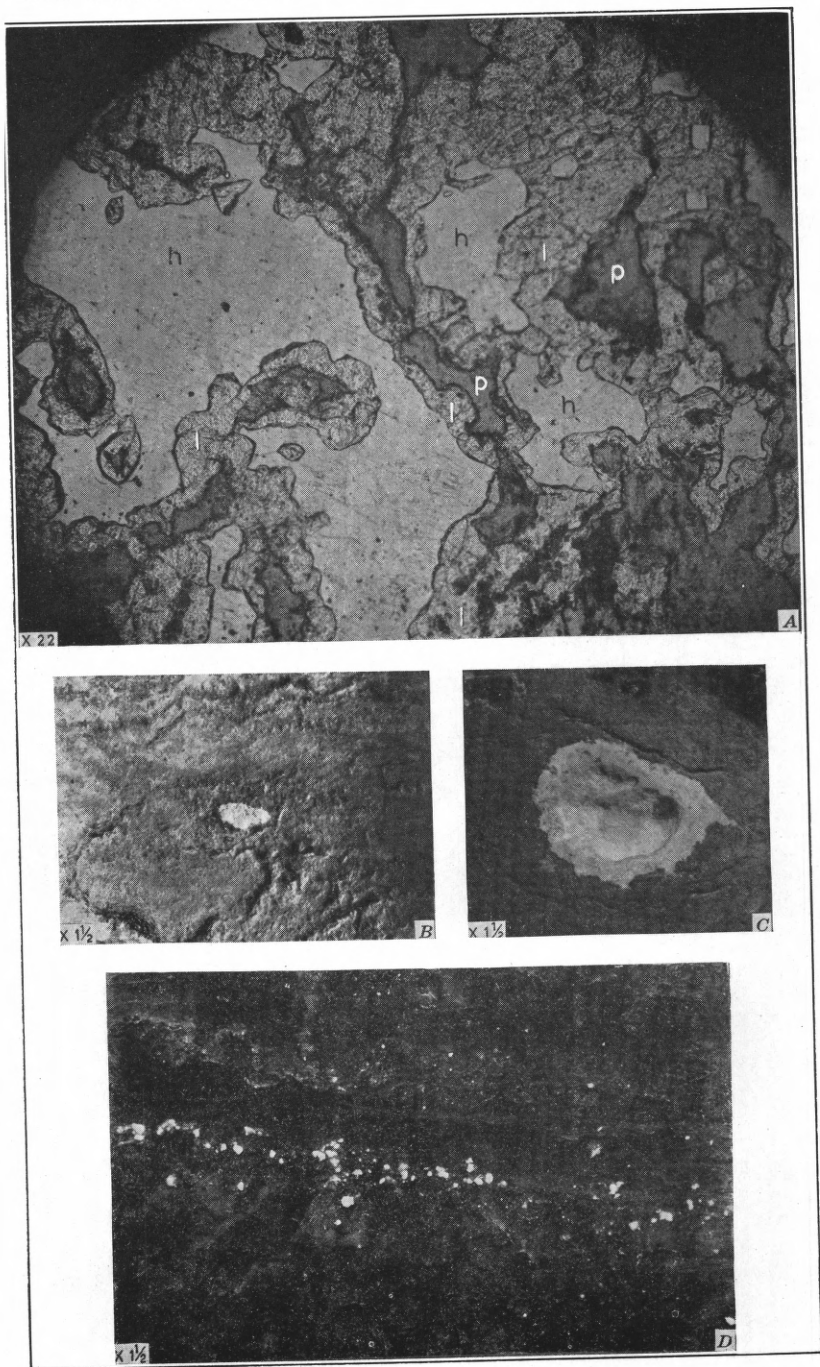
LEONITE AND MAGNESITE

PLATE 17

PHOTOMICROGRAPHS OF LAYERS OF MAGNESITE IN ANHYDRITE ROCK AND IN POLYHALITE ROCK

A. Bands of magnesite (black) in anhydrite rock. From McNutt No. 1 well at a depth of 993 feet 9 inches. A typical illustration of the mode of occurrence of the magnesite layers in anhydrite rock shows the difference in thickness of these bands and also their great irregularity in detail, although in general they are nearly horizontal. Specimens of the anhydrite rock showing these bands of magnesite are illustrated in Plates 1, 2, and 3.

B. Similar bands of magnesite (black) in polyhalite rock. From Eldridge well at a depth of 1,125 feet. Though the general form of the bands is similar to that shown in *A* (in anhydrite rock), there is some difference in detail. The bands are not nearly so numerous nor so thick, and it seems as if they had been concentrated to some extent into more definite lines. There is also a greater tendency for several of them to deviate greatly from a horizontal position. The matrix is a mixture of fine-grained polyhalite with coarser crystals (light).

100
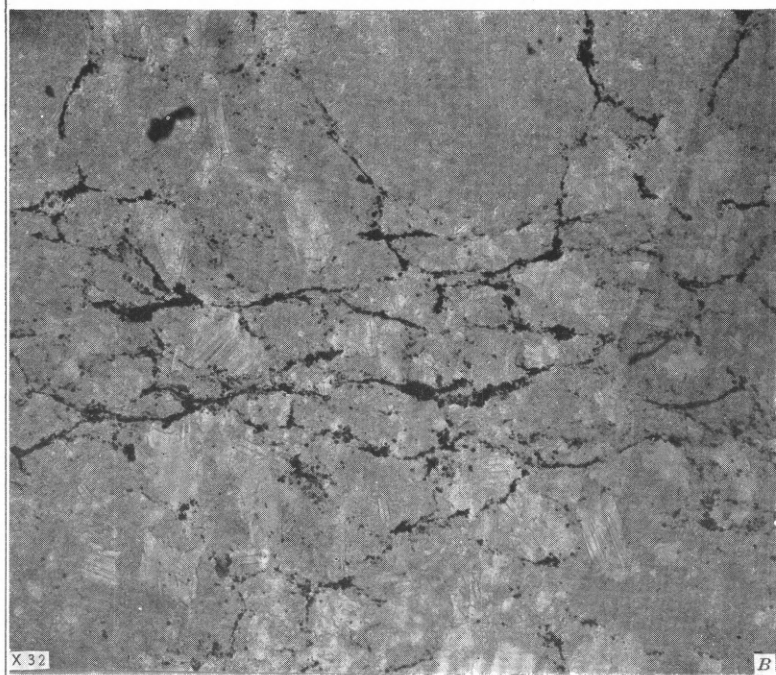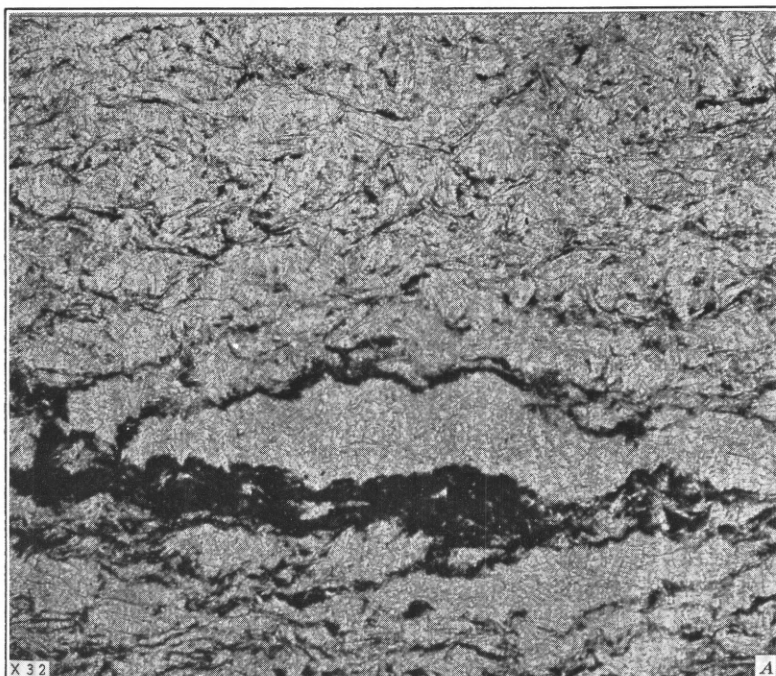
PHOTOMICROGRAPHS OF LAYERS OF MAGNESITE IN ANHYDRITE ROCK AND
IN POLYHALITE ROCK

PLATE 18

PLATE 18

PHOTOMICROGRAPHS OF IRREGULAR AGGREGATES OF MAGNE-
SITE IN ANHYDRITE ROCK AND IN POLYHALITE ROCK

A. Magnesite (black) scattered through the anhydrite rock in no regular form.
From Eldridge well at a depth of 1,172 feet. The magnesite is not a solid,
continuous mass but rather a concentration in certain places, though the
whole, when viewed on the core specimen, forms part of a distinct layer.

B. Magnesite (black) in polyhalite rock in no regular form. From Eldridge well
at a depth of 1,125 feet. Here, as in *A*, the magnesite is scattered irregularly
through the polyhalite, instead of being in distinct layers, as in Plate 17,
A and *B*. There is also a slight tendency for the magnesite to form small
masses, though similar aggregations occur in some of the anhydrite rock.

The specific object of the four photomicrographs in Plates 17 and 18 is
to show that the magnesite occurs in polyhalite rock in a form similar to
that in anhydrite rock, with slight modifications. Therefore *A* and *B* of
Plate 17 should be compared and likewise *A* and *B* of Plate 18.
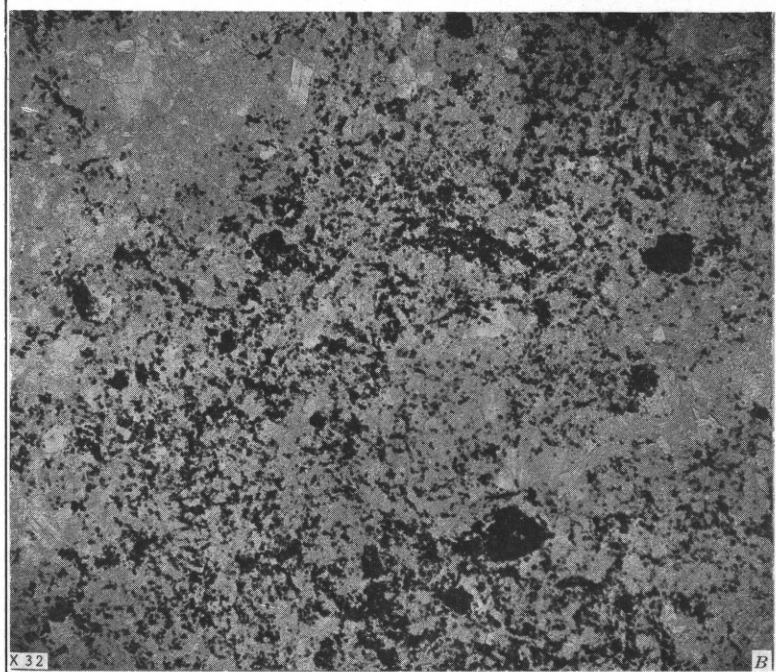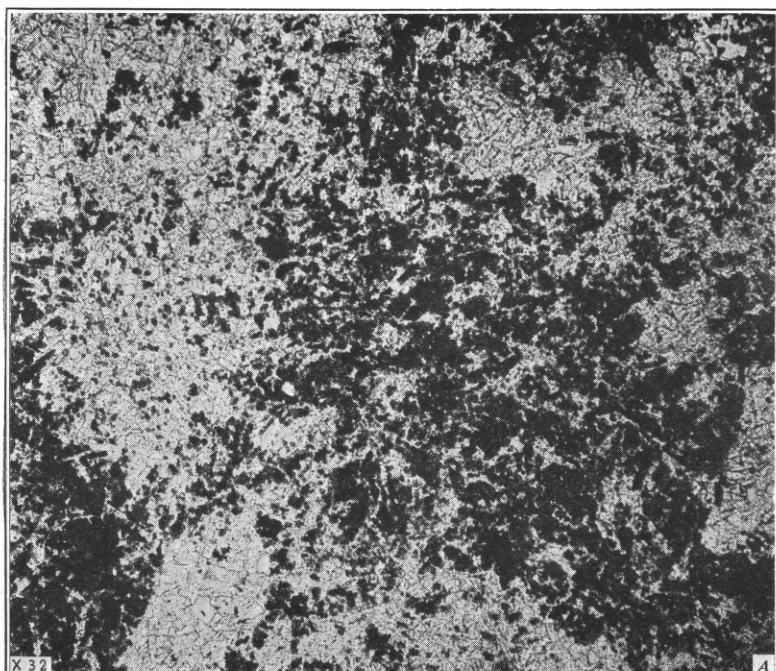
101

PHOTOMICROGRAPHS OF IRREGULAR AGGREGATES OF MAGNESITE IN
ANHYDRITE ROCK AND IN POLYHALITE ROCK

PLATE 19

PHOTOMICROGRAPHS OF POLYHALITE

A. Fine-grained variety.   From Government hole No. 1 at a depth of 1,297 feet. Such fine-grained polyhalite is very abundant, and in thin sections resembles cryptocrystalline quartz.   Much of it is nearly free from any magnesite or in fact from almost any other mineral.   Other specimens, however, contain crystals of anhydrite and kieserite.   The fine-grained variety of polyhalite is more abundant in association with anhydrite than with halite.

B. Coarse-grained variety.   From Government hole No. 1 at a depth of 1,479 feet 9 inches.   The coarse-grained polyhalite is also abundant and in its many varieties, which differ slightly in detail of structure, is typical of much of the polyhalite of the region, both that associated with anhydrite and that occurring in halite.   Many of the individual crystals are crowded together so that they exhibit but poorly developed straight crystal edges.

102

PHOTOMICROGRAPHS OF POLYHALITE

PLATE 20
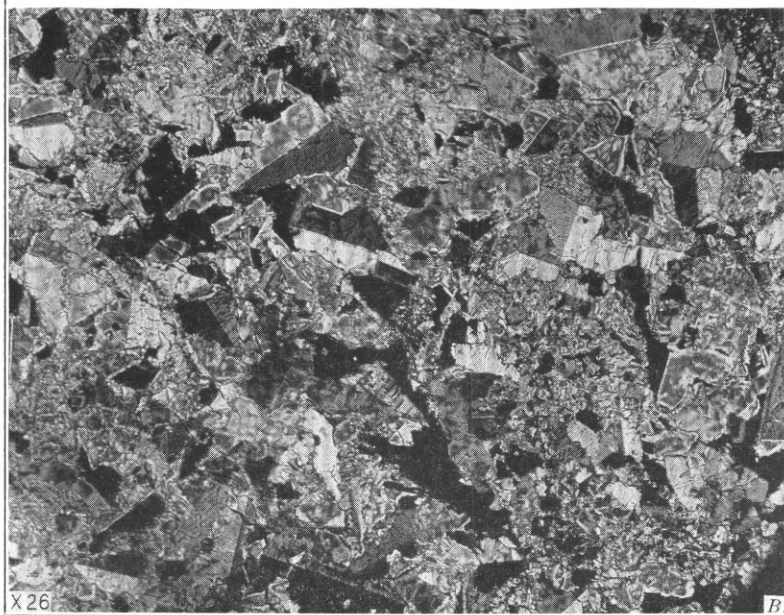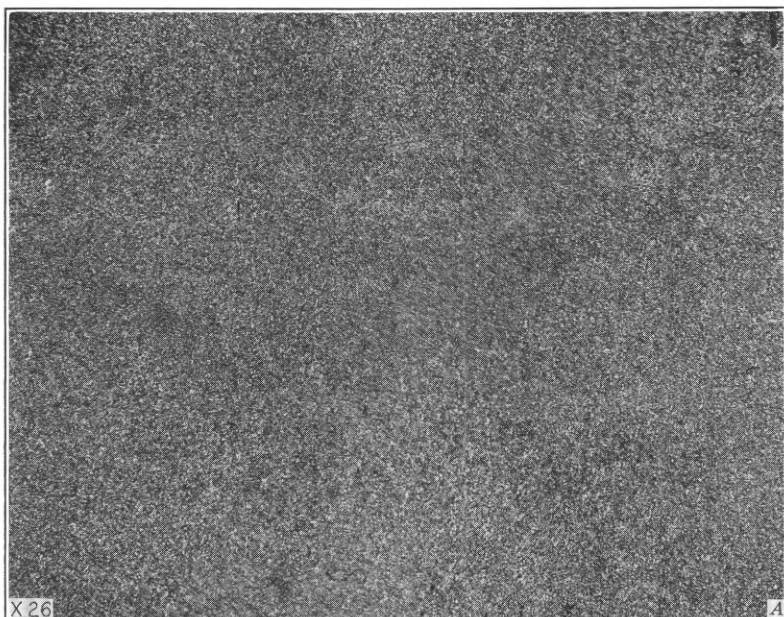
PHOTOMICROGRAPHS OF POLYHALITE

A. Large crystals of the coarse-grained variety embedded in the fine-grained variety. From the McNutt No. 1 well at a depth of 1,281 feet 4 inches. The association of the coarse and fine grained varieties is very common.

B. Euhedral crystals in halite. From Government hole No. 3 at a depth of 910 feet. Where a polyhalite mass borders on halite there is generally a tendency for the polyhalite to occur in euhedral crystals with perfect crystal faces. In places these become relatively large, as shown in Plate 23, *C.*

The twinning of crystals of polyhalite is well shown in both *A* and *B.* (See also fig. 11.)

103

PHOTOMICROGRAPHS OF POLYHALITE

PLATE 21
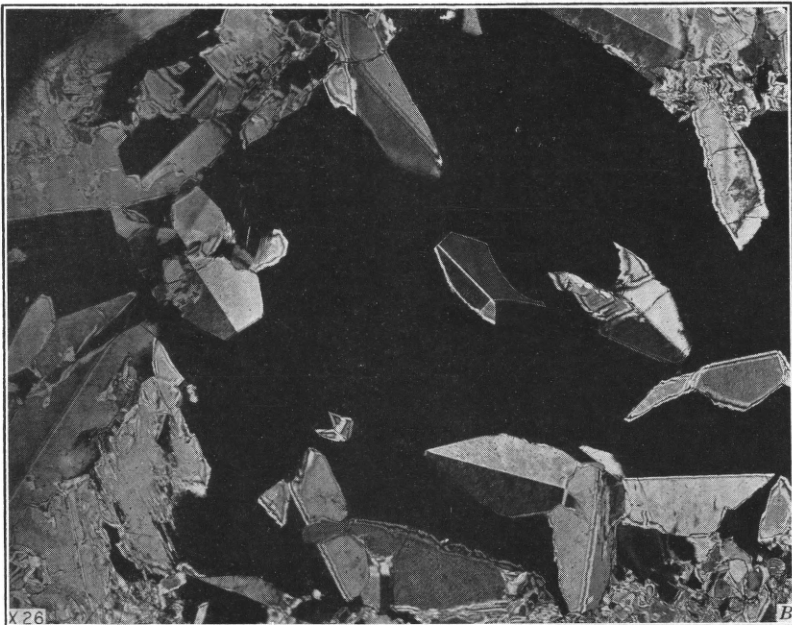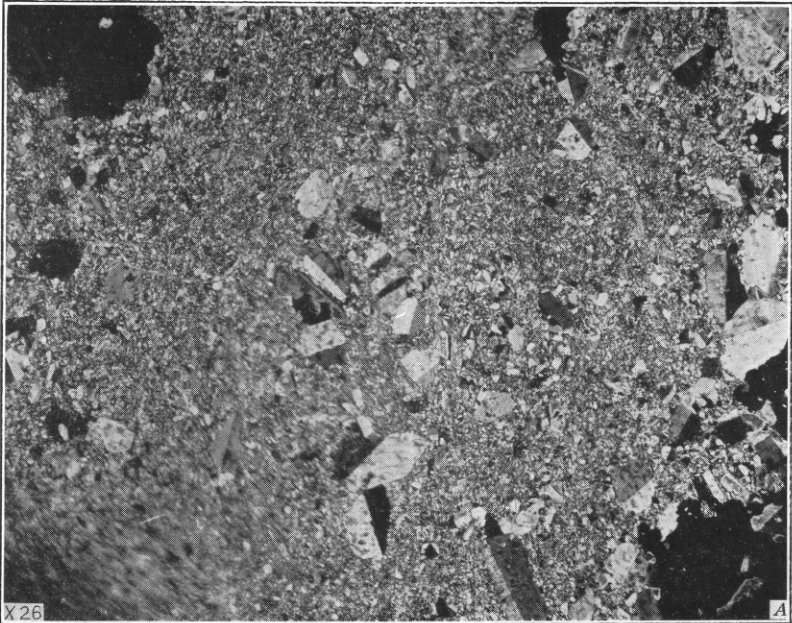
PHOTOMICROGRAPHS OF POLYHALITE

A. Fibrous polyhalite. From the McNutt No. 1 well at a depth of 1,399 feet. The section shown is taken from the specimen of white polyhalite that is illustrated in Plate 31, *C.* Such aggregates of short and long fibers of polyhalite, partly in parallel groups and partly in radiating masses and imperfect spherulites, are very common and constitute much of the compact massive mineral, especially where it is associated with anhydrite.

B. Spherulitic polyhalite. From Government hole No. 1 at a depth of 1,647 feet 2 inches. The view shown has the spherulitic form well developed and more nearly perfect than is commonly found. The narrow black areas are magnesite, which appears to have been pushed aside by the growing spherulite, whose nucleus is nearly free from any magnesite. This spherulitic form is abundant in halite and to a lesser degree in anhydrite.

104

PHOTOMICROGRAPHS OF POLYHALITE

PLATE 22
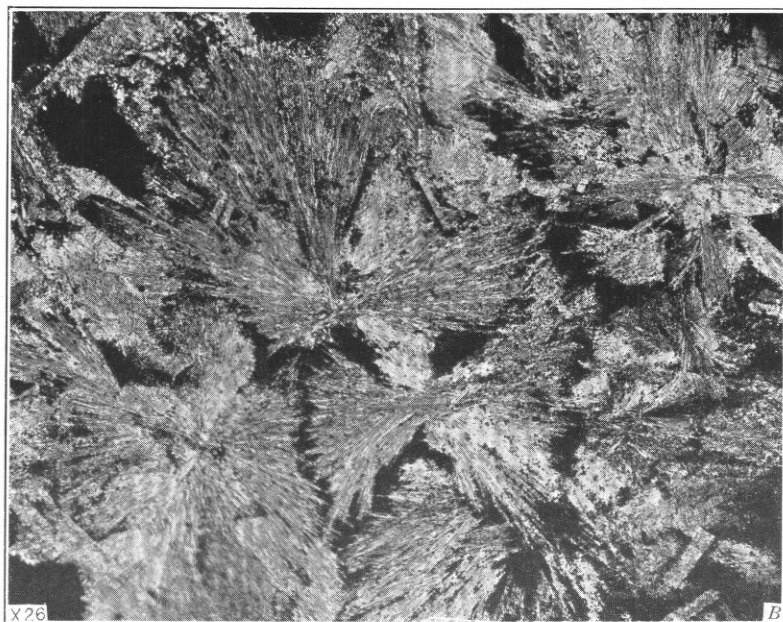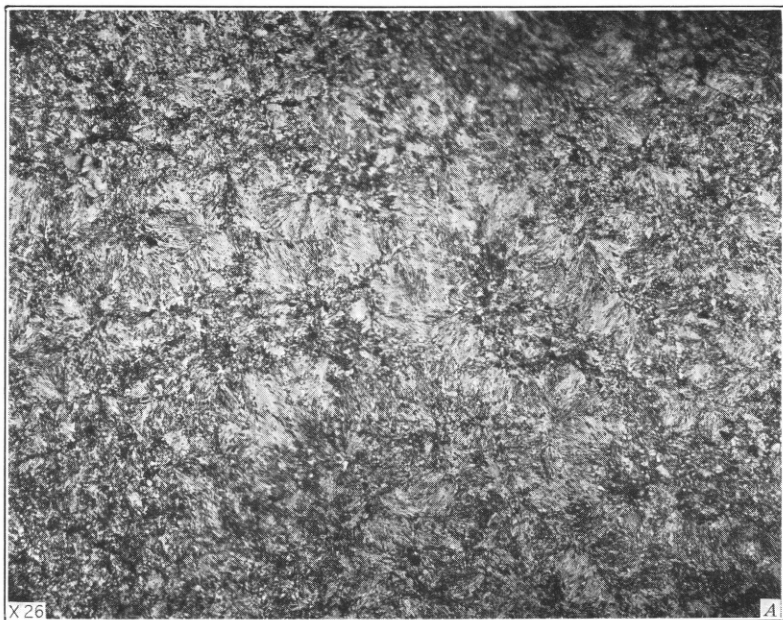
PHOTOMICROGRAPHS OF POLYHALITE

A. Crystal of polyhalite inclosing anhydrite. From McNutt No. 1 well at a depth of 1,570 feet 6 inches. Many of the inclosed crystals of anhydrite are rounded and have the appearance of residua, though they do not differ greatly from the anhydrite grains in the surrounding anhydrite rock.

B. Phantomlike spherulite of polyhalite in halite. From Government hole, number and depth not known. Shows a spherulitic growth of polyhalite surrounded by a much thicker growth of fibers of polyhalite on the outside. Much of the growth of polyhalite in halite and also in glauberite takes place in this way. Although similar growths of polyhalite occur in anhydrite, they are rare, for polyhalite developing in anhydrite usually does not take on the spherulitic form. Most of the fibrous polyhalite is not developed in fine spherulites such as are here shown but occurs in radiating or parallel groups of fibers or in tufts and is in many places mixed with more or less of the fine granular variety, so that it grades into the type shown in Plate 21, *A*.

105
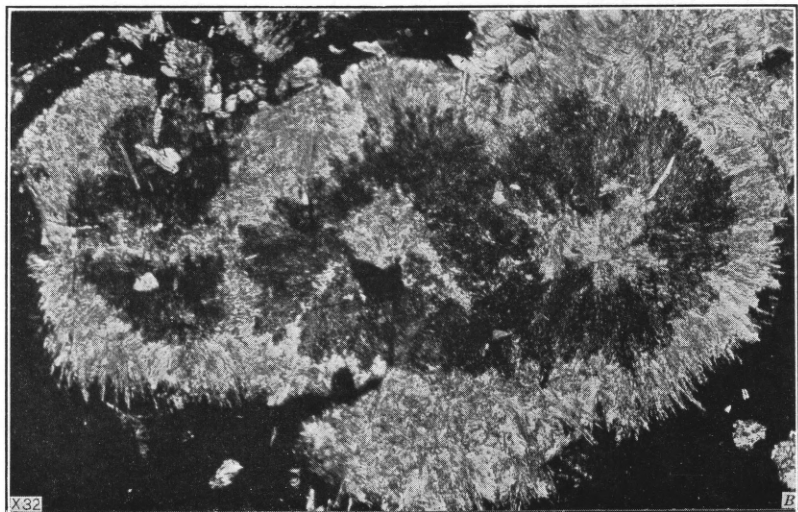
PHOTOMICROGRAPHS OF POLYHALITE

PLATE 23

PHOTOMICROGRAPHS OF HALITE PARTLY REPLACED BY POLYHALITE

A. Fine-grained fibrous polyhalite (p) that has encroached upon rectangular halite (h) (black). From McNutt No. 1 well at a depth of 1,213 feet 2 inches. Nicols crossed. Some of the crystals of halite (upper left and upper right) have been divided into two parts, and a few have been considerably replaced, but all show more or less corrosion by polyhalite.

B. Minute areas of polyhalite that have developed in rectangular cleavage cracks of halite. From Government hole No. 1 at a depth of 1,281 feet. Nicols crossed. The polyhalite (white) is obviously later than the halite (black).

C. Polyhalite fibers (p) that have grown in rectangular cleavage cracks of halite (h). From Ballard well at a depth of 864 feet 2 inches. Nicols crossed. The black areas represent concentrations of hematite, the coloring pigment. The mineral that surrounds the halite and has a more mottled appearance is sylvite (s). A little polyhalite has also grown in the cleavage cracks of the sylvite.
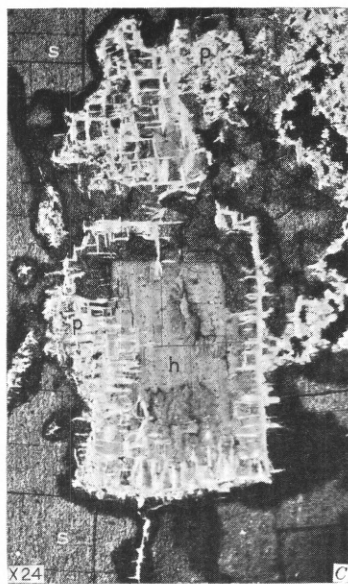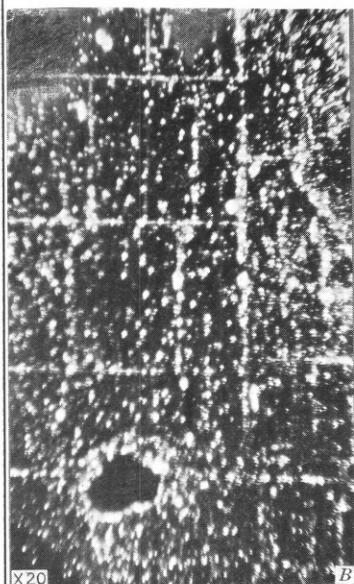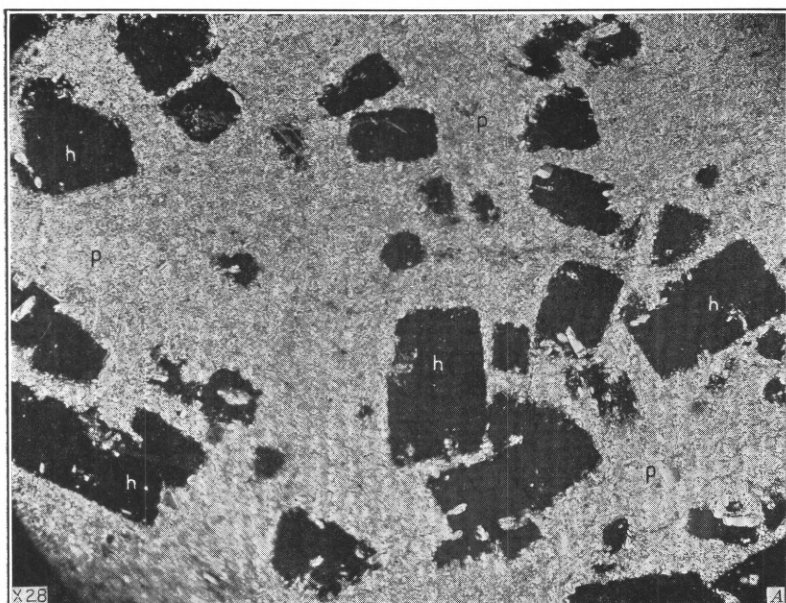
106

PHOTOMICROGRAPHS OF HALITE PARTLY REPLACED BY POLYHALITE

PLATE 24

MASSIVE POLYHALITE SHOWING BANDED STRUCTURE

All these specimens of massive compact reddish brown polyhalite came from the McNutt No. 1 well, but at different depths—*A* at 989 feet 8 inches to 990 feet, *B* at 826 feet 8 inches to 826 feet 10 inches, *C* at 990 feet to 990 feet 4 inches, and *D* at 994 feet 7 inches to 994 feet 11 inches. The wavy bands of magnesite are similar to those in the anhydrite rock (pls. 1, 2, and 3) and are very characteristic of nearly all the polyhalite from this region. The camera brings out the different shades of color much more vividly than they are shown by the specimens, which to the unaided eye appear very uniform in color and structure.

A and *C* show elongated forms, many of them with the "swallowtail" type of twinning. (See p. 59.) They consist of polyhalite, the halite which previously occupied these elongated spaces having been replaced by polyhalite, which developed in the halite generally as spherulites. In thin sections the outlines of the elongated masses can not be detected, because the polyhalite in them merges into the surrounding polyhalite groundmass, but in the specimens themselves, and especially in the photographs, these forms stand out very strongly. The beginning of the growth of spherulites of polyhalite in these elongated forms of halite is shown in Plate 29, *A*, and the completion of the process in Plate 29, *B*, *C*, and *D*.

B and *D* do not show the elongated forms, but the variation in color of the polyhalite is very well brought out, suggesting strongly that the polyhalite replaced the original anhydrite rock during many different periods, each with a varying content of pigment (hematite).

The bands of magnesite, however, have been retained through all the mineralogical changes that have taken place, even though their quantity may have been somewhat reduced.

107
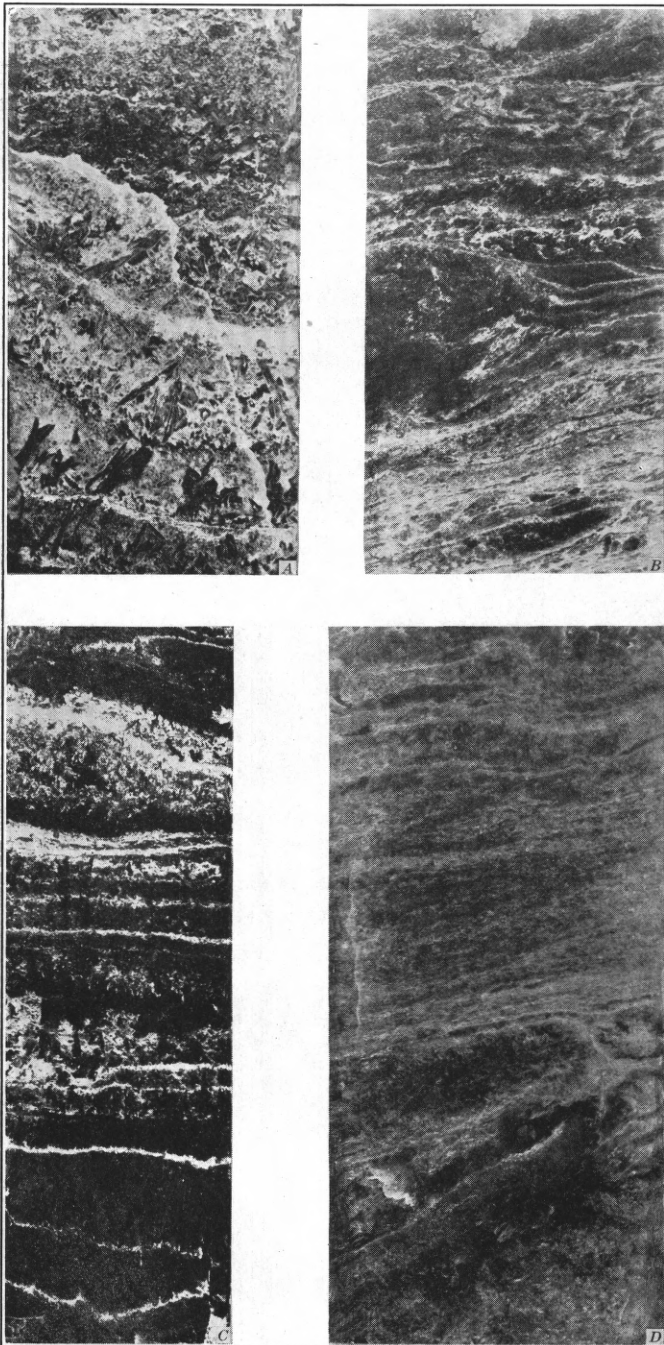
MASSIVE POLYHALITE SHOWING BANDED STRUCTURE

PLATE 25

BLEBBY POLYHALITE IN HALITE, ILLUSTRATING THE GROWTH OF POLYHALITE IN HALITE AND ITS CORRESPONDING RE-PLACEMENT OF THE HALITE

A. From Government hole No. 5 at a depth of 1,491 feet 2 inches to 1,491 feet 6 inches. Only a small quantity of polyhalite in mosslike forms is scattered through the halite. The surface of the halite shows as both light and dark areas, owing to reflections of light, whereas the polyhalite is more gray.

B. From Government hole No. 7 at a depth of 956 feet to 956 feet 4 inches. Shows a greater abundance of blebby polyhalite, as mosslike masses of a gray color. Connected masses of polyhalite extend for relatively considerable distances, but the material is still blebby and does not constitute large masses of pure polyhalite, though in the lower right corner of the view the beginning of such a compact mass of pure mineral may be indicated. Along the edges of some blebs small crystals of polyhalite in mosslike aggregates of spherulites project into adjacent cavities. (See fig. 15.)

C. From Government hole No. 6 at a depth of 631 feet 8 inches to 632 feet. Shows an even greater concentration of the polyhalite, many of the smaller blebs having coalesced into granular masses of polyhalite which still contain many small scattered particles of halite.

D. From Government hole No. 7, depth unknown. Largely polyhalite, with a few large areas of residual halite fringed with projecting crystals of polyhalite. These masses of halite are shown in the upper and central parts of the illustration. The large mass of halite at the bottom, which is transparent enough to show the spherulites of polyhalite in its lower part, may be a later introduction of halite that has replaced polyhalite, for it is not fringed with projecting crystals of polyhalite but contains small isolated masses of polyhalite scattered through it, which may be residual. The clear fringed areas of halite in the middle and upper parts are free from any such included (residual?) masses of polyhalite.

108
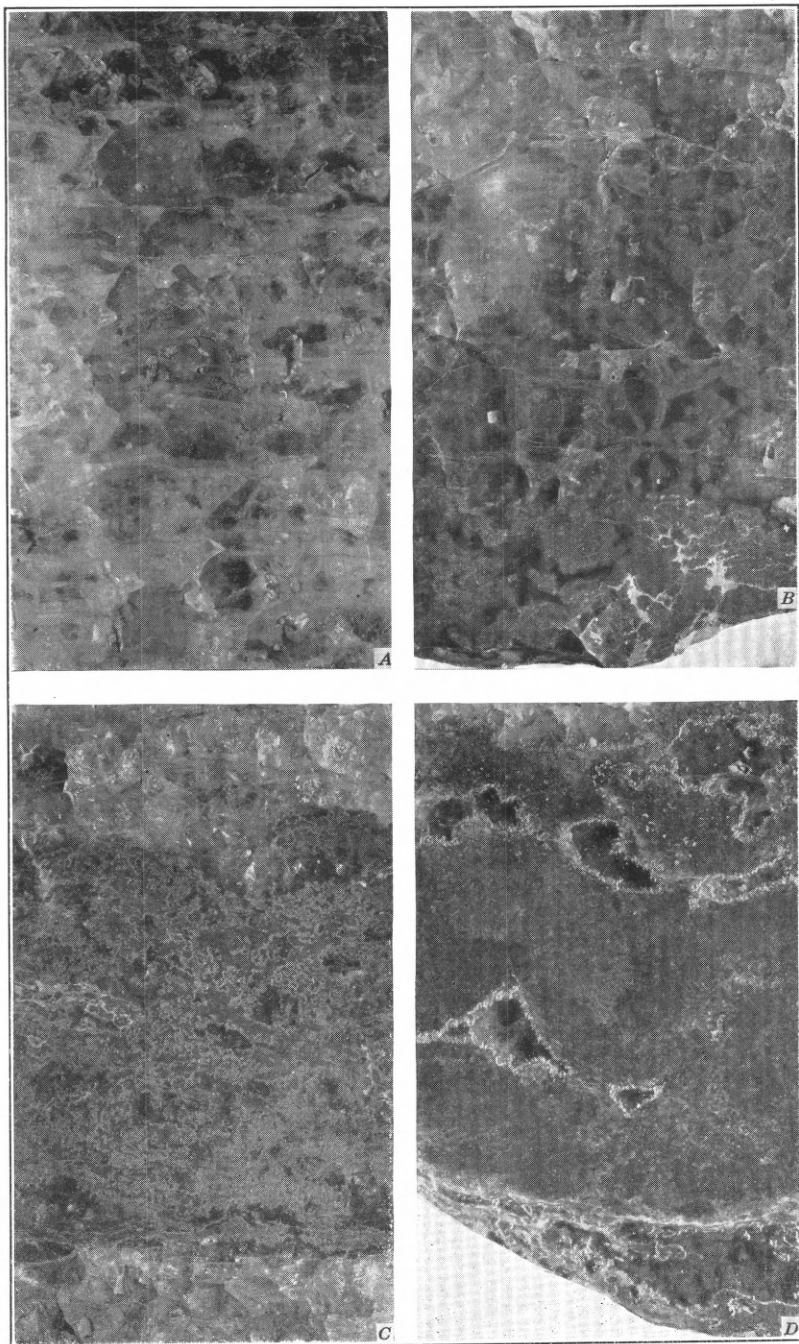
BLEBBY POLYHALITE IN HALITE ROCK

PLATE 26

BLEBBY POLYHALITE IN ANHYDRITE ROCK

A. From Government hole No. 4 at a depth of 1,560 feet 9 inches to 1,561 feet. Essentially banded anhydrite rock with many small blebs of polyhalite (white) scattered through it, the blebs arranged somewhat in imperfect horizontal layers but nowhere showing a continuous layer. The direction of elongation of many of the blebs is vertical, though there is a tendency for them to form elongated horizontal lenslike bodies. The blebs of polyhalite contain many larger prismatic crystals of secondary anhydrite, which are absent in the fine-grained anhydrite rock matrix. The blebs are not spherulitic in structure but consist of fine-grained material.

B. From Government hole No. 1 at a depth of 1,647 feet 10 inches to 1,648 feet 1 inch. About half the specimen is polyhalite (black), mostly in spherulitic form, especially where developed in the layers of magnesite, which are very irregular and considerably broken up and full of spherulites and groups of prismatic crystals of polyhalite. Thin sections of this core exhibit well the spherulitic structure of the polyhalite (see pl. 21, *B*) and show how in the growth of the spherulites of polyhalite the layers of magnesite have been broken and the crystals of magnesite pushed aside, to congregate along the sides of the fibers of the spherulites. The matrix is gray anhydrite, full of blebs, spherulites, and irregular fibrous bunches of reddish-brown polyhalite. Some of the blebs and spherulites have coalesced into larger masses, such as are shown even better in *C* and *D*. Polyhalite makes up about half the entire specimen.

C. From Government hole No. 3 at a depth of 1,364 feet 8 inches to 1,364 feet 11 inches. The blebs of polyhalite (white) scattered through the anhydrite rock, though roughly round, have a hazy and indefinite outline and are surrounded by numerous smaller masses of polyhalite. These all show a decided tendency to coalesce into larger masses through the continued growth of the polyhalite. These blebs are not spherulitic but consist of fine-grained polyhalite that has developed in rounded masses. In the center of the specimen is a clear mass of halite, beneath which is an agglomeration of small balls of polyhalite that strongly suggests that the larger rounded masses are formed by the coalescence of many much smaller rounded balls. Some halite (black) is likewise present at the bottom of the specimen. The masses of polyhalite contain numerous small crystals of anhydrite.

D. From Government hole No. 3 at a depth of 1,365 feet 11 inches to 1,366 feet 1 inch, 1 foot below the specimen shown in *C*, to which it is very similar. However, it shows the coalescing of the smaller blebs still better, for a single large mass of nearly pure polyhalite has formed in this way in the center of the specimen. There are also smaller masses scattered all through the anhydrite matrix. All of this polyhalite contains scattered prisms of anhydrite. The structure of the large masses, as seen through a hand lens, strongly suggests that they were formed by the coalescence of many smaller rounded masses (such as those shown in *A* and *B*), whose outlines are still clearly visible.

109
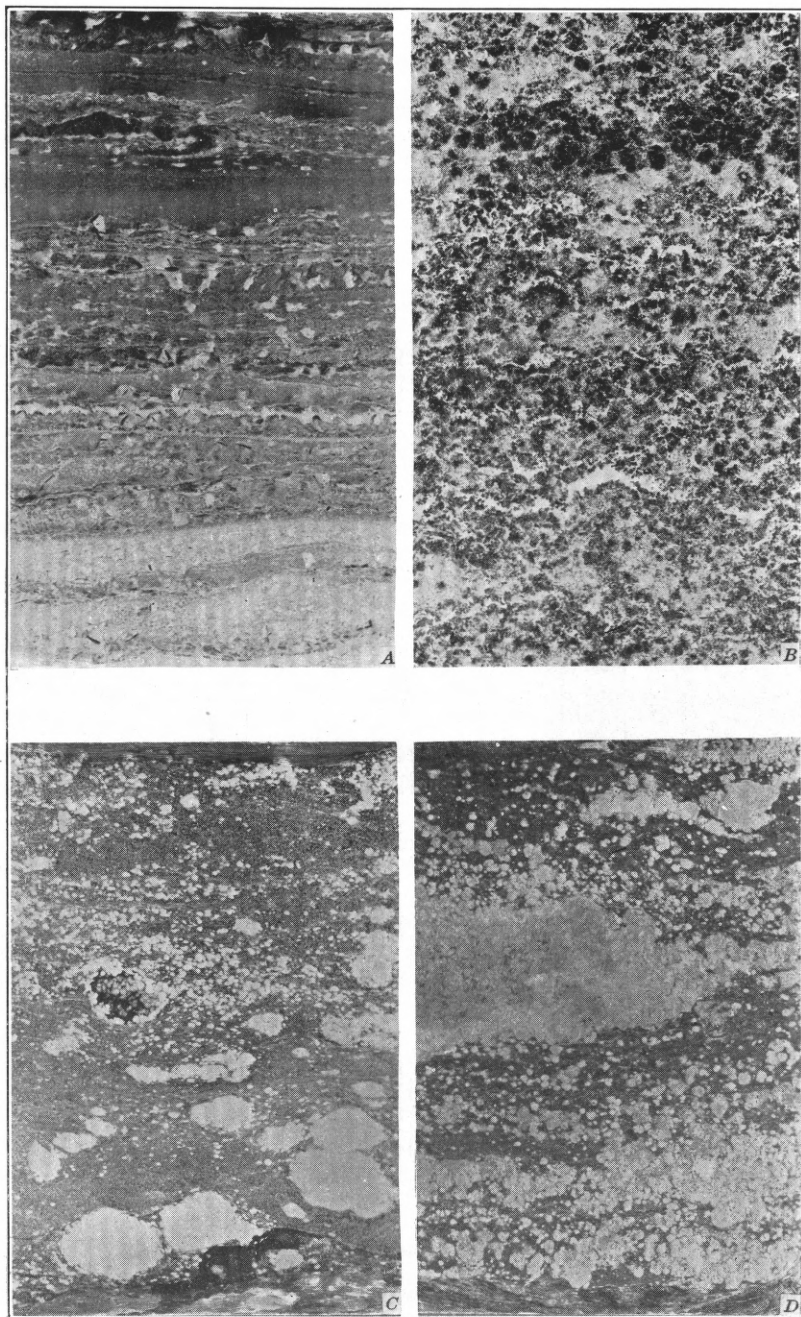
BLEBBY POLYHALITE IN ANHYDRITE ROCK

PLATE 27

BANDED STRUCTURE OF POLYHALITE ROCK

A. From Government hole No. 6 at a depth of 806 feet 4 inches to 806 feet 7 inches. Shows alternating bands of reddish polyhalite (dark), gray anhydrite (gray), and magnesite (white). The boundaries of the different layers are not sharp but grade into one another, especially on the upper side.

B. From Government hole No. 7, exact depth not known. Almost pure polyhalite, except for the bands of magnesite and for a single interrupted layer of halite (light gray) just below the center. The specimens shown in *A* and *B* have a structure (due to the bands of magnesite) almost identical with that of the anhydrite rock free from polyhalite shown in Plates 1, 2, and 3. The similarity in structure is especially well brought out in a comparison of Plate 27, *A*, *B*, and *D* with Plate 1, *A*, *B*, and *D*. The wide bands of magnesite in the lower right portion of Plate 27, *A*, may also be compared with the similar wide bands of magnesite shown in Plate 1, *B*. The magnesite bands in Plate 27, *C*, should also be compared with those in Plate 1, *C*.

C. From Government hole No. 4 at a depth of 1,938 feet 10 inches to 1,939 feet 2 inches. Almost pure polyhalite built up by the coalescence of numerous spherulites. The bands of magnesite have become very uneven and crinkled by the growing polyhalite. Compare these bands with those in Plate 1, *C*. The specimen represents a more advanced stage of the replacement of the banded anhydrite rock by polyhalite than the early stage shown in Plate 26, *B*.

D. From Government hole No. 8 at a depth of 525 feet 11 inches to 526 feet 3 inches. Practically pure polyhalite, showing hardly any structure, though an indistinct nearly horizontal banding can still be recognized. The fine white lines are due to cracks, which have become partly filled with white polishing powder.

110
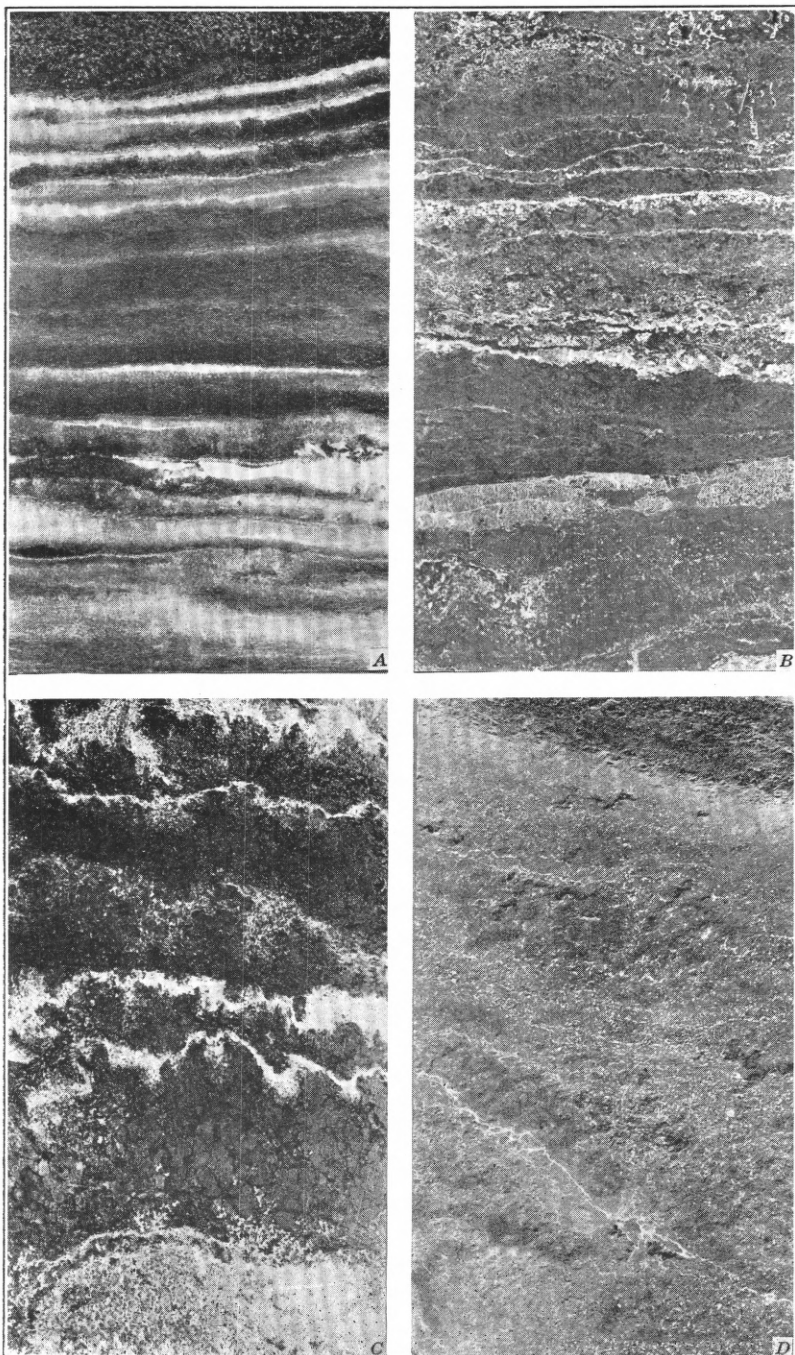
BANDED STRUCTURE OF POLYHALITE ROCK

PLATE 28

VARIOUS MODES OF OCCURRENCE OF POLYHALITE

A. From Government hole No. 6 at a depth of 902 feet 1 inch to 902 feet 4 inches. Mostly compact polyhalite with a little halite. The polyhalite is largely spherulitic and represents the type of occurrence shown in Plate 25 but with a greater concentration, for it has yielded a sample of nearly pure compact polyhalite. Although the spherulitic character of the polyhalite is easily seen under the hand lens along the border of the halite, this structure is largely lost in the middle of the massive polyhalite. Several of the smaller masses of polyhalite have a rectangular outline (in dark area of halite, right side), as if the polyhalite had filled in a negative crystal in the halite. A very much broken, narrow band of magnesite stands out in the center of the specimen.

B. From Eldridge well at a depth of 1,140 feet. Shows the growth of polyhalite in anhydrite, as aggregates of prismatic crystals. (See fig. 12.) The polished specimen has been immersed in water for a few minutes, developing a thin white coating of gypsum on the polyhalite, whose presence in the gray anhydrite can thus be better shown. These masses of polyhalite grow into large bodies of almost pure mineral, which has cauliflower-shaped protuberances extending out into the anhydrite. Along the boundaries there are many very thin, long prismatic crystals of polyhalite, which likewise extend out into the anhydrite.

C. From Government hole No. 6 at a depth of 845 feet to 845 feet 3 inches. Contains mostly polyhalite with banded rock at the top and bottom in which the graphic intergrowths of halite and anhydrite are present. (See also pl. 8.) Between these intergrowths considerable polyhalite has developed, starting as individual spherulites, which soon coalesce to form fairly compact masses.

D. From Government hole No. 5 from a depth of 1,211 feet 4 inches to 1,211 feet 7 inches. Shows a coalescence of the blebby polyhalite in halite, with a decided tendency to form layers or bands, which, however, are clearly only lenslike.

111
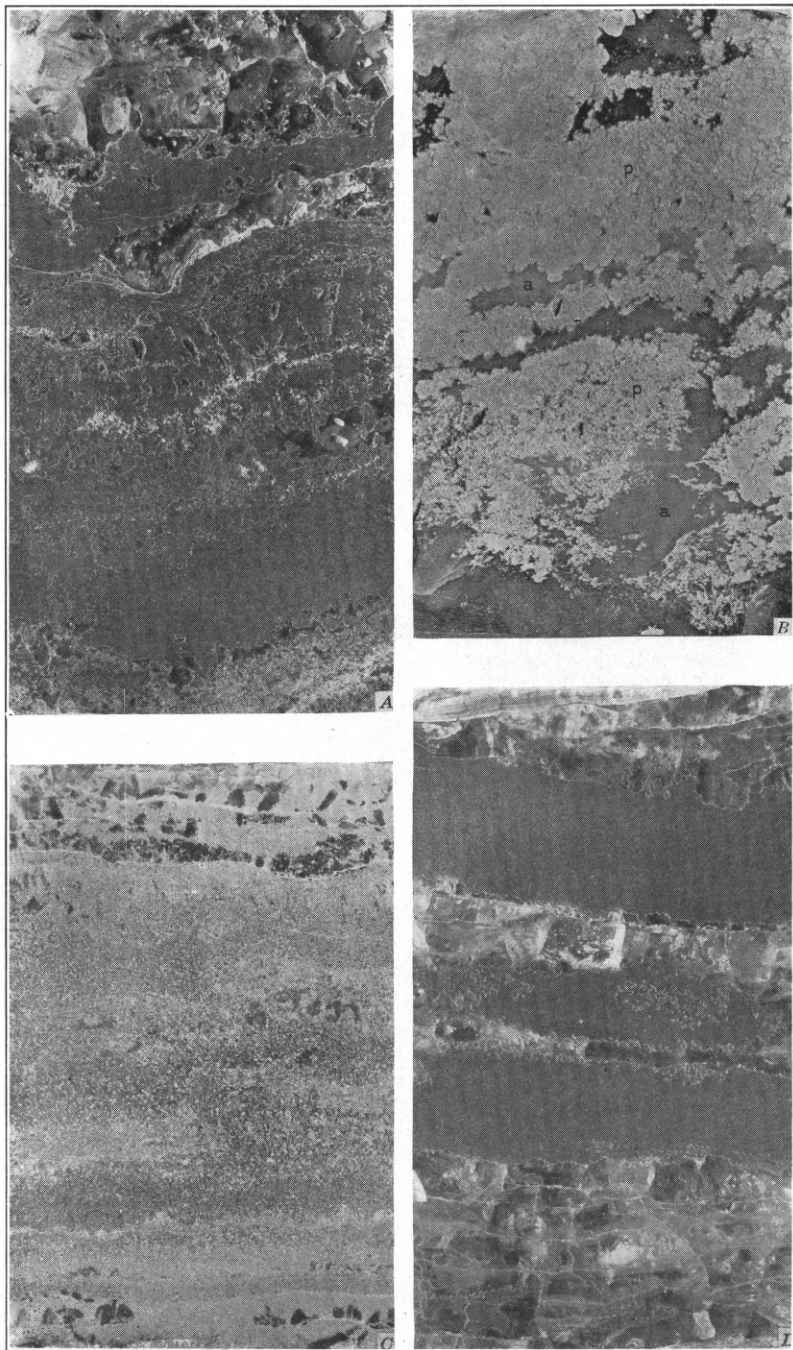
VARIOUS MODES OF OCCURRENCE OF POLYHALITE

PLATE 29

VERTICAL GROWTHS OF POLYHALITE

A. From Government hole No. 4 at a depth of 1,305 feet 3 inches to 1,305 feet 7 inches. The specimen is essentially banded anhydrite rock with numerous vertical growths of halite (black), similar to those shown in Plate 8. In these vertical growths there have developed numerous spherulites of polyhalite, reproduced as small rounded areas. The anhydrite contains similar masses. The growths of polyhalite represent an early stage in the replacement of the halite (and also in part of the anhydrite) by polyhalite, whose completion is shown in B, C, and D.

B. From Government hole No. 6, at a depth of 583 feet 1 inch to 583 feet 5 inches. Shows a similar change but with complete replacement in the center of the specimen. Some of the vertical growths of halite, only partly replaced, are present at the top and bottom. The deep-red polyhalite in this specimen is strongly colored and consequently appears very dark in the illustration. The layers of polyhalite are continuous horizontally but on the specimen can be seen to be made up of coalescing vertical growths. (See fig. 16.)

C. From Government hole No. 4 at a depth of 1,304 feet 10 inches to 1,305 feet 2 inches. Shows similar vertical growths with complete replacement of the halite by polyhalite. At the bottom of the specimen, the white layers of magnesite have been almost undisturbed, but in the upper part, where the vertical growths are much larger, they have broken through the layers of magnesite and produced considerable disruption, though it is obvious that the detached pieces were once continuous. (See also pl. 8, B.) This disruption probably took place when the original gypsum crystals were growing, before the anhydrite rock was finally compacted. In the later changes of the gypsum, first to halite and then to polyhalite, there probably has been very little disturbance of the structure of the specimen.

D. Immediately below specimen shown in C. In the development of the coarser vertical growths, in the bottom of the specimen, there has occurred an almost complete disappearance of the magnesite layers, possibly caused in part by their absorption by the brines in the formation of polyhalite from halite. In several of these coarser vertical growths in the lower part of the specimen, now almost pure polyhalite, there are several very good examples of the "swallowtail" type of twins, referred to gypsum, which have been already described and which are shown in Plates 8, C, and 9.

112

VERTICAL GROWTHS OF POLYHALITE

PLATE 30
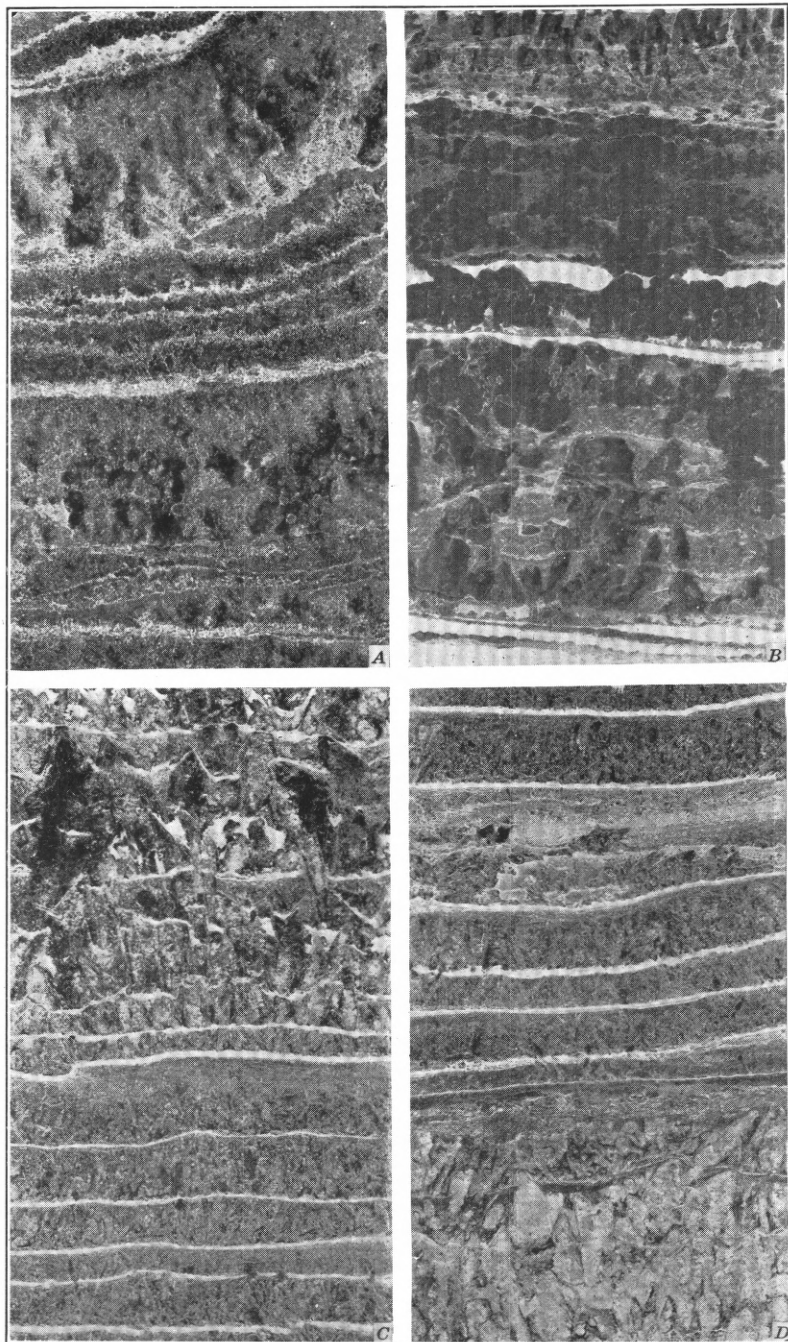
OTHER OCCURRENCES OF POLYHALITE

A. From Government hole No. 2 at a depth of 682 feet 7 inches to 682 feet 11 inches. The polyhalite (dark) occurs in vertical growths and irregular blebs in the anhydrite (upper part) but in spherulitic forms in the clay.

B. From Government hole No. 6 at a depth of 805 feet 11 inches to 806 feet 3 inches. Abundant vertical growths of halite, many more or less replaced by polyhalite, are present, but there are also many horizontal layers of polyhalite (dark), free from any vertical growths, in the anhydrite. Such a specimen probably represents at least two distinct stages in the formation of polyhalite.

C. From Government hole No. 4 at a depth of 1,301 feet. Shows several unusually large crystals of polyhalite (light) in halite (black, in upper right corner). Most of the specimen is anhydrite.

113

OTHER OCCURRENCES OF POLYHALITE

PLATE 31
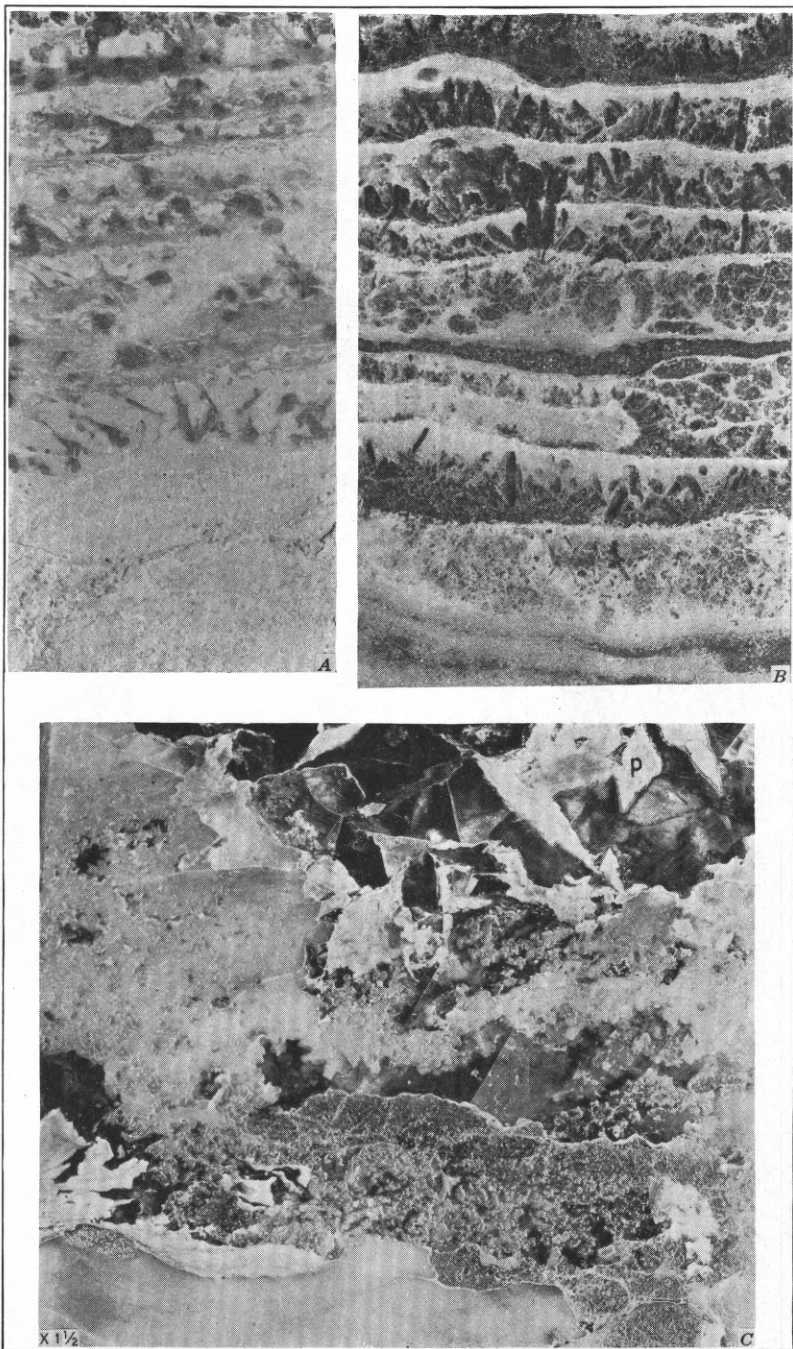
MOTTLED APPEARANCE OF POLYHALITE ROCK

A. From the McNutt No. 1 well at a depth of 794 feet 8 inches to 795 feet. The mottled appearance is due to included crystals of anhydrite, which in thin section (pl. 5) are seen to be largely corroded and replaced by polyhalite. The change of these larger crystals probably follows the change of the fine-grained anhydrite rock to polyhalite.

B. From the McNutt No. 1 well at a depth of 1,130 feet 3 inches to 1,130 feet 7 inches. The mottling is due to a difference in the grain of the polyhalite itself and not to the presence of other included minerals.

C. From the McNutt No. 1 well, at a depth of 1,396 feet 10 inches to 1,397 feet. The mottling effect is due to the presence of halite, scattered through the white polyhalite as short and thin irregular seams.

D. From the McNutt No. 1 well, at a depth of 1,570 feet 1 inch to 1,570 feet 5 inches. As in *B*, the mottling effect is due to the variation in size of grain of the polyhalite itself. The dark areas shown are larger crystals of polyhalite embedded in the fine-grained variety.

114

MOTTLED APPEARANCE OF POLYHALITE ROCK

PLATE 32
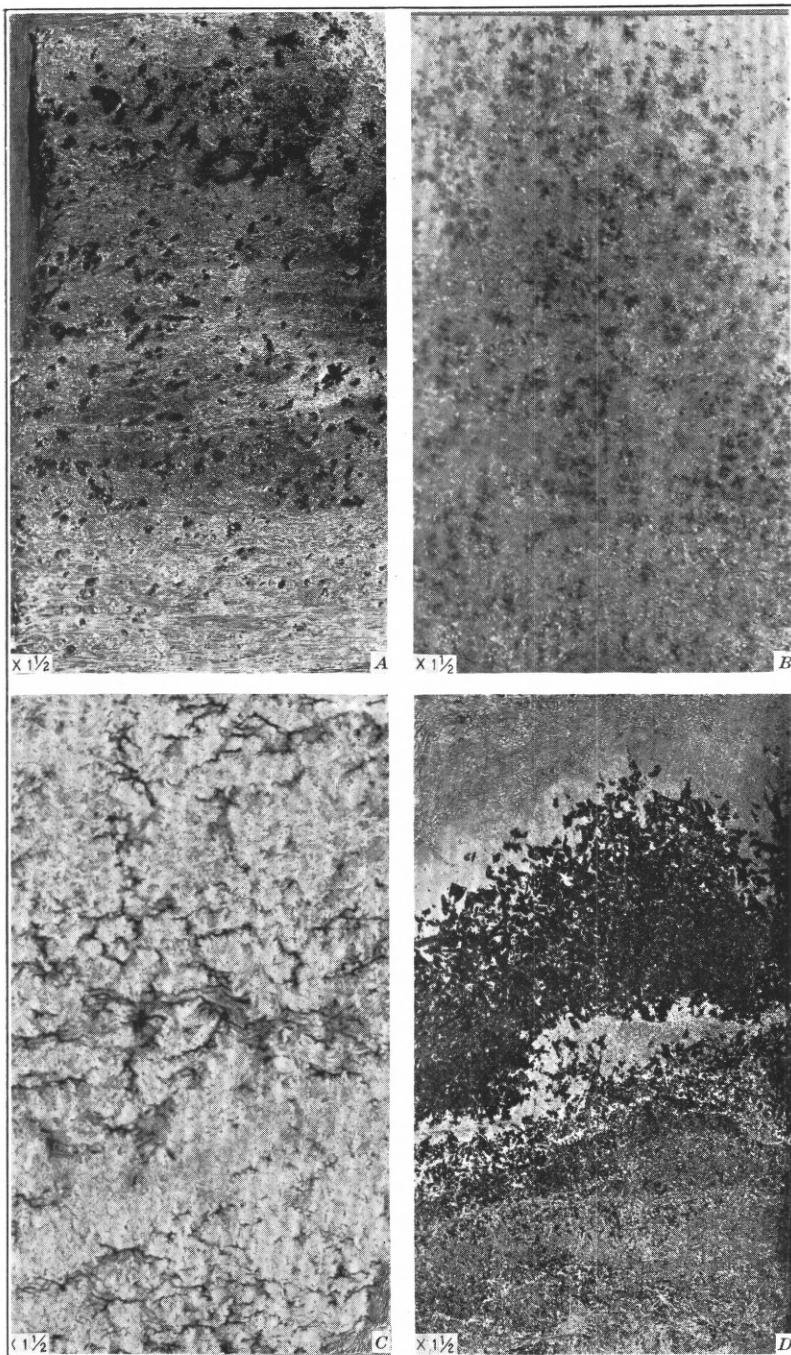
ASSOCIATION OF POLYHALITE WITH OTHER MINERALS

A and *B* show method of detecting the presence of polyhalite that is intimately mixed with other minerals, by immersion in water for a few minutes, thereby developing a coating of white gypsum on the polyhalite when air dried. From McNutt No. 1 well at a depth of 994 feet 5 inches. *A*, polished specimen in which two large blebs of polyhalite (dark) show clearly, but the many smaller blebs of polyhalite scattered through the anhydrite-kieserite-halite matrix are not visible. *B*, same specimen after immersion in water for a few minutes and drying in air. Polyhalite whitened by growth of gypsum is more readily detected.

C. Intimate granular coarse mixture of polyhalite, halite, anhydrite, and kieserite. From McNutt No. 1 well at a depth of 1,900 feet. The polyhalite appears black, but the other minerals, which are well intermingled, can not be recognized.
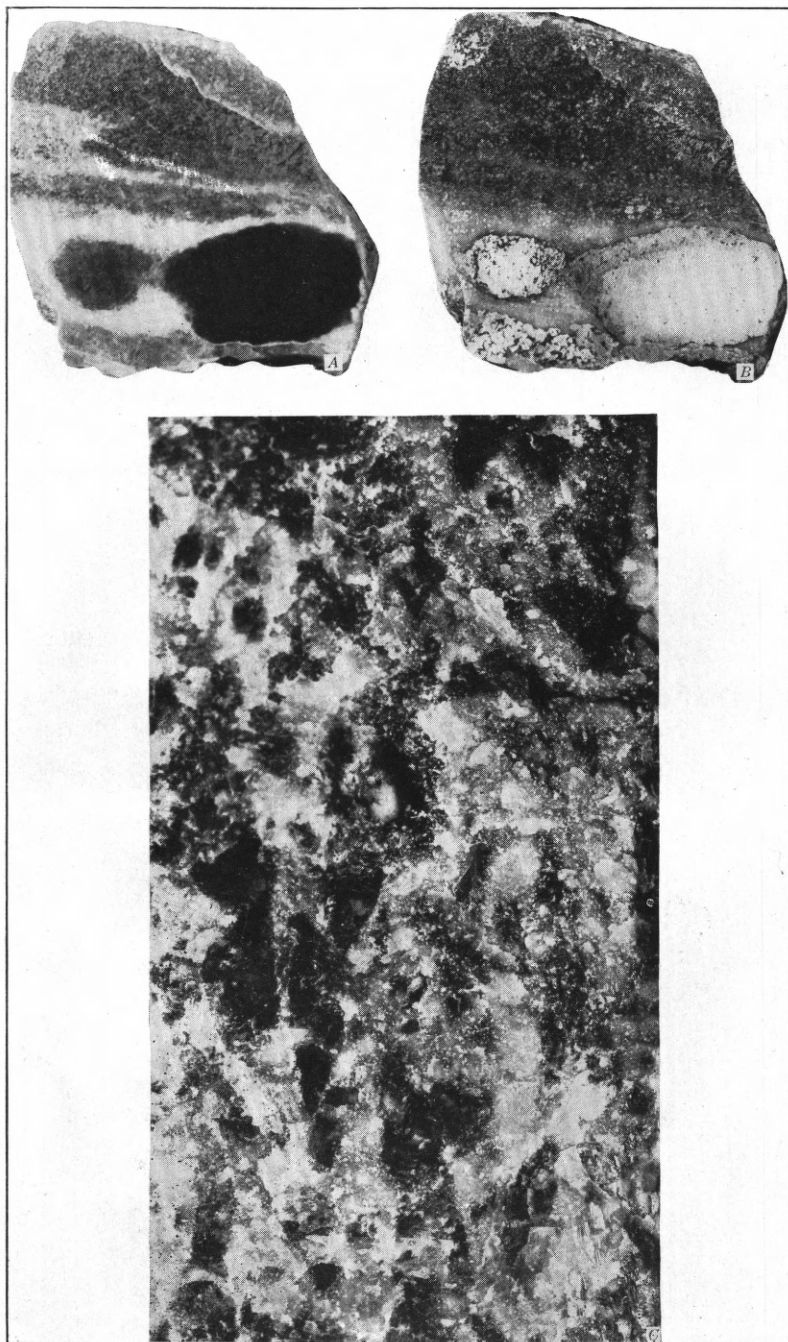
115

ASSOCIATION OF POLYHALITE WITH OTHER MINERALS

PLATE 33

ASSOCIATION OF POLYHALITE WITH OTHER MINERALS

A. Polyhalite, anhydrite, and kieserite. From Eldridge well at a depth of about 1,126 feet. The fine-grained gray groundmass is polyhalite, the prismatic crystals are anhydrite, and the irregular small areas, some black and others white (due to adhering polishing powder), are kieserite. The intimate mixture of polyhalite and anhydrite, in the upper and lower portions (kr) corresponds to what has been called krugite. (See also *B.*)

B. The other half of the core shown in *A*, after immersion in water for a few minutes and drying in air. The anhydrite and kieserite were not attacked, but the polyhalite has all been coated with a thin deposit of white gypsum. The anhydrite (black) forms prismatic crystals, and the kieserite (also black) occurs in the irregular-shaped masses in both the polyhalite (center) and the polyhalite-anhydrite mixture, the so-called krugite (kr). This illustration shows very well how the water-immersion method serves to bring out the structure and mineral relations of these mixtures. Both the anhydrite and the kieserite show stages of replacement by polyhalite.

C. Polyhalite (gray groundmass) with irregular included areas of kieserite (white) and anhydrite (black). From McNutt No. 1 well at a depth of about 1,762 feet.

D. Anhydrite with irregular-shaped included areas of polyhalite (light). From McNutt No. 1 well at a depth of 1,671 feet 5 inches to 1,671 feet 8 inches.

116
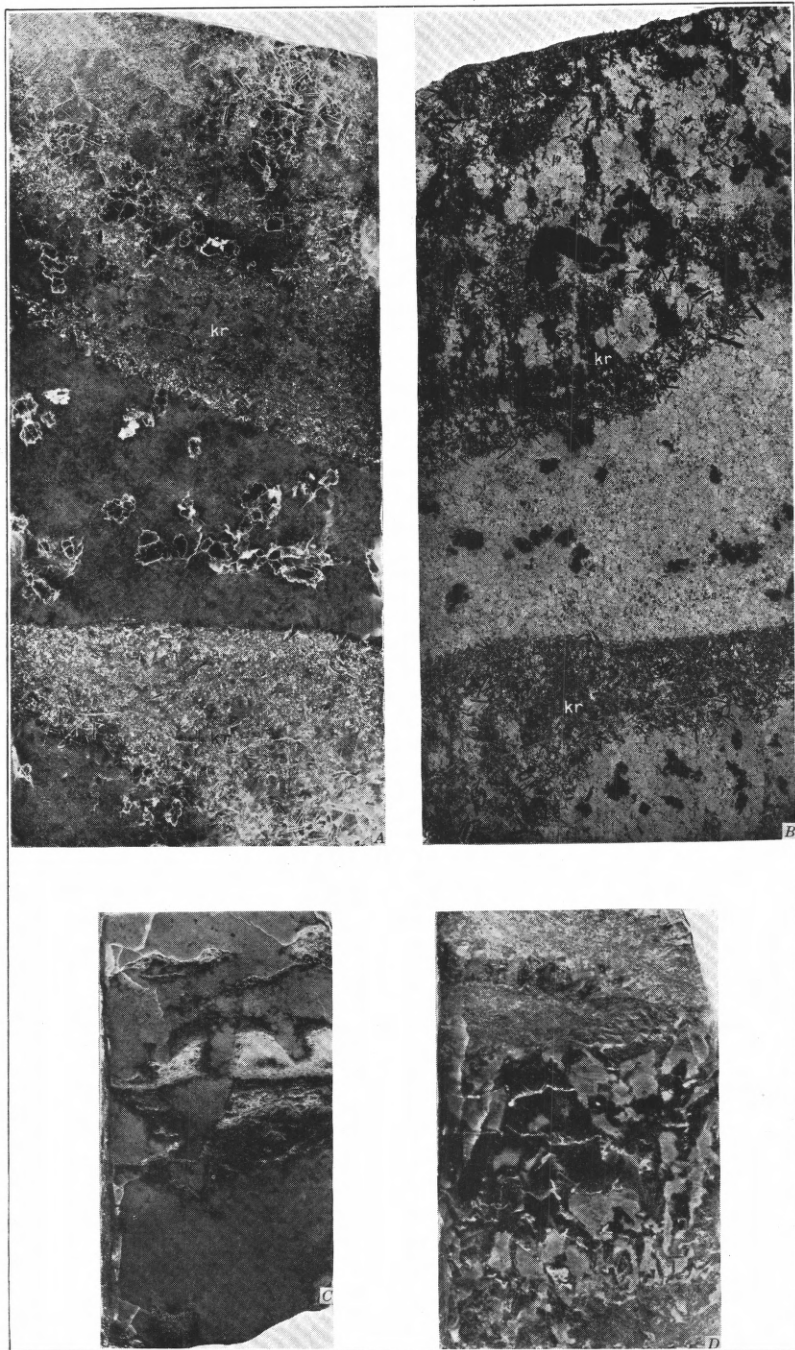
ASSOCIATION OF POLYHALITE WITH OTHER MINERALS

PLATE 34

CONTACT OF POLYHALITE ROCK AND ANHYDRITE ROCK

From Government hole No. 9 at a depth of 1,837 feet 2 inches to 1,837 feet 6 inches. The contact shows that the boundary of the polyhalite is convex against the anhydrite. The polyhalite is a mixture of fine-grained and fibrous varieties. The illustration also shows the dull reddish-brown and light salmon-colored varieties of polyhalite which are interpreted as representing two stages of formation, the light-colored later than the dark. The anhydrite shows faint horizontal banding. A photomicrograph of the contact is shown in Plate 35, *B*.

117
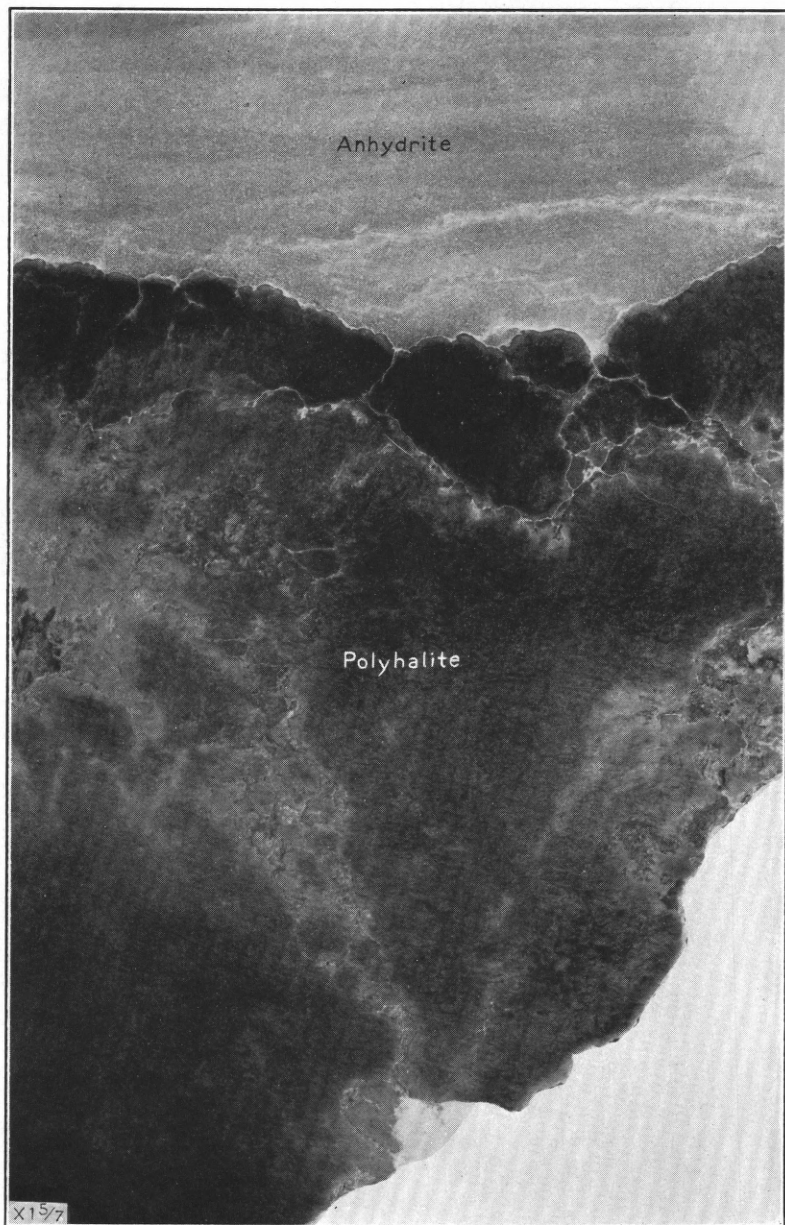
CONTACT OF POLYHALITE ROCK AND ANHYDRITE ROCK

PLATE 35

PHOTOMICROGRAPHS OF CONTACT OF POLYHALITE ROCK WITH ANHYDRITE ROCK

A. Rounded masses of polyhalite (p) in anhydrite (a). These masses present a convex surface to the anhydrite. Some of them have an interrupted border of magnesite, as if in the change of the anhydrite rock banded with magnesite the polyhalite was not able to assimilate or to include the magnesite but pushed it aside. From McNutt No. 1 well at a depth of 994 feet 5 inches.

B. Enlarged view of contact of specimen figured in Plate 34, showing convex surfaces of polyhalite against anhydrite. From Government hole No. 9 at a depth of 1,837 feet 3 inches. The body of polyhalite is made up of adjacent rounded masses, like those shown in *A*. A narrow seam of lighter-colored polyhalite lies next to the anhydrite. Short tongues of anhydrite that extend downward between two adjacent rounded masses of polyhalite are shown. The dark streaks in the polyhalite are hematite, which usually, lie between two coalesced rounded masses of polyhalite.
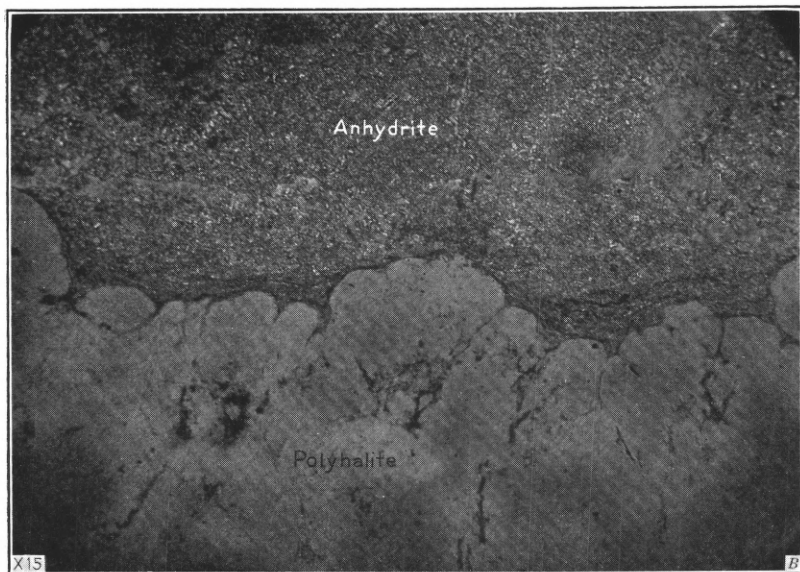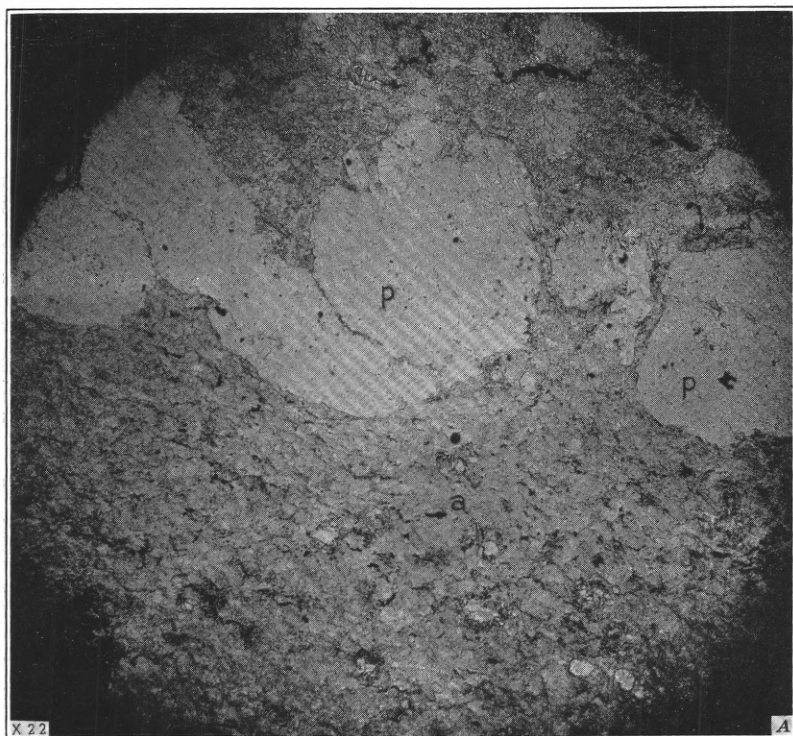
118

PHOTOMICROGRAPHS OF CONTACT OF POLYHALITE ROCK WITH ANHYDRITE
ROCK

PLATE 36

PHOTOMICROGRAPHS OF CONTACT OF POLYHALITE ROCK WITH ANHYDRITE ROCK

A. Rounded masses of polyhalite in anhydrite, with a convex surface against the anhydrite, as well shown in the vein of polyhalite that extends to the left.   This vein also contains many residual masses and streaks of anhydrite.   Along the contact of the large body of polyhalite are mere shreds of residual anhydrite, alined parallel to the contact.   At the right is a long strand of such residual anhydrite, parallel to which and farther away from the main body of anhydrite are several still fainter parallel strands of residual anhydrite.   In the lower center small masses of polyhalite that have developed in the anhydrite can be seen.   From Ballard No. 1 well at a depth of 524 feet 6 inches.

B. A typical irregular and interpenetrating contact, where small areas of the polyhalite have developed in the anhydrite and have left many attached and detached masses of anhydrite, which become smaller as the distance away from the main mass of anhydrite increases.   At the left are several masses of the polyhalite with convex surfaces against the anhydrite.   From Blanchard No. 2 well at a depth of 548 feet 2 inches.

119
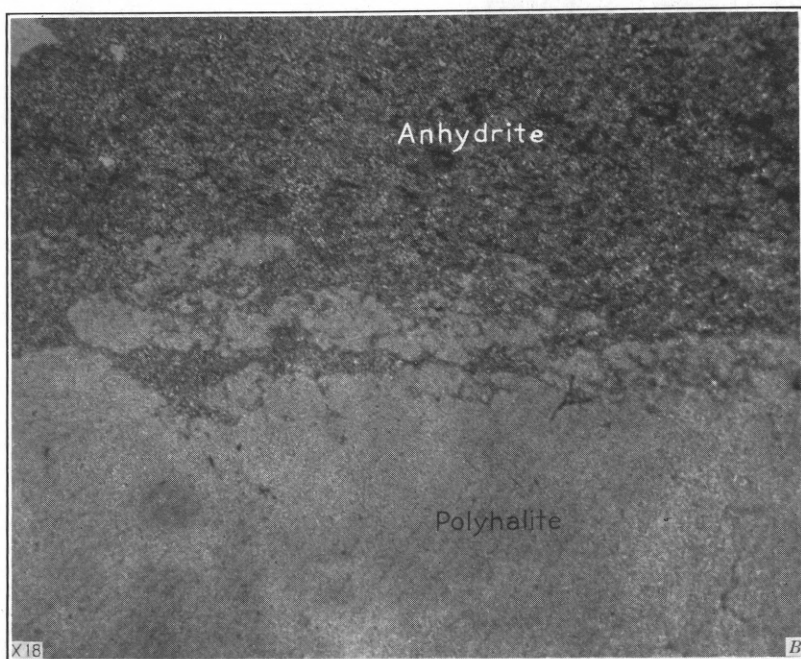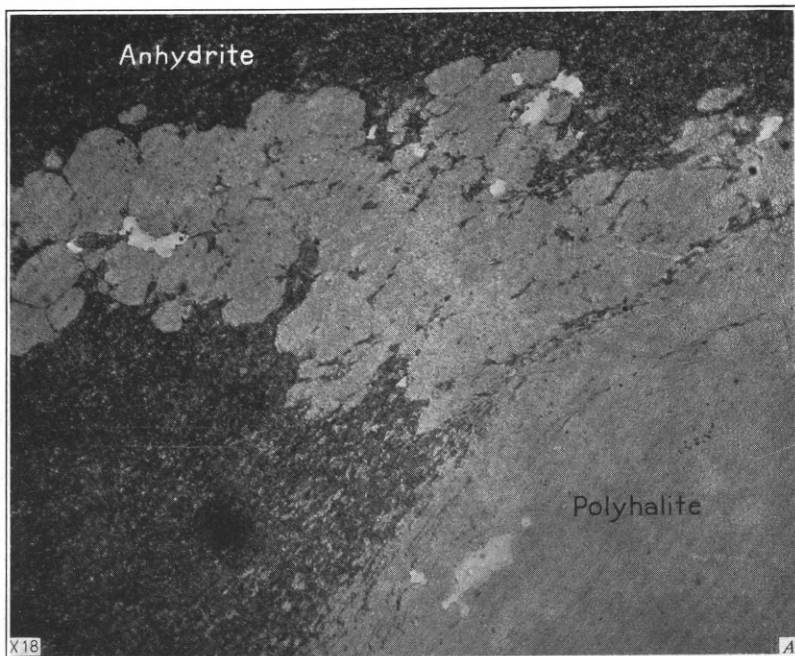
PHOTOMICROGRAPHS OF CONTACT OF POLYHALITE ROCK WITH ANHYDRITE ROCK

PLATE 37

SYLVITE AND HALITE (SYLVINITE)

A. From Martin Yates No. 2 well at a depth of 1,124 feet 1 inch to 1,124 feet 4 inches. Large masses of sylvite (s) associated with halite (h). In the upper part of the specimen are relatively large masses of nearly pure sylvite of the typical reddish-brown color; in the lower part, considerable halite is scattered through it.

B. From Joe Mitchell well at a depth of 1,361 feet 10 inches to 1,362 feet 2 inches. Shows a similar mixture of the two chloride minerals, in which two masses of the reddish-brown sylvite (s) have remaining centers of white sylvite. It is thought that all this sylvite was originally white (or colorless), and that the coloring pigment (hematite) was introduced later. (See pl. 38 and p. 75.)

C. From Amy McNutt No. 1 well at a depth of 1,195 feet 1 inch to 1,195 feet 5 inches. Fine-grained mixture of sylvite and halite, known as sylvinite, in which the individual particles of the two minerals are much smaller and hardly discernible.

D. From Joe Mitchell well at a depth of 1,363 feet 4 inches to 1,363 feet 6½ inches. The outside surface of a core containing large masses of sylvite (s) in halite (h), showing how much of the sylvite has been dissolved by the drilling brine. The cavities shown were filled with sylvite before the core was drilled. The upper left corner of the specimen (s) is essentially white sylvite, partly dissolved.

In many pieces of core large masses of sylvite occur in sylvinite, which is composed of reddish-brown sylvite and colorless and reddish-brown halite.

120

SYLVITE AND HALITE (SYLVINITE)

PLATE 38
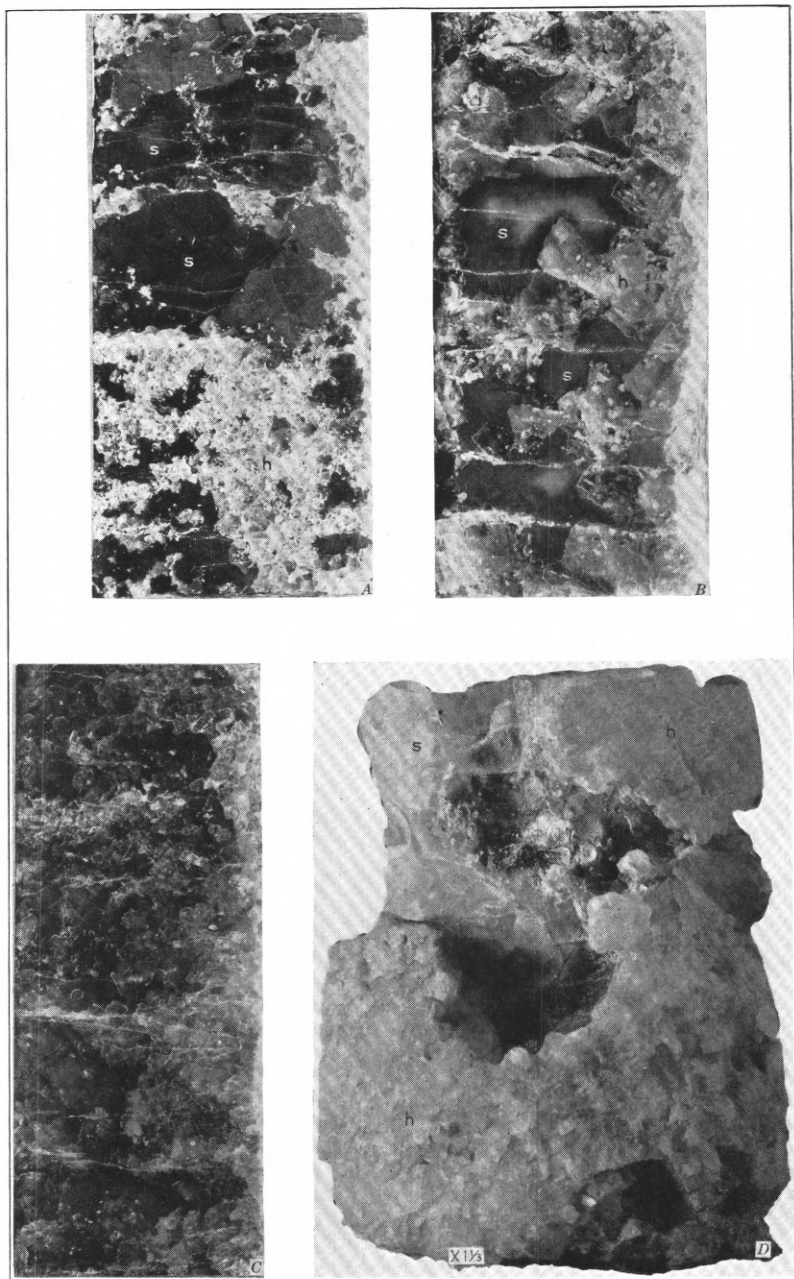
SYLVITE AND HALITE

Narrow zones of reddish sylvite (black) surrounding milky-white sylvite (s), all in halite (h). Two sides (*A* and *B*) of a core from Blanchard No. 1 well at a depth of 962 feet to 962 feet 3 inches. The reddish sylvite lies along the contact of the milky-white sylvite and the inclosing halite but also penetrates cracks and cleavage planes in the white sylvite. At places the reddish sylvite occupies considerable areas and suggests that the specimen illustrated represents an early stage in the formation of reddish sylvite. This raises the question whether all the sylvite, now reddish or reddish-brown, had formed by the introduction of coloring matter (hematite) into previously white or colorless sylvite.

121

SYLVITE AND HALITE

1.450   1.460   1.470   1.480   1.490   1.500   1.510   1.520   1.530   1.540   1.550   1.560   1.570   1.580   1.590   1.600   1.610   1.620   1.630

Mirabilite
α, 1.394 , β, 1.396, γ, 1.398

α, 1.432

Epsomite

Picromerite

Thenardite

Carnallite

+

Leonite

−

Bloedite

Birefringence
Sylvite, langbeinite, halite
Rinneite | Loewite-
Bloedite
Mirabilite, vanthoffite | Vanthoffite

Sylvite

Leonite, aphthitalite
Tachhydrite, celestite
Gypsum, pinnoite | Douglasite +
Boracite | Aphthitalite +
Douglasite
Hydrophilite
Picromerite | Kainite
Sulphoborite | Bischofite
Syngenite | Syngenite
Thenardite, loewite | Tachhydrite-
Ascharite, polyhalite
Kainite, glauberite | Gypsum

Kaliborite

Lueneburgite | Glauberite

Langbeinite

Epsomite, carnallite
Bischofite | Kieserite

Sulphoborite

Lueneburgite

Halite

Ascharite

Zirklerite

Anhydrite | Polyhalite

Pinnoite +

Kaliborite

Anhydrite

Rinneite +

Hydrophilite
Magnesite -   1.700

Celestite
d, 1.622, β, 1.624, γ, 1.631
Boracite
α, 1.662, β, 1.667, γ, 1.673

Kieserite
Magnesite 0.191

REFRACTIVE INDICES OF SALINE MINERALS OCCURRING IN POTASH DEPOSITS

INDEX