The petrology of the evaporites of the Eskdale no. 2 boring, east Yorkshire.

PART I. *The lower evaporite bed.*

(With Plates XXIX–XXXIV.)

By F. H. STEWART, B.Sc., Ph.D., F.G.S.

Department of Geology, Science Laboratories, Durham, University of Durham.

[Read March 31, 1949.]

CONTENTS

S S

I. INTRODUCTION AND ACKNOWLEDGEMENTS.

IN 1938–39 the D'Arcy Exploration Company, Limited, sank a bore-hole (Eskdale well no. 2) to a depth of 5040 feet near Aislaby, Eskdale, Yorkshire, to test the oil or gas possibilities in the Permian Magnesian Limestone. As the well was some distance from any previous boring through the Permian salt series, the Company undertook to carry out continuous coring through this series in the public interest. The boring passed through Lias, Rhaetic, and Trias, and finished in the Permian Lower Magnesian Limestone. The geological results of this boring have been discussed by Lees and Taitt (1945), and fig. 1 has been reproduced from their paper. It can be seen that three evaporite beds were passed through; two in the Upper Permian salt zone, and one in the Middle Permian.

The evaporites consist mainly of halite and anhydrite. In 1942 Tilley exhibited a core specimen of polyhalite, from a depth of about 4500 feet, to the Mineralogical Society (Tilley, 1943). Lees and Taitt (1945) show a 45-foot bed of massive polyhalite in their section (fig. 1) in the lower evaporite bed, and mention a thin zone of sylvinite at the top of the middle evaporite bed. Guppy (1944) has recorded boracite in well cuttings from the middle evaporite bed.

The writer visited the site of the boring in 1942 and collected a number of core samples, many of which consisted largely of polyhalite. He was employed by Imperial Chemical Industries, Limited, at the time, and drew this to their attention, and found that the D'Arcy Exploration Company had arranged with I.C.I. that the latter should undertake chemical analyses and examination of the cores of the boring. The Imperial Chemical Industries had therefore taken core samples from the boring while it was being put down, and by chemical analysis they had found potassium present in considerable quantity in parts of the upper and middle evaporite beds and in one sample from the lower evaporite bed. Sylvine had been found in the upper part of the middle evaporite bed. Since then the writer has examined the available speci-mens petrologically, together with well cuttings supplied by the D'Arcy Exploration Company, and other minerals of potassium-bearing eva-porites have been found (notably carnallite and rinneite in the upper evaporites). Talc has been found as a significant constituent of the upper and lower evaporite beds. The rocks show evidence of many interesting replacement changes since their original deposition.

A petrographic account of the lower evaporites (4313–4773 feet below

surface) is presented in this paper. The upper evaporites will be described in a later communication.

Some of the work was done at the I.C.I. Research Laboratories, Billingham-on-Tees, and it has been continued at Durham University. I should like to express my sincere thanks to Imperial Chemical Industries and the D'Arcy Exploration Company for supplying material for examination; to Durham Colleges for a research grant to defray expenses; to Dr. F. A. Bannister for his X-ray examination of a specimen of talc from this boring; and to Mr. G. O'Neill for taking the photographs which illustrate this paper.

II. MATERIAL EXAMINED.

Core samples of known depth.—These were collected by I.C.I. while drilling was in progress. A considerable number of core samples were taken from the upper evaporite beds, which consist largely of chlorides. Only eleven samples, however, were taken from the lower evaporite bed, which consists largely of sulphates. The presence of polyhalite in considerable quantity was not realized at the time.

The eleven samples preserved consist of pieces of core, 2–4 inches in length, from the following depths: 4312–14, 4314–16, 4350–52, 4352–54, 4356–58, 4415, 4445–47, 4491–93, 4559–61, 4742, 4760–62 feet below surface.

Core samples of unknown depth.—A considerable number of core samples was collected by the writer at the site of the boring in 1942. These had been lying in the open since the boring was completed in 1939, and the more soluble salts had been dissolved away. These specimens, therefore, consist largely of anhydrite with carbonates, although a considerable amount of polyhalite has been preserved within weathered crusts of secondary gypsum in certain specimens.

The exact depth of these specimens is unknown, but since the diameter of the core from the lower evaporite bed was $2\frac{1}{4}$ inches, and of that from the upper evaporites $4\frac{1}{2}$ inches, it is possible to separate the specimens of the lower bed from the others. Since so few samples of known depth have been preserved, these specimens have given valuable information on the petrology of this bed.

Well cuttings.—The D'Arcy Exploration Company has kindly supplied well cuttings taken, at intervals of 5 to 10 feet, from the circulating mud during the drilling. These cover the depth range of all three evaporite beds. They consist of small rock and mineral fragments, up to $\frac{1}{2}$ inch in length, and have given much information on the less soluble

LOG OF AISLABY BORING IN ESKDALE

POSITION OF BORING — — — — — — — — LONG. 0° 41' 50" W.
LAT. 54° 27' 38" N.

COUNTY — — — — — — — — — — — — YORKSHIRE – NORTH RIDING

METHOD — — — — — — — — — — — — ROTARY, 136 FT DERRICK, POWER - DIESEL

DATE — — — — — — — — — — — — COMMENCED – 16 6 38
COMPLETED – 17 11 39

ELEVATION OF ROTARY TABLE — — — — 403 FT. (ABOVE O.D.)

Scale – Feet

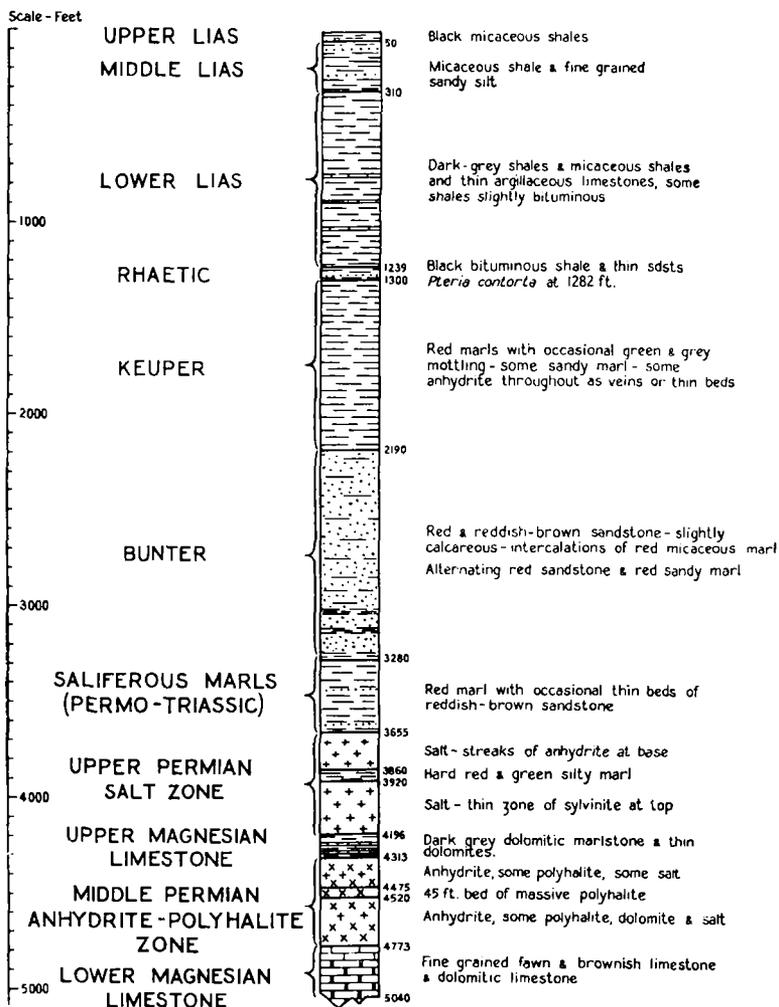|	
UPPER LIAS	50 Black micaceous shales
MIDDLE LIAS	Micaceous shale & fine grained sandy silt
	310
LOWER LIAS	Dark-grey shales & micaceous shales and thin argillaceous limestones, some shales slightly bituminous
–1000	
RHAETIC	1239 Black bituminous shale & thin sdsts
	1300 Pteria contorta at 1282 ft.
KEUPER	Red marls with occasional green & grey mottling - some sandy marl - some anhydrite throughout as veins or thin beds
–2000	
	2190
BUNTER	Red & reddish-brown sandstone - slightly calcareous - intercalations of red micaceous marl
	Alternating red sandstone & red sandy marl
–3000	
	3280
SALIFEROUS MARLS (PERMO-TRIASSIC)	Red marl with occasional thin beds of reddish-brown sandstone
	3655
UPPER PERMIAN SALT ZONE	Salt – streaks of anhydrite at base
–4000	3860 Hard red & green silty marl
	3920
	Salt – thin zone of sylvinite at top
UPPER MAGNESIAN LIMESTONE	4196 Dark grey dolomitic marlstone & thin dolomites.
	4313
MIDDLE PERMIAN ANHYDRITE - POLYHALITE ZONE	Anhydrite, some polyhalite, some salt
	4475 45 ft. bed of massive polyhalite
	4520 Anhydrite, some polyhalite, dolomite & salt
	4773
LOWER MAGNESIAN LIMESTONE	Fine grained fawn & brownish limestone & dolomitic limestone
–5000	5040

FIG. 1. Log of the Aislaby boring (Eskdale no. 2).
Taken from Lees & Taitt, 1946, (Quart. Journ. Geol. Soc., vol. 101, p. 268.)

minerals. The more soluble minerals are not preserved. From a study of these cuttings the upper limit of a mineral can be fixed with reasonable precision, but the lower limit can be found only approximately.

III. GENERAL SUCCESSION IN THE LOWER EVAPORITE BED.

Since so few core samples of known depth have been preserved, our knowledge of the succession is incomplete. The relative distribution of salt, anhydrite, and polyhalite is given in the following table. The distribution of salt and anhydrite is based on the D'Arcy Exploration Company's detailed log of the boring. It is not known whether other chlorides than halite are present, but it is considered probable that they did not occur in significant amount, if at all, as two specimens from the top 3 feet of the bed show colourless halite with no other chloride. The distribution of polyhalite in the table is based on a study of the well cuttings.

		Thickness in feet.
4313 feet		
	Colourless salt	2
	Colourless salt with streaks of anhydrite	10
	Alternating salt and anhydrite	6
Halite-anhydrite zone	Salt	17
	Alternating salt and anhydrite	7
	Salt with disseminated anhydrite	11
	Alternating salt and anhydrite	16
	Anhydrite with irregular inclusions of salt	7
	Alternating salt and anhydrite	10
4399 feet		
Upper anhydrite	Anhydrite with irregular inclusions of salt	11
	Anhydrite	30
4440 feet		
	Salt with irregular inclusions of polyhalite and anhydrite (salt bluish tinge)	34
Polyhalite zone	Polyhalite with irregular inclusions of salt	30
	Polyhalite	15
	Anhydrite and polyhalite	6
4525 feet		
	Anhydrite with occasional irregular inclusions of salt (nests of micaceous mineral)*	12
	Anhydrite	21
Lower anhydrite	Anhydrite with streaks of salt	5
	Anhydrite with occasional irregular inclusions of salt	15
	Anhydrite (locally dolomitic)	131
	Anhydrite with small irregular inclusions of salt	31
	Brecciated anhydrite with small irregular inclusions of salt	17
	Anhydrite with small irregular inclusions of salt	16
4773 feet		
	Dolomitic limestone	to bottom of boring

* The micaceous mineral mentioned in the boring log probably refers to talc.

It can be seen that the general sequence of the dominant minerals from the base upwards is carbonate, anhydrite, polyhalite, halite. The sequence, however, is far from ideal. The presence of halite in the lower part of the anhydrite zone is curious. The upper anhydrite zone might indicate freshening of the water at this stage. The upper evaporites of this boring are simpler in this respect, each having a lower sulphate zone, followed by a mixed sulphate-chloride zone and then a thick chloride zone with relatively little associated sulphate.

IV. THE MINERALS.

The following minerals have been found in the lower evaporite bed:

Chlorides: Halite.
Sulphates: Anhydrite, celestine, gypsum, polyhalite.
Carbonates: Dolomite, magnesite.
Other minerals: Pyrite, quartz, native sulphur, talc.

Another mineral occurs in minute quantity in the well cuttings. This has not yet been identified and is under investigation.

Halite, anhydrite, polyhalite, and the carbonates occur in abundance. Talc has been found in many specimens. Gypsum is present only as a product of weathering, but evidence of its former presence on a considerable scale is given by pseudomorphs in the polyhalite zone. Celestine, pyrite, and sulphur occur in very small amount. Quartz forms a few detrital grains.

In the following description the characters and distribution of the individual minerals will be given, with a short summary of their relations to the other minerals. In later sections the mineral assemblages are described and discussed.

(1) *Anhydrite.*

Anhydrite is the most abundant mineral of the evaporite bed. The lower 250 feet is formed almost wholly of this mineral. It occurs in minor quantity in the polyhalite zone. Above this it forms layers and patches in the upper chloride-rich zone and forms a 30-foot bed at the base of this zone.

Most of the anhydrite is white or grey in colour, but some types have a slight bluish tinge. The refractive indices are normal and correspond with those given by Dunham (1948, p. 221) α 1·570, β 1·576, γ 1·614. The grains vary in size from about 0·002 mm. to 1 cm. The shape

varies a great deal. The main types are as follows (there are, of course, gradations from one type to another):

(a) Irregular grains with interlocking margins, with a tendency to stumpy rectangular habit.

(b) Elongated grains, roughly rectangular with irregular margins. These often tend to form radiate groups.

(c) Radiate fan-like plates with curved cleavages, sometimes reaching 1 cm. in length.

(d) Rectangular euhedral crystals, generally nearly equidimensional, but sometimes much elongated. These occur associated with halite, and as porphyroblasts in anhydrite-rock.

(e) Tabular rectangular euhedral crystals. These occur as porphyroblasts in polyhalite, and sometimes reach nearly 1 cm. in width.

Evidence of recrystallization of anhydrite is widespread, especially where it is associated with halite.

Anhydrite has been found associated with all other minerals of the core specimens. It is generally euhedral towards halite, but has been eaten into and replaced by halite in a specimen from 4559–61 feet (fig. 2). In the polyhalite zone it has replaced gypsum and has been replaced by polyhalite on a large scale. It has partly recrystallized to form large tabular porphyroblasts in polyhalite and these porphyroblasts have themselves been attacked by later polyhalite. Anhydrite has replaced dolomite near the base of the bed, possibly to a considerable extent. Magnesite is nearly always euhedral towards anhydrite, although in a few cases euhedral anhydrite crystals have been seen to cut magnesite plates. Replacement of anhydrite by magnesite has been seen in coarse anhydrite-magnesite-halite-rocks. In the anhydrite-magnesite-dolomite-rock described in a later section, anhydrite appears to be replacing dolomite and it is suggested that brines rich in $MgSO_4$ may cause the production of anhydrite together with magnesite at the expense of dolomite. Plates of talc project from anhydrite into cavities from which halite has probably been dissolved by weathering agents. In one specimen native sulphur has been seen replacing anhydrite. Celestine is euhedral towards anhydrite.

(2) Celestine.

This mineral has been found in very small quantity in a specimen of brecciated anhydrite-dolomite-rock from 4742 feet, and in two other specimens of similar rock of unknown depth. It occurs at the edges of

small cavities which probably originally contained halite, and it forms aggregates of elongated crystals up to 1 mm. long, in approximately parallel growth. It is euhedral towards anhydrite. The refractive indices do not differ from those given in the literature, α 1·622, β 1·624, γ 1·631.

Fowler (1944) has recorded celestine, associated with anhydrite, in joints and cavities and as inclusions in dolomite-rock in the Cleveland Hills boring.

(3) *Dolomite.*

The distribution and mutual relations of the carbonates are discussed in a later section. Dolomite is the carbonate present in the lower part of the evaporite bed. It is also the carbonate of the polyhalite-bearing rocks, and is associated with magnesite in the upper anhydrite zone.

In most of these rocks it forms small rounded granules, like those described by Dunham (1948, p. 219), from 0·001 to 0·02 mm. in diameter. These are brown in colour and often crowded with minute dark inclusions. Occasionally they show clear margins or clear centres. They tend to occur in clusters or in strings or thin layers. At the edges of halite cavities they are euhedral, and form small rhombohedra. In some anhydrite-dolomite-rocks the dolomite forms larger clear euhedral rhombohedra up to 0·3 mm. across, in a matrix of anhydrite. Fifteen refractive-index measurements show no significant variation from the value ω 1·682.

Extensive replacement of dolomite by anhydrite is indicated in anhydrite-dolomite-rocks with coarse fibro-radiate anhydrite from the base of the lower anhydrite zone. Dolomite is associated with magnesite in one specimen from the upper anhydrite zone, and the relations suggest that anhydrite and magnesite have formed at the expense of the dolomite. In the polyhalite-anhydrite-rocks, where polyhalite has replaced anhydrite, the carbonate apparently remains unchanged.

(4) *Gypsum.*

Gypsum has been found only as a product of weathering of polyhalite and anhydrite in the well cuttings and in those specimens which were lying in the open for about three years at the site of the boring. Early gypsum was abundant in the polyhalite-bearing rocks.

Very little gypsum has been formed in the weathered anhydrite-carbonate-rocks. In these it occurs principally at the edges of the halite cavities, replacing anhydrite and often enclosing anhydrite relics. Some of the weathered polyhalite-bearing rocks have been entirely converted

to a porous mass of gypsum. Others show a weathered gypsum crust
of varying thickness with a central core of fresh polyhalite. The contact
of this gypsum crust with the fresh material is remarkably sharp. The
gypsum forms a porous mass of elongated crystals up to 5 mm. in
length, radiating from the central core (e.g. pl. XXXIII, fig. 37).

Abundant evidence of early gypsum is found in the polyhalite-bearing
rocks, where anhydrite, halite, and polyhalite form pseudomorphs after
gypsum. The evidence suggests that part of the gypsum was primary,
and that some of it was derived from anhydrite in unconsolidated
anhydrite-dolomite layers. Later the gypsum was replaced by anhy-
drite and halite and these were replaced by polyhalite. These rocks are
described in detail and discussed in the later sections on polyhalite-
bearing rocks.

(5) *Halite.*

This mineral has been preserved only in the core samples of known
depth. The bore journal shows that it is the most abundant mineral of
the upper 100 feet of the evaporite bed, and the well cuttings show that
it is there associated with anhydrite. It is also present in large quantity
from 4440 to 4474 feet associated with polyhalite, anhydrite, and talc. It
occurs as irregular inclusions in polyhalite-rocks and anhydrite-rocks
below this depth at several horizons.

In the core specimens it is colourless, in marked contrast to the pre-
dominantly pink or brown varieties of the upper evaporites. The bore
journal records a bluish tinge in the halite associated with polyhalite
through the depth range 4440–4474 feet.

The grains vary from a few millimetres to about an inch in diameter,
and their boundaries are irregular. In general they are nearly equi-
dimensional, but in a specimen from the top of the evaporite bed
(4312–14 feet), which consists almost entirely of halite, the grains are
markedly flattened, and impart distinct horizontal platy parallelism to
the rock, which splits with ease along the cross-section of the core. This
is believed to be due to recrystallization under pressure. The available
specimens of halite-anhydrite assemblages from the upper part of the
evaporite bed show structures indicating that much of the halite of this
zone has recrystallized since its formation, as shown by contortion of
anhydrite bands.

Halite has been found associated with anhydrite, polyhalite, mag-
nesite, and talc. It is allotriomorphic towards all these minerals. Where
halite is in contact with anhydrite, the latter mineral tends to form

larger crystals than it does in the body of the rock. This feature has been commented on by Schaller and Henderson (1932, p. 16) and by Dunham (1948, pp. 222, 223), and it has been suggested that it indicates recrystallization of the anhydrite next to invading halite. It is probable, however, that this texture can arise by recrystallization of anhydrite during recrystallization 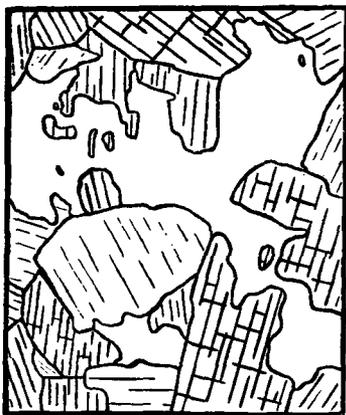of halite, without attendant replacement. In the case of the polyhalite-rocks, large crystals of polyhalite are apparently formed at the expense of halite in some cases.

FIG. 2. Halite-anhydrite-rock, showing replacement of anhydrite by halite. 4559–61 feet below surface. ×30.

Direct evidence of the replacement of anhydrite by halite is shown in a specimen from 4559–61 feet. Here the halite encloses small rounded detached relics of anhydrite which have common optical orientation (fig. 2).

Replacement of halite by polyhalite has been seen in the halite-anhydrite-polyhalite-talc-rock from 4445–47 feet and has probably taken place on a considerable scale in the rocks of the polyhalite zone.

Replacement of gypsum by halite is suggested by pseudomorphs in the rock from 4445–47 feet and other rocks of the polyhalite zone. Anhydrite may form an intermediate stage in this replacement (pl. XXX, figs. 21, 22).

No definite replacement relationship has been seen between halite and the carbonates. Talc occurs as thin plates which almost invariably lie along the cleavages of the halite (figs. 19, 20).

(6) *Magnesite.*

This mineral is the carbonate of the halite-anhydrite zone. It occurs with dolomite in the upper anhydrite zone, and also occurs in anhydrite-magnesite-talc-halite-rock which is probably to be referred to a layer near the top of the lower anhydrite zone. The distribution and relationships of magnesite and dolomite are discussed in a later section.

The magnesite forms platy crystals, tabular parallel to (0001), which reach one cm. in width in the coarse anhydrite-magnesite-halite-rocks.

These plates often have ragged edges, but are sometimes edged with a flat rhombohedron. In some rocks they tend to form radiate bunches. In others they occur as isolated crystals, either with even or patchy distribution. Cases have been found where plates have been cut and faulted by later plates.

Twelve refractive index measurements give ω 1·700–1·703, indicating almost pure magnesite. Chemical tests show the virtual absence of calcium and only a trace of iron.

The mineral is always associated with anhydrite, towards which it is almost invariably euhedral. Euhedral crystals sometimes project from anhydrite into halite. It has replaced anhydrite in coarse anhydrite-magnesite-halite-rock (fig. 9 B). In one specimen (4415 feet) euhedral plates of magnesite cut dolomite and the relations suggest that anhydrite and magnesite have formed at the expense of dolomite (fig. 10).

So far as the writer is aware, this boring gives the first record of magnesite in British evaporites.

(7) *Polyhalite.*

This is an important mineral of the lower evaporite bed at Eskdale. The well cuttings show that the polyhalite zone extends from about 4440 to 4525 feet. The cuttings and the detailed log of the boring show that the upper 34 feet of this zone consists largely of chloride, with minor quantities of polyhalite and anhydrite. Below this the rocks consist largely of polyhalite, with subordinate halite and anhydrite, and these grade downwards into massive anhydrite-dolomite-rock. Polyhalite is present in two specimens of known depth (4445–47, 4491–93) and in a large number of specimens of unknown depth.

The mineral normally occurs as fine-grained aggregates (0·001–0·2 mm. grain-size) of irregular grains which may be equidimensional or elongated. The elongated grains may be arranged with random orientation, or in fibrous aggregates or spherulitic groups. Much larger sub-hedral or euhedral grains (up to 1·5 mm. in length) are occasionally found associated with anhydrite, lining halite cavities, or enclosed in halite (fig. 32). Tiny plates and rods are found in the early stages of replacement of halite and anhydrite.

Most grains of polyhalite show twinning. Lamellar twinning, resembling that of the felspars, is very common. The large euhedral crystals generally show simple or sector twinning. These crystals are generally spear-shaped in section, and may be divided by twinning into two or four parts with different orientation. The crystal-form and twin-

laws have not been worked out, but the crystals are similar to those figured by Schaller and Henderson (1932, p. 53) and described by Görgey (1914).

Measurements of refractive indices give α 1·546, β 1·559, γ 1·568. The average of five measurements of the optic axial angle gives 2V 61°, negative. Chemical analyses of polyhalite-rocks are given in table I (p. 657). The rock A consists of almost pure polyhalite.

The origin of the polyhalite-bearing rocks is discussed in detail in a later section, where evidence is given suggesting that the polyhalite has been derived almost entirely by replacement of halite and anhydrite. Gypsum was an early constituent of these rocks, but there is no evidence of direct replacement of gypsum by polyhalite. Polyhalite forms pseudo-morphs after gypsum, but it is probable that anhydrite was an inter-mediate stage in the formation of these. Dolomite has apparently played no part in the replacement. Talc appears to be of later formation than polyhalite.

(8) *Pyrite.*

Pyrite has been found in only one specimen. Two idiomorphic crystal groups have been observed in a slice of an anhydrite-dolomite-rock, embedded in anhydrite and associated with native sulphur. The larger group is 0·5 mm. in diameter.

(9) *Quartz.*

Crystals of quartz occur in fair quantity in parts of the upper eva-porites of this boring, but in the lower evaporite only a few small rounded detrital grains have been detected.

(10) *Native Sulphur.*

Sulphur has been observed as small grains in 21 of the well-cutting samples from the upper anhydrite, polyhalite, and lower anhydrite zones. A sample from 4450 feet contains 8 grains of sulphur, and the others 1–3 grains each.

Sulphur has also been seen in two core samples of unknown depth. These consist of anhydrite-dolomite-rock, and the sulphur occurs re-placing anhydrite, and also associated with pyrite. The largest aggregate seen is 1·5 mm. across, and encloses corroded anhydrite relics. It is noteworthy that small blebs of sulphur are developed in areas of fine-grained anhydrite which contain a considerable amount of carbonaceous impurity (pl. XXIX, fig. 13).

(11) Talc.

Talc has been found to be a widespread constituent of the upper and lower evaporites in the Eskdale boring (figs. 18, 19, 20). As far as the writer is aware, this boring provides the first published record of the occurrence of this mineral in evaporites, and it is very peculiar that it should occur in such a paragenesis.

The mineral occurs in specimens from the halite-anhydrite zone, the polyhalite zone, and the lower anhydrite, and appears to be invariably associated with halite. Its distribution and origin are discussed in a later section.

It occurs as thin plates, up to 5 mm. in diameter, and 0·2 mm. thick. These plates show a pearly lustre on (001), and a perfect micaceous cleavage parallel to (001). They are very soft, flexible, and insoluble in acids. They give a negative pseudo-uniaxial interference figure. The refractive indices are α 1·540, $\beta = \gamma$ 1·588±0·002. Small liquid inclusions occur along the cleavages.

Dr. F. A. Bannister of the British Museum of Natural History has kindly confirmed the identification by comparing the rotation photograph of a flake of the mineral with that of a talc from Zillerthal. He found that the basal diffractions were identical in position and relative intensities.

Since this mineral was found in the Eskdale evaporites, the writer has heard from W. T. Schaller, in a personal communication, that talc has been found in the Texas–New Mexico salt-field. The mineral described as 'polyhalite fibres (p)' in the legend facing pl. 23 c in Schaller and Henderson (1932) has proved to be talc.

At Eskdale, the plates of talc lie along the cleavages of halite grains. The same is true of the American illustration. It is suggested in a later section that the talc is a late secondary mineral, formed from solutions which were particularly associated with halite.

V. HALITE-ANHYDRITE-ROCKS.

This description is based on those core specimens of known depth which consist largely of halite and anhydrite, without polyhalite. Halite-anhydrite assemblages are preserved in specimens from the following depths: 4312–14, 4314–16, 4350–52, 4352–54, 4356–58, 4559–61 feet.

The first five of these specimens belong to the chloride-rich zone of the upper part of the evaporite bed. They consist of colourless halite

with irregular layers and patches of white or grey anhydrite. Thin sections show the presence of small quantities of magnesite and talc.

The halite forms irregular grains, with interlocking margins, up to about an inch across. In the specimen from 4312–14 feet, the grains (up to 1 cm. across) are flattened, and the rock shows marked horizontal platy parallelism. In the other specimens the grains are nearly equidimensional.

The anhydrite layers and patches are irregular and the thinner layers are contorted and squeezed out in places. In the interiors of the layers most of the anhydrite grains are small (0·001 to 0·2 mm. diameter), and show irregular and interlocking margins. Layers rich in dusty impurities are taken to indicate original bedding, and contortion and crenulation of these has probably been caused by deformation due to recrystallization of the halite enclosing the anhydrite layers, and sometimes partial recrystallization of the anhydrite. Bedding is also indicated by variations in grain-size. In this fine-grained anhydrite, much larger grains are often found (up to 1 mm. in length). These are sometimes euhedral rectangular crystals with sharp boundaries, probably formed by recrystallization. In other cases the larger crystals have corroded edges and appear to be breaking down to form fine-grained material.

Towards the edges of the anhydrite layers, the grain-size generally increases greatly (up to 1 mm.) and well-formed crystals project into halite (fig. 3 B). Small irregular patches of anhydrite in halite sometimes show aggregates of large anhydrite grains surrounding a central core of fine-grained anhydrite. This would indicate either replacement of anhydrite by halite with concomitant recrystallization of anhydrite (Dunham, 1948, p. 223), or breaking up of anhydrite layers by recrystallizing halite (almost a plastic flow effect), with recrystallization of anhydrite.

Where isolated crystals of anhydrite are enclosed in halite, they are euhedral and often fairly large. Sometimes strings of these crystals fringe the halite grains, as if the halite had pushed them out during recrystallization.

A few crystals of magnesite have been found in most of these thin sections. The mineral occurs as platy crystals up to 1 mm. across and 0·2 mm. thick, tabular parallel to (0001). It is euhedral towards halite and anhydrite, and has been seen to cut across the large euhedral anhydrite crystals in fine-grained anhydrite.

A few very thin flakes of talc (up to 0·5 mm. long) lie along the cleavages of the halite in the thin sections of the rock from 4314–16 feet.

The other specimen (4559–61 feet) in which halite has been preserved is from the zone of anhydrite with halite inclusions below the polyhalite zone. It consists largely of anhydrite, with irregular patches of halite. The anhydrite grains are fairly large, and are, in general, of two types— roughly rectangular equidimensional grains and elongated grains with irregular boundaries which often coalesce to form fibro-radiate bunches
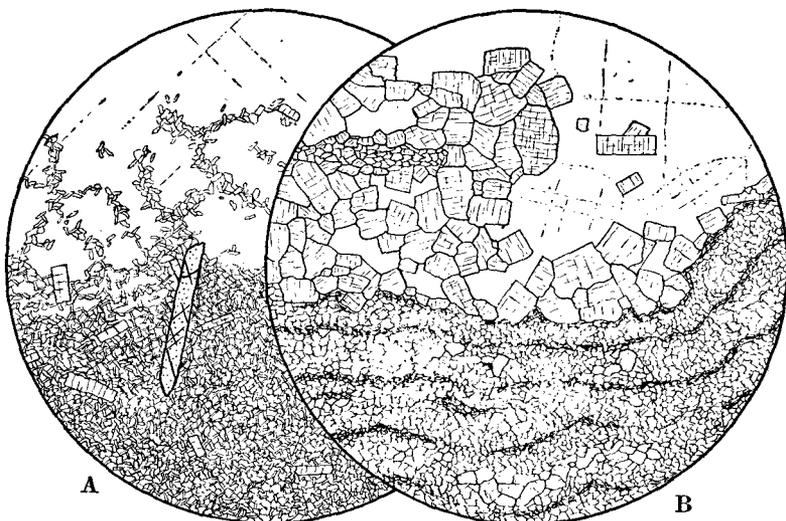

FIG. 3 A. Halite-anhydrite-rock, with magnesite plate. Edge of thinfine-grained anhydrite layer. 4314–16 feet below surface. × 40.

FIG. 3 B. Halite-anhydrite-rock, suggesting recrystallization of anhydrite adjacent to halite. 4350–52 feet below surface. × 17.

and fan-like aggregates. The rectangular grains appear to have formed at the expense of the fan-like type. Many of the grains show cataclastic structures—bending, opening of cleavages, and secondary twinning. The halite occurs in irregular areas and shows direct evidence of replacement of anhydrite by enclosing small rounded anhydrite relics with the same orientation as anhydrite grains adjacent to the halite (fig. 2). A few clusters of minute rounded grains of dolomite have been observed in the anhydrite.

In many of the specimens of unknown depth, consisting largely of anhydrite, cavities indicate the previous presence of halite. All the halite has been removed by weathering.

To summarize the features shown by the anhydrite-halite assemblages:

In the rocks from the upper halite-rich zone we find evidence sug-
gesting considerable recrystallization of the halite since its formation.
The rude schistose structure of the halite in the uppermost specimen
indicates that in this case recrystallization probably took place after
the evaporite had been covered by a considerable amount of rock. The
associated anhydrite has at least partly recrystallized. It is possible
that the fine-grained centres of the thicker bands are original. No direct
evidence of replacement of anhydrite by halite has been found in this
zone, although this has possibly taken place. If the large euhedral
anhydrite crystals are recrystallized porphyroblasts, then the magnesite
crystals cutting these have also recrystallized.

In the rock beneath the polyhalite zone direct evidence of replace-
ment of anhydrite by halite has been observed. There has also been
a considerable amount of recrystallization of the anhydrite, which shows
no sign of bedding.

VI. ANHYDRITE-CARBONATE-ROCKS.

Practically all available specimens of the rocks consisting largely of
anhydrite contain some carbonate. This section therefore includes all
the specimens of unknown depth except those containing polyhalite.
Three specimens of known depth are included here (4415; 4742; 4760–62
feet). The well cuttings give some idea of the distribution of the
different varieties.

Several of the rocks described here contain irregular cavities which
indicate the previous presence of halite. A little residual halite was
found in one of these cavities in the middle of a weathered specimen,
but such rocks are so porous that in all other cases the mineral has been
dissolved out of the samples of unknown depth.

Apart from the halite, anhydrite forms more than 80 % of nearly all
these rocks, except the anhydrite-dolomite-rock near the base of the
lower anhydrite zone, in which dolomite is sometimes very abundant.
Normally, the carbonates are present only in small quantity. Two
carbonates have been found—dolomite and magnesite. They have been
found together only in one specimen and the relations here suggest that
magnesite and anhydrite were being formed at the expense of dolomite.
The dolomite in these rocks occurs either as small rounded granules or as
larger euhedral rhombohedra. The magnesite forms thin platy crystals,
tabular parallel to (0001).

Other minerals found are talc, celestine, sulphur, and pyrite. Talc is
present in many of the rocks in halite cavities, forming thin ragged

plates. It occurs in considerable quantity in a few specimens. Celestine, sulphur, and pyrite have been found in very small quantity. A considerable amount of carbonaceous matter is present in certain cases. Gypsum occurs only as a product of weathering, in the specimens of unknown depth.

Bedding structures are not well developed. In some cases they are indicated by thin layers of impurity, often crenulated, or by strings of dolomite granules. Differences in grain-size and texture of different layers may also indicate bedding. Normally the minerals show no sign of platy or linear parallelism.

Evidence of recrystallization of anhydrite is widespread. Cataclastic structures are occasionally found. Evidence of replacement of dolomite by anhydrite on a considerable scale has been found in rocks from near the base of the lower anhydrite zone. As mentioned above, it appears likely that dolomite has been replaced by magnesite and anhydrite in one specimen from the upper anhydrite zone. Magnesite has replaced anhydrite in the coarse anhydrite-magnesite-halite-rock. Sulphur has been seen to replace anhydrite.

On the basis of their petrographic character these rocks can be divided into the following groups:

1. Anhydrite-dolomite-rock ($\pm$ halite, $\pm$ talc).
2. Brecciated anhydrite-dolomite-rock ($\pm$ halite, $\pm$ talc, $\pm$ celestine).
3. Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite ($\pm$ halite).
4. Compact anhydrite-magnesite-rock.
5. Coarse anhydrite-magnesite-halite-rock ($\pm$ talc).
6. Anhydrite-magnesite-talc-halite-rock.
7. Anhydrite-dolomite-magnesite-rock.

(1) *Anhydrite-dolomite-rock.*

These rocks probably form a large part of the lower anhydrite zone and may also occur in the upper anhydrite. They are fine to medium grained, and light to dark grey in colour. Dolomite is normally present only in small quantity, up to about 5 %. Cavities indicating the previous presence of halite are present in many specimens. Slices show that the anhydrite varies considerably in texture. In some cases it consists largely of a fine-grained interlocking mass of shapeless grains. In other cases the grains tend to express a stumpy rectangular habit. Sometimes they are much elongated. All these types may occur together

T t

in the same specimen. Many of the rocks are almost even-grained, while others show marked variation in grain-size either in a patchy fashion or with a tendency to layering.

The dolomite occurs in two varieties (fig. 4). In many rocks it forms rounded brown granules from 0·001 to 0·02 mm. in diameter, apparently similar to those described by Dunham (1948, p. 219). These occur disseminated through the rock, or in thin layers and clusters giving a
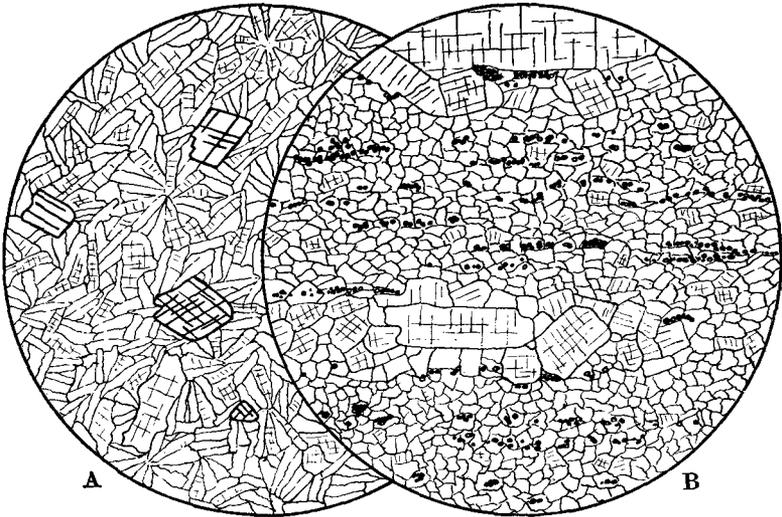

FIG. 4. Anhydrite-dolomite-rocks. ×40.

suggestion of bedding. In other rocks the dolomite forms larger clear euhedral rhombohedra up to 0·3 mm. across, often grouped together in patches. Here the associated anhydrite forms small grains with interlocking boundaries, frequently elongated.

No replacement relationship between dolomite and anhydrite has been seen in these rocks. Replacement of anhydrite by polyhalite in rocks of this general type will be described later.

In one of these rocks pyrite has been found, associated with sulphur. Sulphur has been found in two cases, in small quantity. A few small yellow patches can be seen in the hand-specimen. In one slice two small idiomorphic crystal groups of pyrite are enclosed in anhydrite. Close to these are several aggregates of sulphur up to 1·5 mm. across, and one of the pyrite grains has a small patch of sulphur projecting into it.

The sulphur has been derived, at least in part, from anhydrite, as it encloses relics of this mineral. In one case an elongated anhydrite grain has been cut into four distinct corroded relics. In other parts of the slice, where fine-grained anhydrite is associated with clots of carbonaceous matter, numbers of small rounded patches of sulphur have been developed (pl. XXIX, fig. 13).
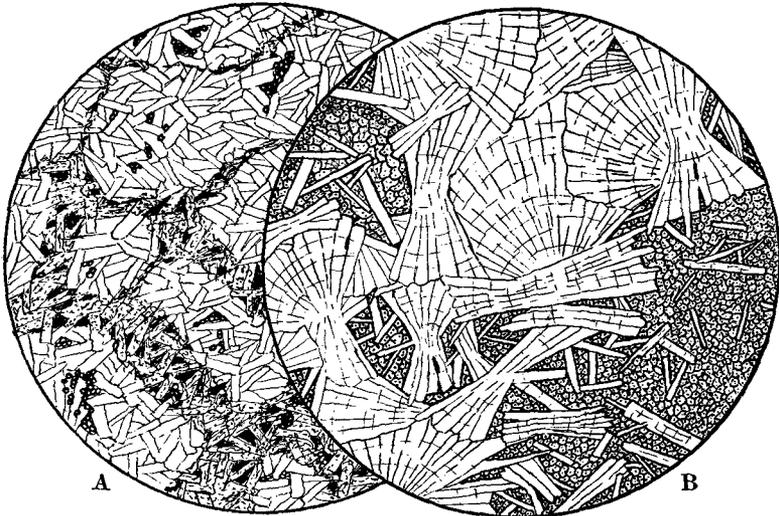

FIG. 5 A. Brecciated anhydrite-dolomite-rock, with carbonaceous impurity. × 20.
FIG. 5 B. Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite. × 10.

(2) *Brecciated anhydrite-dolomite-rock.*

The detailed log of the boring indicates a layer of brecciated anhydrite with small irregular inclusions of salt near the base of the lower anhydrite zone from 4740 to 4757 feet. One specimen of known depth (4742 feet) belongs here, and this and the well cuttings show that the rock is very distinctive, and justify the grouping of several similar specimens of unknown depth in this category.

Hand-specimens show light-coloured fragments up to ½ inch long embedded in a dark matrix. The fragments are sometimes angular and in some cases rounded or flattened and streaky. The matrix is rich in carbonaceous impurity. Small irregular cavities indicate the previous presence of halite, and occasional thin plates of talc are found in these. They are lined with euhedral anhydrite crystals, associated in rare cases

with celestine. They occur mainly in the light fragments, but occasionally in the matrix.

Slices show that the light-coloured fragments consist largely of elongated anhydrite grains, up to 2 mm. long, sometimes arranged in radiate bunches. More or less dolomite is associated with the anhydrite, and this mineral forms small rounded grains which tend to occur in clusters of varying size. The dark matrix is composed largely of anhydrite like that of the fragments, but the grains are crowded with dusty impurities. Some dolomite is also present in this matrix and a considerable amount of carbonaceous material forms interstitial patches between anhydrite laths. The boundaries between fragments and matrix are marked mainly by the distribution of carbonaceous material, and not by the anhydrite, whose grains form a continuous mass cutting across the boundaries.

FIG. 6. Brecciated anhydrite-dolomite-rock.
Polished surface. Nat. size.

Celestine has been observed in slices of three specimens and in one hand-specimen. It forms small groups of euhedral platy crystals in approximately parallel orientation, about 1 mm. wide, projecting into cavities.

In this rock there is no direct evidence of replacement of dolomite by anhydrite. The structure and textures suggest that a dolomite-anhydrite-rock was broken up on the sea floor and the fragments enclosed by a carbonaceous anhydrite-dolomite mud. Later recrystallization of the anhydrite has to a considerable extent obscured the boundaries between fragments and matrix, but these are now indicated by the distribution of carbonaceous material. The lack of any tendency to parallel orientation of the anhydrite crystals would seem to indicate that recrystallization did not take place under much pressure and was therefore effected early, but later than the flattening and streaking out of the brecciated anhydrite-dolomite fragments (fig. 6).

(3) *Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite.*

The characteristics of this type are that most of the anhydrite occurs as large fibro-radiate aggregates of elongated grains, usually showing a replacement relationship to the dolomite, which forms small rounded grains.

One specimen of known depth (4760–62 feet) belongs to this group, as do several specimens of unknown depth. The well cuttings show that these rocks occur at the base of the evaporite bed, below the brecciated type.

The amount of dolomite present varies considerably. One specimen shows about 40 % dolomite, others much less. In hand-specimens the anhydrite has a bluish tinge, and tends to form fan-like platy aggregates sometimes up to as much as 1 cm. in length. Where dolomite is abundant the rock is brown in colour. In some specimens small irregular cavities are lined with euhedral anhydrite crystals.

Slices show that most of the anhydrite forms much-elongated lath-like grains very often arranged in radiate or fan-shaped bunches. These generally have irregular margins, but are euhedral when cutting dolomite. Dolomite forms small rounded grains, about 0·02 mm. in diameter. These are brownish in colour and turbid with tiny dark inclusions. They occur as patchy aggregates, occasionally showing a central area of larger clear dolomite grains, up to 0·2 mm. across. These aggregates show all stages of replacement by anhydrite. Some are cut through sharply at their edges by elongated euhedral anhydrite crystals. In other cases the anhydrite porphyroblasts develop inside the dolomite areas. In the later stages the anhydrite grains break up the dolomite aggregates so that angular dolomite relics occur interstitially in a mesh of anhydrite crystals. Anhydrite grains have been observed to enclose several relics of dolomite with common optical orientation. In one section a dolomite area has been broken into several pieces by thin veins of fine-grained anhydrite, the anhydrite crystals showing an orientation normal to the walls of the veins. In another case dolomite, partly replaced by elongated anhydrite crystals, is cut by fairly sharp-edged vein-like masses of coarse fibro-radiate anhydrite up to about 1 cm. across. The anhydrite crystals radiate from centres at the edges of the veins (figs. 7, 14).

The well cuttings show that these rocks can almost certainly be referred to the layer below the brecciated anhydrite at the base of the lower anhydrite zone (4757–73 feet). All the rocks with predominantly coarse fibro-radiate anhydrite show replacement of dolomite by anhy-

drite, and this strongly suggests that this basal layer has been formed largely by metasomatic replacement of dolomite due to sulphate-rich brines. This cannot be definitely asserted, since no core series was preserved, but it seems likely.

Fowler (1944) and Dunham (1948) have given impressive evidence of replacement of dolomite by anhydrite in other borings in the Permian evaporites of north-eastern England, and Hollingworth (1948) has recorded such replacement in west Cumberland.
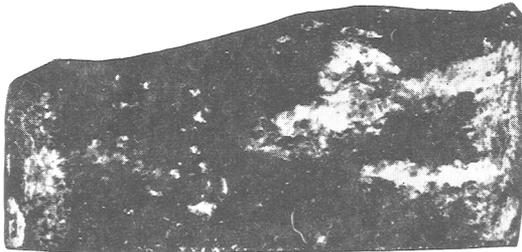

FIG. 7. Vein-like masses of anhydrite in anhydrite-dolomite-rock with coarse fibro-radiate anhydrite. Polished surface. ×3/2.

(4) Compact anhydrite-magnesite-rock.

Many of the specimens of unknown depth belong to this group. The commonest type is a light grey sugary rock sometimes showing crenulated lines of impurity which appear to indicate original bedding (fig. 15), but usually without any definite bedding structure (fig. 16). Other types are darker and richer in carbonaceous matter. Thin sections show anhydrite, magnesite, and a small amount of very fine-grained impurity. The anhydrite generally makes up 80 to 95 % of the rock, and varies considerably in grain-size and texture. Some slices show an aggregate of stumpy subhedral grains up to 1 mm. in length. Others show a groundmass of irregular interlocking grains about 0·1 mm. in length with larger irregular grains up to 1 mm. scattered through it. In other cases the grains tend to be elongated and occasionally form radiate aggregates. The magnesite is in all cases euhedral, and forms platy crystals, up to 2 mm. in width and 0·3 mm. in thickness, tabular parallel to (0001). Sometimes these plates form radiate sheaves. Many of the crystals contain small shapeless inclusions of anhydrite, and these are sometimes concentrated towards the centre of the crystal. The magnesite forms up to 15 % of the rock. The crystals show no tendency to parallel orientation.

(5) Coarse anhydrite-magnesite-halite-rock.

These rocks are very striking in hand-specimens. They are light grey in colour and show large plates of magnesite, up to 1 cm. across, with random orientation, enclosed in sugary anhydrite. The rock is full of small irregular cavities which almost certainly contained halite. The magnesite plates project into and often cut across the cavities. Occasional thin plates of talc also occur in the cavities.

Thin sections show an-hydrite, magnesite, and secondary gypsum (figs. 9 B, 17). The gypsum is apparently due to weathering while the specimens were lying in the open at the site of the boring, and tends to occur at the edges of the cavities, replacing anhydrite. Much of the anhydrite forms irregular grains and large fan-like crystals with curved cleavages, up to 5 mm. across. These commonly show strain shadows and bending of
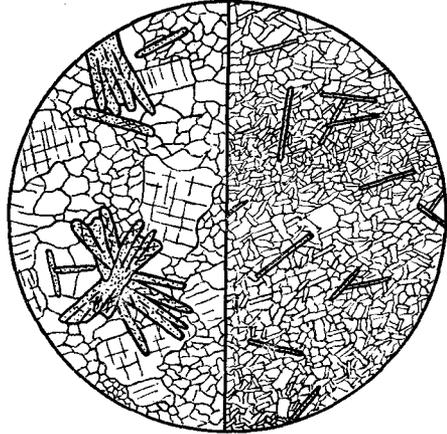
FIG. 8. Anhydrite-magnesite-rocks. ×17.

grains. They are cut into and sometimes enclose sharp rectangular euhedral crystals of anhydrite, which have apparently recrystallized at their expense. Magnesite forms up to 20 % of the rock and occurs as large thin plates, with cigar-shaped cross-section. It is euhedral towards the anhydrite, and in a few cases shows definite evidence of replacement origin, containing corroded relics of anhydrite with the same optical orientation as the adjacent anhydrite grains (fig. 9 B).

The relations suggest extensive recrystallization in this rock since its consolidation. Cataclastic structures are common in the fan-shaped and large irregular grains of anhydrite. These are cut by euhedral anhydrite and by magnesite, and as neither of the latter show strain-shadows or bending, they must be of later formation.

(6) Anhydrite-magnesite-halite-talc-rock.

In a few specimens talc is fairly abundant in certain bands, as groups of silvery flakes up to 5 mm. across, in small cavities which apparently

contained halite. The rocks are grey or bluish in colour and fine-grained. Slices show anhydrite, magnesite, talc, and a small amount of carbonaceous impurity (figs. 9 A, 18). The anhydrite, which forms about 85 % of the rock, occurs mainly as irregular interlocking grains, sometimes markedly elongated, from 0·05 to 0·2 mm. in size. There are coarser patches where the grain-size reaches 0·5 mm. Through this anhydrite
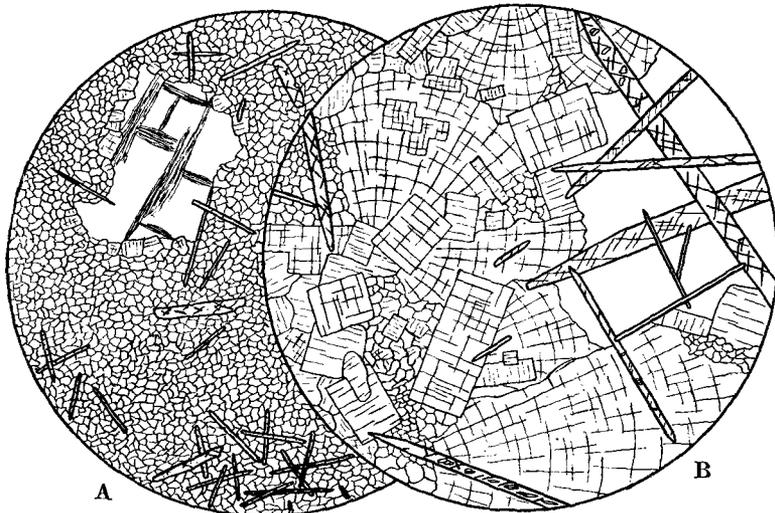

Fig. 9 A. Anhydrite-magnesite-halite-talc-rock, showing a halite cavity crossed by a rectangular network of talc plates. × 10.

Fig. 9 B. Coarse anhydrite-magnesite-halite-rock: Secondary rectangular anhydrite porphyroblasts cut fine-grained and fibro-radiate anhydrite. Some magnesite plates enclose relics of anhydrite with the same optical orientation as the surrounding grains, showing that magnesite has replaced anhydrite. To the right is a halite cavity crossed by a network of magnesite plates. × 10.

are scattered numerous euhedral plates of magnesite, with random orientation, most of these being about 1 mm. wide and 0·05 mm. thick. As a rule they are distributed fairly evenly through the rock, making up about 10 % of it, but there are occasional small patches much richer in magnesite (up to 20 %). In certain layers in this rock, small cavities are seen. The anhydrite lining these cavities often forms relatively large euhedral crystals like those seen in contact with halite in the halite-anhydrite assemblages. These cavities almost certainly contained halite. It is in these that the talc occurs, as thin ragged plates, several millimetres in width. The plates sometimes penetrate the cleavages, some-

times the intergranular boundaries of the anhydrite, at the edges of the cavities. In a few cases they have been seen to cut obliquely across an anhydrite grain. From the anhydrite they cut across the cavities to form a rectangular criss-cross network (fig. 9 B). It is practically certain that this pattern means that talc lay along the cleavages of the halite in the cavities. Wherever talc has been found associated with halite in this evaporite, it lies along the cleavages of the halite.
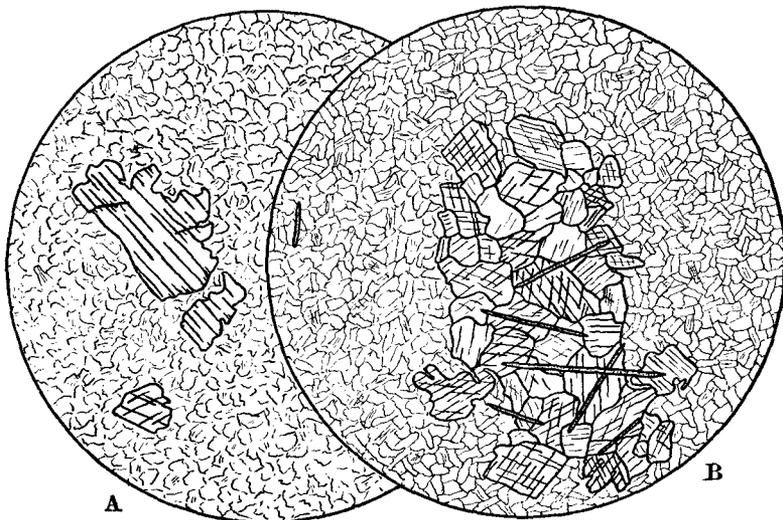

FIG. 10. Anhydrite-dolomite-magnesite-rock. 4415 feet below surface. × 20.
A. Large crystal of dolomite cut in two by replacing anhydrite.
B. Aggregate of dolomite eaten into by anhydrite, while magnesite cuts both dolomite and anhydrite.

The bore journal records a band about 12 feet thick of 'anhydrite with occasional irregular inclusions of salt (nests of micaceous mineral)' from 4525 to 4537 feet below the polyhalite zone. This may refer to the rocks described here.

(7) *Anhydrite-dolomite-magnesite-rock.*

This group is represented by a single specimen from 4415 feet, in the upper anhydrite zone. The rock is especially interesting in being the only one with both carbonates present. It is a dark grey fine-grained rock, with a suggestion of bedding shown by slight differences in colour in different layers. The polished surface shows a few small patches, up

to 5 mm. across, of light brown colour, and slices show that these are dolomite-magnesite aggregates.

The rock is rather like the anhydrite-dolomite-rocks with euhedral dolomite. The anhydrite forms an interlocking mass of small grains, some elongated, 0·002 to 0·2 mm. in length. In this matrix are dolomite grains up to 0·3 mm. across, which tend to occur in groups, and some- times form relatively large aggregates. Some of these dolomite grains show fairly definite rhombohedral boundaries, but many appear cor- roded and eaten into by fine-grained anhydrite. The grains are some- times broken into separate pieces by the invading anhydrite. Magnesite occurs as thin plates up to 1 mm. wide, as dispersed crystals in the anhydrite, and also in the dolomite aggregates. Some of these aggre- gates, consisting of a large number of dolomite grains, show fine-grained anhydrite apparently eating its way along intergranular boundaries, while euhedral magnesite plates cut through both dolomite and anhy- drite (fig. 10 B). The relations suggest that both anhydrite and magnesite may have formed at the expense of dolomite. This is discussed in a later section, where it is suggested that brines rich in $MgSO_4$ might produce magnesite and anhydrite at the expense of dolomite.

VII. POLYHALITE-BEARING ROCKS.

The well cuttings show that the polyhalite zone extends from about 4440 to 4525 feet. By consideration of the detailed log of the boring and the well cuttings, the rocks of this zone can be divided into the following groups:

	Feet
Salt with irregular inclusions of polyhalite and anhydrite	34
Polyhalite with irregular inclusions of salt	30
Polyhalite	15
Anhydrite and polyhalite...	6

The lower layer contains a considerable amount of anhydrite and apparently grades into anhydrite-dolomite-rock at its base. The well cuttings show that small quantities of anhydrite are present in the layers above this.

Only a single specimen (4445–47 feet) is available from the upper halite-rich layer. This is a halite-anhydrite-polyhalite-talc-rock with pseudomorphs after gypsum. The lower layers are represented by one specimen of known depth (4491–93 feet) and many specimens of unknown depth, collected at the site of the boring in 1942. The speci- mens of unknown depth, containing polyhalite or its alteration product

gypsum, total about 14 feet in length. They had been lying at the site of the borehole, partly embedded in mud, for about three years, and as a result the polyhalite has been partly converted to gypsum by the leaching out of potassium and magnesium sulphates. This alteration has proceeded to various stages in different specimens. The amount of alteration was partly dependent on the amount of anhydrite present in the specimen; some of the anhydrite-polyhalite-rocks show very little change. The alteration was probably also dependent on the protection afforded by the cover of mud, and on the porosity of the gypsum crust. Few of these rocks contain halite cavities and presumably most of the halite-polyhalite-rocks disintegrated rapidly. A total length of about 7 feet of core consists almost entirely of gypsum, but the gypsum derived from polyhalite shows a characteristic structure, and there can be no doubt whatever that these specimens originally consisted almost entirely of polyhalite. The remaining 7 feet or so of core consists of polyhalite and polyhalite-anhydrite-rock, with a gypsum crust of variable thickness.

The polyhalite of the well cuttings has been largely altered to gypsum by the drilling water, although some of the larger cuttings contain some unaltered material. They are therefore of little value for petrological studies, but have given valuable evidence on the depth range of the polyhalite.

The polyhalite of these rocks is white or grey in colour and variable in grain-size and shape. Many rocks show an equigranular texture, the grains being interlocking and anhedral, and the grain-size varying from 0·001 to 0·1 mm. In other cases we find an interlocking mass of small elongated grains. Often the polyhalite forms fibrous aggregates of elongated grains up to 0·2 mm. in length, and these may form radiate groups or spherulitic growths. Tiny plates and rod-like crystals are found in the early stages of replacement of halite or large anhydrite grains. Large euhedral twinned crystals, often spear-shaped, up to 1·5 mm. in length are found enclosed in or projecting into halite, or associated with anhydrite. Often these large crystals appear to have developed by recrystallization of fine-grained polyhalite. In other cases they seem to be breaking down to form finer-grained material. Most of the polyhalite grains show simple, lamellar, or sector twinning.

The other minerals of these rocks are anhydrite, dolomite, halite, and talc. Anhydrite is present in large quantity in some specimens and in small quantity in most. Dolomite is commonly present in small amount, as small granules like those of the anhydrite-dolomite-rocks. Halite has

been preserved in one specimen and small halite cavities occur in several. Talc is especially associated with halite.

Nearly all these specimens give direct evidence that the polyhalite is secondary in origin, and has been derived at the expense of some pre-existing mineral—anhydrite or halite. Many of them give evidence of the previous occurrence of gypsum. In the following petrographic description particular stress will be laid on these replacement effects. Firstly, the rock from the upper halite-rich layer will be described, as it gives evidence of replacement of anhydrite and halite by polyhalite, and of the previous presence of gypsum. Next the development of polyhalite in compact anhydrite-dolomite-rock will be described. This will be followed by consideration of the rocks with abundant polyhalite, which give much evidence of the previous presence of gypsum, and of replacement of anhydrite and halite by polyhalite.

(1) *Halite-anhydrite-polyhalite-talc-rock.*

One specimen (4445–47 feet) shows the association of anhydrite and polyhalite with abundant halite, and this rock gives interesting evidence of the relation of these minerals to one another and of the original occurrence of primary gypsum.

The hand-specimen (pl. XXXIII, fig. 33) shows a marked banding, with layers of colourless halite, as crystals up to one inch across, alternating with complex halite-sulphate layers. The individual layers are up to about an inch in thickness. Talc flakes, up to 5 mm. in diameter and 0·2 mm. thick, are associated with the halite at the edges of the complex layers. The sulphates form a white fine-grained lacy network enclosing irregular areas of halite.

On polished surfaces the complex layers show a fine-scale pseudomorphous structure. Small light-coloured needle-like pseudomorphous crystals, up to 2 mm. long, project into halite from the sulphate-rich layers, and inside these layers are similar pseudomorphs, often consisting of a white rim of sulphate and a dark interior of halite.

Slices (figs. 20, 21, 22) show that the minerals halite, anhydrite, polyhalite, and talc are present. No carbonate has been detected. The halite-rich layers consist almost entirely of halite, with a few flakes of talc and small crystals of anhydrite and polyhalite appearing as the complex layers are approached. In the complex layers the halite forms irregular areas surrounded by a network of anhydrite and polyhalite. Fairly large euhedral crystals of anhydrite and polyhalite (up to 0·5 mm. in length) sometimes project into or are enclosed in halite. Tiny negative

cubic cavities are present in some of the halite grains, and are filled with liquid. In one of these cavities a small bubble has been observed, and this moves if the slice is tilted. Fine-grained anhydrite (grain-size 0·002–0·05 mm.) appears to have once formed the whole of the sulphate network, but it has been partly converted to polyhalite.

The greater part of these complex layers shows the pseudomorphous structure mentioned above. Sometimes the pseudomorphs consist almost wholly of fine-grained anhydrite, but usually they show a central irregular zone of halite with an outer zone of anhydrite. The relative quantities of halite and anhydrite vary considerably. Sometimes the outer anhydrite zone is very thin and in part broken through by the inner halite (fig. 22). The junctions between the two zones are irregular. The outer boundaries of the pseudomorphs are relatively sharp. In cross-sections, the pseudomorphs are roughly hexagonal in outline. In longitudinal sections they are much elongated. The terminations are generally irregular, but are occasionally sharp and shaped like swallow-tail twins of gypsum (fig. 21). Sometimes the original mineral has grown as radiating groups of prismatic crystals. It is believed that these pseudomorphs represent gypsum, although none of the original mineral remains. The interfacial angles in cross-sections of the sharper pseudomorphs agree closely with those of the prism zone of gypsum. Such pseudomorphs are widespread in the other polyhalite-bearing rocks of this boring, and in some cases are remarkably sharp, so that the writer is confident that gypsum was the original mineral. Gypsum pseudomorphs are also widespread in similar rocks of the Texas-New Mexico evaporites (Schaller and Henderson, 1932).

Polyhalite is seen to have partially replaced both anhydrite and halite. Much of the fine-grained anhydrite shows partial or complete replacement by fine-grained polyhalite, the polyhalite often containing darker irregular relics of anhydrite. Sometimes rounded areas of anhydrite in halite have radiate bunches of large euhedral polyhalite crystals growing out from them into the surrounding halite. Large crystals of polyhalite also project from the edges of fine-grained polyhalite areas. In many cases the anhydrite of the outer rims of gypsum pseudomorphs has been converted into polyhalite. Spear-shaped polyhalite crystals are found enclosed in halite inside and outside these pseudomorphs.

Where irregular halite areas are enclosed in a polyhalite network, the polyhalite can be seen to be encroaching upon the halite (fig. 20). This replacement begins with the development of clouds of minute rod-like or rounded platy crystals of polyhalite, scattered with random orienta-

tion through the halite near the edges of the halite areas. These tiny crystals grow larger and more numerous until all the halite has been replaced by a uniform interlocking mass of polyhalite grains. Occasionally the polyhalite develops as small spherulitic growths in halite.

The talc in this rock forms thin plates lying along the cleavages of the halite (fig. 20). It is fairly abundant. The plates often form a rectangular network along the halite cleavages. They show no sign of having developed at the expense of any other mineral, but occasionally several plates seem to have formed from some sort of central nucleus. Their edges occasionally cut into polyhalite or anhydrite crystals. They have not been found in the fine-grained polyhalite derived by replacement of halite, and are therefore probably of later formation than the polyhalite.

It seems likely that this rock originally consisted of halite interbanded with gypsum-halite layers. There is no evidence that the gypsum was not original. This gypsum has been replaced by anhydrite and halite. Were these minerals formed simultaneously, or did one precede the other? The change from gypsum to halite would require removal of gypsum and deposition of halite, as there is no common chemical constituent involved. Such infiltration pseudomorphs have been described by Schaller and Henderson (1932, p. 34), and are found in the upper evaporites of the Eskdale boring. The change from gypsum to anhydrite is a simple one, requiring removal of water. In the latter change there would be a volume contraction. It is interesting in this connexion that the halite occurs in the interiors of the pseudomorphs. If increased concentration of the brines converted gypsum to anhydrite, the resulting shrinkage might leave spaces in the centres of the pseudomorphs, in which halite could be deposited. The wide variation in the relative amounts of halite and anhydrite in these pseudomorphs, and the fact that some of them have only a very thin outer zone of anhydrite, would suggest that part of the anhydrite or gypsum has been removed and replaced by halite. This may have taken place almost simultaneously with, or at a later date than, the initial change of gypsum to anhydrite.

It appears likely, then, that the first replacement effects in this rock were:

Gypsum → anhydrite → halite.

We have evidence of replacements by polyhalite at a later date:

Anhydrite → polyhalite.
Halite → polyhalite.

The latter changes were effected by brines rich in potassium and magnesium. These brines must have been capable of removing some $CaSO_4$, as there is no sign of volume change in the first replacement, and they must also have removed NaCl.

Apparently, at a still later date, talc plates formed in the cleavages of the halite.

It is unlikely that the halite of this rock has suffered appreciable recrystallization since Permian times, as the pseudomorphs are apparently undisturbed.

(2) *Development of polyhalite in compact anhydrite-dolomite-rock.*

The early stages of the development of polyhalite at the expense of anhydrite are well shown by a specimen of unknown depth which consists largely of anhydrite, with scarce, small rounded grains of dolomite. The hand-specimen looks like a typical anhydrite-dolomite-rock, consisting of fine-grained anhydrite with larger subhedral grains. Slices show that most of the rock consists of small irregular grains of anhydrite. Much larger subhedral crystals or groups of crystals are distributed through this matrix. Small dolomite granules are present as clusters and strings in the fine-grained material. In fact, apart from the presence of polyhalite, this rock is typical of the compact anhydrite-dolomite-rocks described in an earlier section.

Polyhalite is found attacking both the fine-grained material and the larger subhedral grains. The larger grains are replaced by fine fibrous masses of polyhalite along their boundaries and along cleavages and cracks (fig. 23). Many of these crystals are separated into several parts by tiny veinlets of fibrous polyhalite which connect with irregular areas of fine-grained polyhalite in the groundmass. Rod-like or platy grains of polyhalite appear inside the large anhydrite grains, and sometimes larger spear-shaped crystals occur. The rod-like grains may have a random distribution or may tend to form radiate groups. In the groundmass of the rock, fine-grained polyhalite forms irregular areas. Under high magnification, the polyhalite can be seen to be eating into fine-grained anhydrite in the same way as it replaces the larger crystals. The strings and clusters of dolomite granules are found in both polyhalite and anhydrite, and appear to have played no part in the replacement.

Here we have an early stage in the replacement of anhydrite by polyhalite in anhydrite-dolomite-rock. If this process were continued, the final product would be a polyhalite-dolomite-rock, showing little trace of its replacement origin, except in the presence of strings and

clusters of the original dolomite (fig. 24). Several specimens of such rocks have been found, though most of these contain a little residual anhydrite in certain layers. In many cases thin bands of this type are found, alternating with bands of polyhalite-anhydrite-rock or polyhalite-rock, containing pseudomorphs after gypsum. There is reason to believe that in some cases secondary gypsum grew in anhydrite-dolomite-rock, and was later replaced by anhydrite and polyhalite. This will be discussed below.

(3) *Polyhalite-bearing rocks with pseudomorphous structure after gypsum.*

The majority of the specimens of polyhalite-bearing rock show a definite pseudomorphous structure, indicated by differences in colour from light to dark grey. The pseudomorphs are believed to represent previous gypsum crystals which have been completely replaced by anhydrite and polyhalite. The original mineral formed elongated prismatic crystals. The edges in the prism zone are often sharply indicated by lines of impurity, or by sudden changes in texture of the polyhalite, inside and outside the pseudomorphs. Cross-sections are hexagonal in outline, and measurements, in thin sections, of the interfacial angles in the prism zone correspond closely with those of the (110) and (010) forms of gypsum. The terminations of the pseudomorphs are generally irregular, but agree in general inclination with the common pyramids of gypsum. In several cases the terminations show twinning of 'swallow-tail' type (fig. 39).

The longest pseudomorph observed is about $1\frac{1}{2}$ inches in length and $\frac{1}{4}$ inch in width, but most are considerably smaller than this. They show a marked tendency to grow in a vertical direction in the core, often in groups radiating from centres at the edges of layers of more uniform material below. Analogy with the vertical growths described by Schaller and Henderson (1932) indicates that they grew upwards rather than downwards, although we do not know which were the upper sides of the Eskdale specimens.

Many of the larger specimens show a layered structure in which layers composed largely of pseudomorphs alternate with more massive layers without much trace of pseudomorphous structure (pl. XXXIV, fig. 38). The massive layers often show thin approximately horizontal bands of dark impurity (fig. 37), perhaps indicating original bedding, and are believed to have originally been anhydrite-dolomite layers. At the upper edges of these massive layers, pseudomorphs appear and grow

upwards to form layers composed largely of pseudomorphs. At the top of the pseudomorphous layers, the pseudomorphs project into the next layer of massive material. In a few cases pseudomorphs have been observed to break through from one pseudomorphous layer to the next. In these cases the lines of impurity of the massive layers can sometimes be traced passing through the pseudomorphs, but partly distorted by them, as though the gypsum crystals had grown partly at the expense of anhydrite in an unconsolidated anhydrite-dolomite mud.

The pseudomorphous structure is shown particularly well by rocks containing a considerable amount of anhydrite as well as polyhalite. In most of such rocks the anhydrite is largely confined to the pseudomorphs, and is scarce or absent in the interstices. Sometimes the pseudomorphs consist almost entirely of anhydrite, of medium grain-size. In this anhydrite are a few relatively large (up to 0·5 mm.) twinned subhedral polyhalite grains. Fine-grained polyhalite can be seen eating its way into the anhydrite at the edges of the pseudomorphs (pl. XXXI, fig. 25). Adjacent pseudomorphs show further stages in this type of replacement, the fine-grained polyhalite encroaching farther on the anhydrite, sometimes in an irregular way, so that the anhydrite area gets broken up and grows smaller and smaller until it finally disappears. The larger subhedral polyhalite crystals break down to form finer-grained material and eventually the pseudomorph consists entirely of fine-grained polyhalite, separated from that of the interstices by a thin brownish line of impurity (fig. 28). Ultimately this line of impurity may also disappear, so that the final product is a uniform rock composed of fine-grained polyhalite. Usually slight differences in texture between the polyhalite derived from the pseudomorphs, which tends to be equigranular, and that of the interstices, which is usually fibrous, indicate the replacement origin of the rock.

In many cases the pseudomorphs of anhydrite are attacked by polyhalite at their centres as well as at the edges. This produces a simple zoned structure which is often obvious in hand-specimens. The intermediate anhydrite zone is darker in colour than the outer and inner polyhalite zones. The zones are irregular and the anhydrite zone is frequently broken across by irregular masses of polyhalite.

In a few specimens a much sharper and more regular multiple zoning is seen (figs. 11, 27, 35). Again the zones are composed alternately of anhydrite and polyhalite, and are parallel to the edges of the pseudomorphs. As many as six zones have been observed in the pseudomorphs of one specimen. Here the centre of each anhydrite zone is marked by

a sharp, thin brown band, rich in dusty impurity. The anhydrite zones
are relatively thin and are being encroached upon by the polyhalite
zones. In this rock the outermost zone consists of anhydrite and the
innermost zone of polyhalite. The anhydrite of the outer zone some-
times continues into the interstices of this rock.

Occasionally, longitudinal sections of pseudomorphs show a curious
'herring-bone' structure, quite distinct from the zoning described above
(figs. 12, 39). This is emphasized in specimens which have been polished
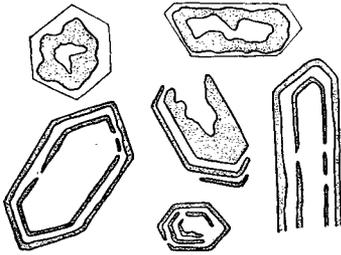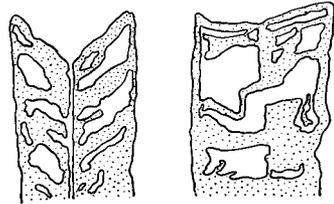
FIG. 11.   FIG. 12.

FIG. 11. Zoning in pseudomorphs of anhydrite and polyhalite after gypsum. The
upper two diagrams show simple zoning, the edges of the pseudomorphs being
marked by lines of impurity. The anhydrite is stippled. ×3½.

FIG. 12. 'Herring-bone' structure in anhydrite-polyhalite pseudomorphs after
gypsum. The anhydrite is stippled. × 2.

and then submerged in water for a few minutes. When dried, the poly-
halite is covered with a thin white crust of gypsum, while the anhydrite
remains dark grey. The structure is seen in 'swallow-tail' twin pseudo-
morphs. These have an outer zone of anhydrite, and a central partition
of anhydrite, or sometimes of polyhalite, along the composition-plane
of the twin. On either side of this partition, bands of anhydrite alternate
with polyhalite areas to form a 'herring-bone' structure roughly parallel
to the terminal faces. Similar structures involving anhydrite and halite
are found in the upper evaporites.

In most of the polyhalite-anhydrite-rocks consisting largely of gypsum
pseudomorphs, the interstices between the pseudomorphs consist almost
entirely of fine-grained fibrous polyhalite, in which the fibres are per-
pendicular to the edges of the pseudomorphs (figs. 25, 26, 28). In most
cases anhydrite and dolomite are completely absent from the interstices,
even when the pseudomorphs consist largely of anhydrite. In these
cases it is believed that halite originally occupied the interstices. In

a few specimens the interstices bear central cavities, lined with euhedral polyhalite crystals. A few small plates of talc have been observed in such cavities in two specimens, indicating the previous presence of halite.

A few specimens, including one with sharp multiple zoning in the pseudomorphs, show residual anhydrite and dolomite in the interstices. These may represent original anhydrite-dolomite-rock, in which gypsum developed at the expense of anhydrite.

Dolomite is scarce in these rocks. Where present it forms small rounded granules exactly like those of the compact anhydrite-dolomite-rocks. In one specimen, however, it is abundant, forming about 10 % of the specimen. This is a most curious rock. It consists entirely of polyhalite and dolomite. It is banded, one band showing many small polyhalite pseudomorphs after gypsum, each with an outer zone of dolomite granules (fig. 29). Other parts of the rock show an irregular mottling due to the aggregation of dolomite granules in strings and clusters enclosing irregular areas of polyhalite. The meaning of this structure is not clear. It is possible that gypsum crystals grew in anhydrite-dolomite mud unusually rich in dolomite, and that the polyhalite which later replaced the anhydrite of the interstices managed to push the dolomite grains to the edges of the pseudomorphs. The mottled structure of the rest of the rock might be caused by polyhalite crystallizing from various centres in the anhydrite, the polyhalite of one centre pushing the dolomite forward until it met another growth of polyhalite.

(4) *Rocks consisting almost entirely of polyhalite.*

Many of the specimens of unknown depth consist entirely or almost entirely of polyhalite, with subordinate dolomite, and with little or no trace of residual anhydrite. Most of these rocks evidently represent a late stage in the replacement of the rocks described in the preceding section (figs. 28, 40, 41). These show pseudomorphs of polyhalite after gypsum, marked by slight differences in colour between pseudomorphs and groundmass. In slice, the structure is shown by lines of impurity or variations in texture. The rocks also tend to develop cracks along the edges of the pseudomorphs. Occasionally, the presence of pseudomorphs cannot be detected in thin sections, but is apparent in polished specimens.

A few specimens of polyhalite-rock show no trace of pseudomorphous structure, but show lines of dolomite granules and dusty impurity, often crenulated, giving an approximately horizontal banding (figs. 24, 37). This would seem to indicate original bedding, and these rocks are

believed to represent original anhydrite-dolomite-rocks. In many cases a few grains of corroded residual anhydrite are found, and in some cases large anhydrite porphyroblasts which show all stages of attack by polyhalite. Rocks of this type are interbanded with the types consisting largely of pseudomorphs after gypsum, and sometimes contain a few such pseudomorphs themselves.

Very few of the polyhalite rocks show no sign of pseudomorphous or bedding structures. These consist of uniform fine-grained polyhalite, with occasional aggregates of coarse, subhedral polyhalite grains radiating into small cavities which are believed to have contained halite (fig. 32). The cavities are abundant in certain layers (fig. 34). Layers of this type are occasionally found in the rocks described above, and probably represent original halite layers, almost completely replaced by polyhalite.

Nearly all the rocks consisting almost entirely of polyhalite show structures indicating a replacement origin. The very few rocks which show no direct evidence of pre-existing minerals apparently occur interbanded with the replacement rocks, indicating that they too were formed by replacement.

(5) Anhydrite porphyroblasts in polyhalite-bearing rocks.

Several of these specimens show large platy rectangular porphyroblasts of anhydrite enclosed in polyhalite-rock. The plates are sometimes as much as a centimetre across and a few millimetres in thickness. They are sometimes sharply euhedral, but generally show evidence of corrosion and conversion to polyhalite, the crystals often being broken into many detached pieces. They are found in polyhalite-anhydrite pseudomorphs after gypsum (fig. 30), and in polyhalite-rocks with bedding structures probably derived from anhydrite-dolomite-rocks (figs. 31, 36). Schaller and Henderson (1932, p. 65) have recorded similar crystals in the polyhalite-rocks of Texas and New Mexico, and have suggested that they are due to recrystallization of excess $CaSO_4$ during replacement of anhydrite-rock by polyhalite, the secondary anhydrite crystals being later partly transformed to polyhalite by continuation of the replacement process or by later brines.

(6) Chemical composition.

The results of chemical analyses of three polyhalite-bearing rocks are given in table I. The rock A consists of fine-grained massive polyhalite with only a trace of carbonate. Patches of fibrous polyhalite suggest

that the rock is pseudomorphous after halite-rock. Halite cavities occur in neighbouring layers. The analysis shows very close agreement with the calculated composition of polyhalite.

The rock *B* is a polyhalite-dolomite-rock, derived from original anhydrite-dolomite-rock. It consists of fine-grained polyhalite with less than 1 % of minute granules of dolomite, and a few corroded grains of residual anhydrite (about 0·5 %). The dolomite granules are arranged in strings and thin layers, giving an indication of original roughly horizontal bedding.

The rock *C* (pl. XXXIV, fig. 40) is a polyhalite-rock, showing well-developed pseudomorphs after gypsum, consisting of nearly equidimensional polyhalite grains, with interstices of fibrous polyhalite after halite. A trace of carbonate is present, and a little secondary gypsum.

TABLE I. Chemical analyses of polyhalite-bearing rocks

	A.	B.	C.	D.
SO_3	53·04	52·50	52·87	53·11
MgO...	6·72	6·87	6·47	6·68
CaO	18·71	18·90	18·62	18·61
Na_2O	nil	0·02	0·01	—
K_2O...	15·64	15·42	15·53	15·62
$H_2O + 110°C.$	5·92	5·77	5·87	5·98
$H_2O–110°C.$	0·16	0·07	0·13	—
CO_2	trace	0·39	trace	—
Cl	nil	nil	nil	—
Insol.	0·18	0·27	0·18	—
	100·37	100·21	99·68	100·00

A. Polyhalite-rock, derived from original halite-rock.
B. Polyhalite-dolomite-rock, derived from original anhydrite-dolomite-rock.
C. Polyhalite-rock, derived from original gypsum-halite-rock.
D. Calculated composition of polyhalite, $Ca_2MgK_2(SO_4)_4.2H_2O$.

VIII. ORIGIN OF THE POLYHALITE-BEARING ROCKS.

The evidence given above shows that practically all the available specimens of polyhalite-bearing rock have had a complex history and do not represent original precipitates. All specimens containing anhydrite or halite as well as polyhalite show evidence of replacement of these minerals by polyhalite. Most of those consisting entirely of polyhalite (with accessory dolomite) show pseudomorphous structures indicating a replacement origin. The very few specimens which show no definite evidence of replacement and consist of uniform fine-grained polyhalite may well represent the ultimate stage in replacement of

halite-rock or anhydrite-rock. There is no evidence of direct precipitation of polyhalite in the Eskdale evaporites. In fact it is considered certain that most, and probable that all the polyhalite of the available specimens is due to metasomatic replacement of anhydrite and halite by the action of later brines rich in potassium and magnesium. This does not preclude the possibility of direct precipitation of polyhalite, since the available specimens represent only part of the core of the polyhalite zone.

Many of these rocks show evidence of the previous occurrence of gypsum, which is now represented by pseudomorphs consisting of anhydrite, halite, or polyhalite. In some cases, where the gypsum pseudomorphs are enclosed in halite or in fine-grained fibrous polyhalite apparently derived from halite, the evidence suggests that the gypsum was a primary mineral. In other cases, where the pseudomorphs are enclosed in polyhalite-dolomite-rock with residual anhydrite, the mineral was apparently derived from anhydrite, as the bedding structures of the groundmass pass through the pseudomorphs.

In considering the original nature of these rocks it is relevant to refer briefly to the succession in the upper Eskdale evaporites. Fortunately a larger number of specimens of known depth have been preserved from these, although the sequence is by no means completely represented. Each of these evaporites possesses a basal zone of massive anhydrite-rock with subordinate carbonate. This is followed upwards by a complex zone consisting largely of anhydrite and halite with subordinate carbonate. Above this is a thick zone consisting largely of chlorides. It is the intermediate complex zone which throws considerable light on the origin of the polyhalite-bearing rocks of the lower evaporite.

The complex zones of the upper evaporites show alternations of anhydrite-carbonate-rock with bedding structures, anhydrite-halite-rock with pseudomorphs after gypsum, and bands of almost pure halite-rock. The anhydrite-carbonate layers are often massive, but occasionally contain pseudomorphs of halite and anhydrite after gypsum, the pseudomorphs sometimes enclosing and sometimes distorting the bedding structures. The anhydrite-halite layers consisting largely of pseudomorphs show anhydrite-halite pseudomorphs after gypsum, with either anhydrite or halite in the interstices. Simple zoning of pseudomorphs is found, the zones consisting of anhydrite and halite. 'Herring-bone' structure is beautifully developed in some cases, and is identical with that of the rocks of the lower evaporite bed except that halite takes the place of the polyhalite of the latter rocks.

It is believed that the rocks of the polyhalite zone of the lower evaporite bed are due to the metasomatism of rocks similar to those of the complex zones of the upper evaporites. However, even these have suffered changes since their original deposition—particularly in the replacement of gypsum by anhydrite and halite. The polyhalite zone of the lower evaporite bed occupies a similar position in the sequence to that of the complex zones of the upper evaporites. It lies above anhydrite-dolomite-rock and has a halite-rich upper part. The upper anhydrite above it may be due to interruption of the normal sequence by freshening of the water.

It is probable that the polyhalite zone originally consisted of a series of layers of halite-, gypsum-halite-, and anhydrite-dolomite-rocks. The presence of early gypsum at this stage in all three evaporite beds is curious. Experimental evidence suggests that gypsum should form early in the evaporation sequence, when the brines were relatively dilute. Posnjak (1938, 1940), studying the system $CaSO_4$–H_2O and the stability relations of gypsum and anhydrite in sea-water at 30° C., has shown that during evaporation below 42° C. (the transition point gypsum–anhydrite) the calcium sulphate should first precipitate as gypsum, at about 3·35 times the normal salinity, and that anhydrite should not appear until the water has reached about 4·8 times the usual salinity and a considerable amount of gypsum has been precipitated. In the Eskdale evaporites the basal sulphate layer consists of anhydrite-carbonate-rock. There is no evidence that this anhydrite has been derived from pre-existing gypsum. Even where halite is present below the polyhalite zone, there is no sign of pseudomorphs after gypsum like those so abundant in the polyhalite zone and the intermediate zones of the upper evaporites. Dunham (1948) has indicated that the anhydrite near the edge of this salt-field is primary. The basal anhydrite zones of all three evaporite beds at Eskdale are followed upwards by zones with abundant pseudomorphs after gypsum. Some of the gypsum here is believed to be primary, and some to have been derived from anhydrite in unconsolidated anhydrite-dolomite layers. At any rate, the gypsum here was formed before the advent of the brines which introduced poly-halite and is therefore presumably early, being replaced by anhydrite and halite before polyhalite appeared. In these evaporites gypsum appears to have been a transitory mineral, stable only for a short period during the early stages of chloride deposition. In the complex zones slight changes in conditions caused alternate deposition of thin anhydrite-dolomite layers and gypsum-halite layers. Rhythmic changes in

temperature might have been responsible for this, but other factors must have been responsible for the development of gypsum at this stage in all three distinct evaporites.

Schaller and Henderson (1932) have described rather similar rocks, with pseudomorphs of halite after gypsum sometimes replaced later by polyhalite. In the Texas-New Mexico rocks there is apparently no evidence of primary gypsum and the pseudomorphs are enclosed in anhydrite-rock. All the same, the gypsum was of earlier formation than polyhalite, and the authors suggest that it may have formed while the rocks were in a mushy state. It is significant that the general sequence is similar to that at Eskdale. The authors give vertical sections from three borings showing clay, overlain by anhydrite, and the latter by anhydrite with pseudomorphs of halite after gypsum (1932, p. 36).

Let us now consider the details of the replacements which have transformed these halite-, gypsum-halite-, and anhydrite-dolomite-rocks into the existing polyhalite-bearing rocks.

Layers of almost pure halite are found in the halite-anhydrite-poly-halite-talc-rock from 4445–47 feet (fig. 33). Here polyhalite is seen to have replaced halite to a slight extent, adjacent to the sulphate-bearing layers in the rock. It is possible that the few uniform polyhalite-rocks of unknown depth may have been formed by replacement of halite-rock, and some of these contain cavities lined with euhedral polyhalite crystals (fig. 34). The detailed log of the boring shows that halite is the predominant mineral of the upper part of the polyhalite zone, but since this is represented by only a single specimen, we know practically nothing of these rocks.

Halite-gypsum layers are represented by the halite-anhydrite-poly-halite-talc layers in the specimen from 4445–47 feet (figs. 21, 22). These layers probably represent practically contemporaneous precipitation of gypsum and halite. The evidence suggests that the gypsum was primary and was later converted to anhydrite and halite. Halite occupies the centres of the pseudomorphs and it is possible that the shrinkage in the conversion of gypsum to anhydrite allowed access to the halite-bearing solutions. Part of the secondary anhydrite was probably attacked by halite, and both halite and anhydrite have been partially replaced by polyhalite. The changes can be represented as follows:

Gypsum → anhydrite → halite → polyhalite.

Gypsum → anhydrite → polyhalite.

Halite → polyhalite (in the halite matrix).

Many of the specimens of unknown depth were probably originally primary gypsum-halite-rocks (e.g. figs. 25, 26, 28, 40, and pseudo-morphous layers of figs. 38, 39). These now consist of pseudomorphs of anhydrite, or polyhalite or both, after gypsum, and interstices filled with fibrous polyhalite. The absence of residual anhydrite and dolomite from these interstices, and the occasional presence of interstitial cavities containing talc, suggest that the original mineral here was halite. In these rocks we have further evidence of the replacements mentioned above. The gypsum has been converted to anhydrite, and the simple zoning and 'herring-bone' structure in the pseudomorphs is so like that of the anhydrite-halite pseudomorphs of the upper evaporites that halite also has probably been involved in the replacement. The anhy-drite and halite of pseudomorphs and interstices has then been replaced by polyhalite.

The primary *anhydrite-dolomite layers* are now represented by one specimen showing the early stages in the development of polyhalite at the expense of anhydrite (fig. 23), and by other specimens which consist largely or wholly of polyhalite with residual dolomite (figs. 24, 31, 36, 37). The arrangement of thin layers of dolomite and dusty impurity indicates original roughly horizontal bedding. Some residual anhydrite is often present. The replacement here is:

$$\text{Anhydrite} \rightarrow \text{polyhalite,}$$

the dolomite apparently remaining unchanged.

Some of these layers derived from anhydrite-dolomite-rock contain pseudomorphs after gypsum. The continuation of thin layers of im-purity from the matrix through the pseudomorphs indicates that the gypsum here was secondary, and derived from pre-existing anhydrite. The disturbance of these layers of impurity at the edges of the pseudo-morphs indicates that the gypsum may have grown before the matrix had properly solidified. The gypsum has later been changed back to anhydrite and this replaced by polyhalite. The sequence is as follows:

$$\text{Anhydrite} \rightarrow \text{gypsum} \rightarrow \text{anhydrite} \rightarrow \text{polyhalite.}$$

The multiple zoning present in some of these pseudomorphs is ex-tremely like that figured by Dunham (1948, p. 225 and pl. X, fig. 1), in which secondary gypsum in anhydrite-dolomite-rock contains zones of residual anhydrite. This might suggest that polyhalite has directly replaced gypsum in such zoned pseudomorphs, but the polyhalite-bearing rocks give no other evidence of direct replacement of gypsum by polyhalite, and it seems probable that the Eskdale pseudomorphs

consisted of anhydrite and halite zones. Such pseudomorphs could be derived from gypsum-anhydrite pseudomorphs by solution of the gypsum by halite-depositing brines. This seems to have happened in the upper evaporites, and the writer thinks it likely that the rocks of the polyhalite zone were similar to those of the upper evaporites before the appearance of polyhalite.

Hollingworth (1948, p. 197) has suggested that the gypsum porphyroblasts which are widespread in anhydrite-rocks in other parts of this salt-field may have similar origin to those of the Texas-New Mexico salt-field and may be of fairly early formation. The porphyroblasts in the Billingham anhydrite mine are much less regular than the pseudomorphs of the Eskdale rocks, and do not show such a marked tendency to grow upwards. However, it seems likely that, as Hollingworth suggests, they were of relatively early formation and not due to hydration of anhydrite by meteoric waters.

The changes gypsum → anhydrite and anhydrite → gypsum require only subtraction or addition of water. The changes gypsum → halite and anhydrite → halite require solution and removal of these minerals and deposition of halite in their place, as there is no common chemical constituent involved.

The replacement halite → polyhalite requires removal of halite and introduction of polyhalite. That from anhydrite → polyhalite requires addition of K_2SO_4, $MgSO_4$, and H_2O. In the latter change the $CaSO_4$ of the polyhalite was presumably derived from the anhydrite, and a good deal of $CaSO_4$ must have been carried away in solution, since there is no sign of volume change. Some of the excess $CaSO_4$ recrystallized to form porphyroblasts of anhydrite in polyhalite-rock, and these were attacked by later polyhalite. Some of the excess $CaSO_4$ may have taken part in the replacement of halite by polyhalite.

It seems likely that the replacements described in this section took place during the formation of the evaporite. The early formed gypsum presumably became unstable in the presence of brines of changing composition and concentration, percolating from above, and was pseudomorphed by anhydrite and halite, and these minerals were later replaced by polyhalite when the overlying brines became rich in potassium and magnesium. The upper anhydrite may be due to a freshening of the water, stopping this replacement and sealing off the polyhalite zone. If material becomes available from future borings in this region, it will be interesting to find out whether the lower part of the upper anhydrite shows any development of polyhalite. If it does, then the brines

responsible for the metasomatism may have migrated into the rocks of the polyhalite zone at a late stage.

Schaller and Henderson (1932) have shown that most of the polyhalite of the Texas-New Mexico salt-field is secondary, and has been formed by replacement of anhydrite, halite, and gypsum. They have described many of the effects noted above, and although the details of the replacements are slightly different in some respects, the general story is similar. Replacement of anhydrite by polyhalite in the German salt deposits has also been described (e.g. Lueck, 1913).

Van't Hoff (1912, pp. 280, 322–23) showed that solutions rich in potassium and magnesium sulphates can change gypsum and anhydrite into polyhalite, and suggested that chloride solutions might also effect this change. Schaller and Henderson (1932, p. 72) tentatively favoured chloride solutions as being more likely to dissolve anhydrite. Cunningham (1934) states that two beds of polyhalite near the base of the upper salt are practically continuous over the Texas-New Mexico salt-basin, and may be due to primary precipitation from sulphate-rich brines. He also states that most of the polyhalite is secondary and occurs in areas near the edge of the basin, where land masses gave a source of $CaSO_4$, and where the sulphate-rich solutions would change gypsum and anhydrite to secondary polyhalite. Mansfield and Lang (1934) give a great deal of data on borehole sequences in the Texas-New Mexico basin, and show that a bed of polyhalite may pass locally into anhydrite or halite and then back to polyhalite. Lateral variation of this type may be expected in the British salt-field, since here also the polyhalite seems to be largely secondary.

IX. THE RELATION BETWEEN MAGNESITE AND DOLOMITE.

Nearly all the rocks of this evaporite bed contain a certain amount of carbonate. In some cases this is dolomite, in others magnesite. It is most unfortunate that the core of this evaporite bed was not properly preserved, and that the distribution of the two carbonates cannot be fully worked out. Some idea of this distribution can be got from the well cuttings and the few specimens of known depth, and although this is not really satisfactory it shows that there is an interesting problem here, which should be studied in detail in any future boring in this part of the salt-field.

Only magnesite, and no dolomite, has been found in the rocks from the halite-anhydrite zone. Both dolomite and magnesite have been found in a rock from the upper anhydrite (4415 feet). No carbonate

is present in the specimen of halite-polyhalite-anhydrite-talc-rock from 4445–47 feet. The polyhalite and polyhalite-anhydrite-rocks contain dolomite, not magnesite. Magnesite has been found in well cuttings a short distance below the polyhalite zone, and it seems likely that the rock with 'nests of micaceous mineral' near the top of the lower anhydrite, mentioned in the detailed log of the boring, is the anhydrite-magnesite-talc-halite-rock found in specimens of unknown depth. A specimen from 4559–61 feet contains dolomite, and the well cuttings indicate that the carbonate of the rocks below this is dolomite.

In general, then, it appears that dolomite is the carbonate of most of the lower anhydrite and of the polyhalite zone. Magnesite is the carbonate of the halite-anhydrite zone and of a layer in the upper part of the lower anhydrite. Both magnesite and dolomite occur in the upper anhydrite.

In the anhydrite-dolomite-magnesite-rock from 4415 feet fine-grained anhydrite is seen to be eating its way into dolomite, while the magnesite occurs as euhedral porphyroblasts cutting dolomite. Brines rich in $MgSO_4$ might, under certain conditions, produce magnesite and anhydrite at the expense of dolomite according to the equation

$$MgSO_4 + CaMg(CO_3)_2 = 2MgCO_3 + CaSO_4.$$
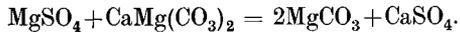
If this were so, magnesite and anhydrite might be the equivalents of dolomite and kieserite ($MgSO_4 . H_2O$). Kieserite has not been found in this evaporite, although it might be expected in such a paragenesis. Both kieserite and magnesite are recorded in fair quantity from the Texas-New Mexico potash field by Schaller and Henderson (1932), who found no definite evidence of the presence of dolomite. Kieserite generally forms fairly late in the evaporation series, as does magnesite in the Eskdale boring.

It is odd that the carbonate of the polyhalite zone is dolomite, since magnesite apparently occurs both below and above this zone. The polyhalite is believed to be almost entirely, if not entirely, secondary, due to metasomatic replacement of halite and anhydrite. The dolomite in the polyhalite-bearing rocks is very similar to that in the lower anhydrite, and is believed to have suffered no change in the conversion of anhydrite to polyhalite. It appears possible that the lower anhydrite represents a fairly normal sequence, with dolomite as the earlier carbonate and magnesite (possibly derived from dolomite) in the upper part. A freshening of the water near the top of the lower anhydrite may have then interrupted the sequence and caused precipitation of

dolomite again with anhydrite; most of this second layer of anhydrite-dolomite-rock being converted to polyhalite-bearing rock with the original dolomite unchanged, by the action of later brines. A second freshening of the water could produce the upper anhydrite, with dolomite later giving place to magnesite as the brines became richer in $MgSO_4$.

The above suggestions must be considered as tentative. Much more definite information is needed on the distribution of the carbonates here, but there is an interesting problem, which should be reconsidered when more material from this salt-field is available.

No magnesite has been recorded from other parts of this salt-field. Dunham (1948, p. 219) has particularly searched for this mineral in the material from other borings, and has found that the carbonate of these is dolomite; these other borings were put down nearer the edge of the salt-field, where no potash salts have been found, and this again indicates that magnesite occurs fairly late in the evaporation sequence.

There is one other question: how much of the carbonate represents a primary precipitation and how much is due to secondary replacement? It seems likely that much of the dolomite associated with anhydrite is primary. In some rocks the dolomite shows evidence of recrystallization, especially at the edges of halite cavities, but the small rounded dolomite grains in most of the anhydrite-dolomite-rocks are probably primary. Similarly, the small rounded dolomite grains in the polyhalite-bearing rocks are probably the unaltered primary grains previously associated with anhydrite and gypsum in these rocks. Some of the magnesite appears to have been produced by replacement of dolomite, and replacement of anhydrite by magnesite has been observed in coarse anhydrite-magnesite-halite-rock, but there is no evidence suggesting that all, or even most, of the magnesite was produced in this way. It appears likely that the magnesite of the Texas-New Mexico evaporites was mainly primary since it is often associated with clays (Schaller and Henderson, 1932), and there seems to be no reason why some of the magnesite of the Eskdale evaporite should not have been primary. Much of it, however, must have recrystallized since formation if it is not secondary, as in many cases magnesite plates are found cutting recrystallized euhedral porphyroblasts of anhydrite.

X. THE DISTRIBUTION AND ORIGIN OF TALC.

The identification and properties of this mineral have been described above. In the lower evaporite bed the mineral has been found in specimens from a wide depth range. It occurs in small quantity in specimens

from the halite-anhydrite zone. A specimen a few feet from the top of the evaporite bed (4314–16 feet) shows a few flakes of talc associated with halite. It is present in larger quantity in the halite-polyhalite-anhydrite-talc-rock from 4445–47 feet in the polyhalite zone, and a few flakes of the mineral have been found in cavities in other polyhalite-bearing rocks. It also occurs in small quantity in halite cavities in anhydrite-magnesite-rocks and anhydrite-dolomite-rocks of unknown depth, and in considerable quantity in certain layers of the anhydrite-magnesite-halite-talc-rock probably to be referred to 4525–37 feet, near the top of the lower anhydrite. Here the detailed log of the boring shows a layer of 'anhydrite with occasional irregular inclusions of salt (nests of micaceous mineral)'. A few small flakes of talc have also been found in halite cavities in a specimen of brecciated anhydrite-dolomite-rock from 4742 feet, not far from the base of the lower anhydrite. The mineral therefore occurs from the top to near the base of the evaporite bed.

In these rocks talc has been found only where halite is present, or in cavities from which halite has presumably been dissolved out during weathering. The mineral has not been found in massive anhydrite-rocks. In all cases where the halite has been preserved the talc forms thin plates, lying along the halite cleavages and often forming a rectangular network. In the anhydrite-magnesite-talc-halite-rocks the mineral forms such a network, crossing halite cavities and anchored at each side by the surrounding anhydrite. At the edges of the cavities the talc plates are attached to the anhydrite along its cleavages or along inter-granular boundaries.

In the upper evaporite bed of the Eskdale boring, talc occurs in con-siderable quantity in the middle of the chloride zone. This evaporite bed will be described in a later communication, but it is relevant to state here that the talc is again especially associated with halite, and the plates nearly always lie along halite cleavages. In some cases talc has been found between halite grains, and in these cases a series of parallel plates runs from the boundaries along the cleavages of the halite grains on either side.

This boring provides the first published record of talc in evaporites, so far as the writer is aware. However, W. T. Schaller, in a personal communication, has stated that the mineral occurs in the Texas-New Mexico evaporites, and that the mineral described as 'polyhalite fibres (p)' in the legend opposite pl. 23 c (Schaller and Henderson, 1932) has later been identified as talc. Here again the talc lies along the cleavages

of the halite, and along intergranular boundaries. Plates project to a lesser extent along sylvine cleavages.

It is most remarkable that talc should be found in such a paragenesis. In discussing the mode of origin of the mineral the following points must be borne in mind:

The constant association of talc with halite.

The occurrence of talc in all zones where halite is present.

The absence of talc in massive anhydrite-carbonate-rocks.

The almost invariable occurrence of talc along the cleavages of the halite.

The occasional occurrence of talc along intergranular boundaries of halite.

The attachment of talc, at the edges of the halite cavities, along intergranular boundaries, and along cleavages of euhedral anhydrite crystals.

The occurrence of talc along cleavages of sylvine (Schaller and Henderson, 1932, pl. 23 c).

The occasional concentration of talc plates near the edges of the halite grains.

The apparent absence of talc in rocks nearer the edge of this salt-field.

The occurrence of talc along the cleavages and intergranular boundaries of halite strongly suggests that the mineral is secondary, and not a primary precipitate. It cannot have grown before the halite was deposited, as it is not present in massive anhydrite-carbonate-rocks. It must have grown later than the euhedral anhydrite at the edges of the halite cavities, as it is generally attached to this anhydrite along intergranular boundaries or along cleavages. Its occurrence along intergranular boundaries of halite and sylvine shows that in these cases it is later than halite and sylvine—as does the concentration of talc plates near the edges of the chloride grains. In the cases where talc plates occur along the cleavages inside halite grains and not in intergranular boundaries, the talc is almost certainly again secondary, as it is very difficult to believe that talc and halite could grow simultaneously in this orientation. Neither is there any reason to believe that recrystallizing halite could force pre-existing talc plates into positions parallel to its cleavages. Magnesite plates show no tendency to any special orientation in halite. The talc, then, is considered to

have formed later than halite in these rocks, and to be a secondary product.

The Texas-New Mexico occurrence suggests replacement of halite, and to a lesser extent sylvine, by talc. Similar cases are found in the upper evaporite at Eskdale. However, such a replacement would be a very curious one, as there is no common chemical constituent involved. In the Eskdale rocks there is no evidence that talc has formed at the expense of any other mineral. It is true that all the Eskdale rocks contain some other magnesian mineral (dolomite, magnesite, or polyhalite) and that crystalline quartz is present in the talc-bearing rocks of the upper evaporite bed, but there is no evidence whatever that these minerals played any part in the production of talc.

Rather than chemical replacement, some type of mechanical replacement is likely. It is easy to believe that solutions could work their way along intergranular boundaries and deposit talc there. By virtue of its crystalloblastic strength the talc might be able to push its way from these boundaries into the cleavages of adjacent halite grains. In the lower evaporite bed it is common to find talc inside the halite and not in intergranular boundaries. It is possible that under slight stress halite might yield by development of potentially open cleavages rather than by weakening of intergranular boundaries. In that case solutions might gain access to the cleavages more easily than to the boundaries of the grains.

The origin of the solutions has still to be discussed. The constant association of talc with halite would indicate either that the solutions were especially associated with those which deposited halite, or that only halite gave access to such solutions. It would be expected that if the talc-bearing solutions had migrated through these rocks for any appreciable distance, talc would be found commonly in massive anhydrite-carbonate-rocks. Its absence here indicates that solutions capable of depositing talc were especially associated with halite, and were possibly present as inclusions in halite.

There is still the question of the date of formation of the talc. This cannot be decided. There seems no reason why it should not have formed since Permian times, when the evaporites were under a considerable cover of overlying rocks. It would seem more reasonable that talc should form under such conditions, where the temperature might be considerably higher than that existing at the time of deposition of the evaporites. It would be interesting to know the mode of occurrence of talc in halite which has recrystallized since Permian times. In the

halite-anhydrite zone there is evidence suggesting that such recrystal-lization has taken place. However, in the specimen of halite which shows definite platy parallelism no talc has been seen. Future borings may throw more light on this problem.

It is interesting that talc has not been described from other bor-ings nearer the edge of the salt-field. It occurs in the brecciated anhydrite-dolomite-rock near the base of the Eskdale lower evapor-ite bed—a position low in the evaporation sequence. A special search for this mineral should be made in the halite-bearing rocks of other borings.

XI. SUMMARY AND CONCLUSIONS.

This communication gives the results of a petrological study of rocks from the lowest of the three Permian evaporite beds passed through by the D'Arcy Exploration Company's boring in 1938–39, near Aislaby, Eskdale, east Yorkshire. Unfortunately very few core specimens of known depth were preserved. This study is therefore based on examina-tion of these few specimens, a large number of specimens of unknown depth collected at the site of the boring in 1942, and a set of well cuttings provided by the D'Arcy Exploration Company.

The evaporite bed is 460 feet thick and is underlain by dolomite. The well cuttings and the detailed log of the boring show that it can be divided into four main zones. There is a thick lower anhydrite zone (248 feet), consisting largely of anhydrite, with inclusions of halite towards the base and top, and with subordinate carbonate. This is followed by a polyhalite zone (85 feet) which has a halite-rich upper part, followed downwards by about 45 feet consisting largely of poly-halite and apparently grading into anhydrite-dolomite-rock at the base. Above the polyhalite zone is an upper anhydrite zone (41 feet) with subordinate halite and carbonate, followed by a halite-anhydrite zone (86 feet) with predominant halite.

The following minerals have been found: anhydrite, celestine, dolo-mite, gypsum, halite, magnesite, polyhalite, pyrite, quartz, sulphur, and talc. Anhydrite, halite, the carbonates, and polyhalite are the major constituents, and talc has a wide distribution. Early gypsum is repre-sented by pseudomorphs consisting of anhydrite, halite, and polyhalite. The other minerals occur only in small amount.

Detailed petrographic descriptions of the halite-anhydrite-rocks, anhydrite-carbonate-rocks, and polyhalite-bearing rocks are given. This study shows that many of these rocks have suffered large-scale changes

due to replacement and recrystallization since original precipitation. There is evidence of the following replacements:

Dolomite → anhydrite

Dolomite → anhydrite + magnesite

Anhydrite → magnesite

Anhydrite → halite

Anhydrite → gypsum

Anhydrite → polyhalite

Anhydrite → sulphur

Gypsum → anhydrite

Gypsum → halite

Halite → polyhalite

In the polyhalite-bearing rocks evidence suggesting the following replacement sequences is found:

Gypsum → anhydrite → halite → polyhalite

Gypsum → anhydrite → polyhalite

Anhydrite → gypsum → anhydrite → polyhalite

It is probable that most of these replacements took place during the formation of the evaporite, and were due to minerals already deposited becoming unstable as the supernatant brines changed in composition, these minerals being dissolved or reacting with percolating brines to form secondary products.

The replacement of dolomite by anhydrite has probably taken place on a fairly large scale in the basal 20 feet or so of the lower anhydrite zone. There is no evidence to date this replacement, and it seems possible that it may have taken place at almost any time during or after the formation of the evaporite.

The replacement of dolomite by anhydrite and magnesite is suggested by the relations between these minerals in a specimen from the upper anhydrite zone. The distribution and relations of these two carbonates are discussed, and it is suggested that such a replacement might have been effected by brines rich in $MgSO_4$, and that in these evaporites magnesite may be partially equivalent to kieserite. Replacement of anhydrite by magnesite is seen in coarse anhydrite-magnesite-halite-rocks. The magnesite cuts through anhydrite grains which show cataclastic structures, and this indicates that the replacement took place when the anhydrite rock was at least partially solid.

Replacement of anhydrite by halite has been seen in an anhydrite-halite-dolomite-rock from near the top of the lower anhydrite zone, and in rocks from the polyhalite zone. It is impossible to determine the extent of such replacement as so few specimens containing halite have been preserved. This replacement was an early one in the polyhalite-bearing rocks.

The replacements involving gypsum are found in the polyhalite zone. Gypsum was widespread as an early mineral in this zone, and the evidence suggests that some of it was primary, and some derived at the expense of anhydrite at a very early stage in the history of these rocks. It was apparently replaced by anhydrite and halite before the appearance of polyhalite.

It is considered that most, if not all the polyhalite of these rocks is secondary in origin, and was formed by replacement of anhydrite and halite due to the action of potassium- and magnesium-rich brines. These changes probably took place during the formation of the evaporites, as the polyhalite zone is cut off at the top by a massive anhydrite zone apparently containing no polyhalite. The rocks of the polyhalite zone have probably been derived from an original layered series of halite-, gypsum-halite-, and anhydrite-dolomite-rocks.

The small traces of sulphur found in anhydrite-carbonate-rocks have been derived from anhydrite, in the presence of carbonaceous matter.

There is evidence that many of these rocks have suffered at least partial recrystallization since their formation. Evidence of recrystallization is widespread in many anhydrite-carbonate-rocks and halite-anhydrite-rocks. It is considered probable that much of this recrystallization took place at an early stage, as there is very little sign of parallelism of the grains. However, in some anhydrite-carbonate-rocks we find cataclastic textures preceding recrystallization, and in one halite-rock we find platy parallelism of halite grains, suggesting recrystallization under pressure, presumably effected when the rocks were under considerable cover. In the polyhalite zone there is no evidence of recrystallization later than the formation of polyhalite, and this also indicates that the bulk of the recrystallization was early. Recrystallization has accompanied replacement in the latter rocks, excess $CaSO_4$ apparently recrystallizing to form anhydrite porphyroblasts in polyhalite-rock, these porphyroblasts often being attacked by later polyhalite.

Evidence of abundant early gypsum has been found in the polyhalite zone, but there is no evidence to suggest that the anhydrite of the lower anhydrite zone is not primary, except where it has replaced dolomite towards the base of this zone. Gypsum apparently had a transitory existence at a stage near the beginning of chloride deposition, and later changed to anhydrite and halite.

The distribution and origin of talc are discussed. This mineral occurs especially associated with halite, and appears to be of later formation

than the minerals with which it is found. The mineral may have been formed after the evaporite bed had solidified. It was probably due to solutions which were especially associated with halite-bearing rocks and did not travel any appreciable distance. As far as the writer is aware, this boring gives the first published record of talc in evaporites.

List of references.

CUNNINGHAM (W. A.), 1934. The potassium sulfate mineral polyhalite in Texas. Bull. Univ. Texas, Bur. Econ. Geol., no. 3401, pp. 833–867.

DUNHAM (K. C.), 1948. A contribution to the petrology of the Permian evaporite deposits of north-eastern England. Proc. Yorks. Geol. Soc., vol. 27, pp. 217–227. [M.A. 10–568.]

FOWLER (A.), 1944. A deep bore in the Cleveland Hills. Geol. Mag., vol. 81, pp. 193–206, 254–265. [M.A. 9–312.]

GÖRGEY (R.), 1914. Über die Krystallform des Polyhalits. Tschermaks Min. Petr. Mitt., vol. 33, pp. 48–102.

GUPPY (E. M.), 1944. Boracite from a boring at Aislaby, Yorkshire. Min. Mag., vol. 27, pp. 51–53.

HOLLINGWORTH (S. E.), 1948. Evaporites. Proc. Yorks. Geol. Soc., vol. 27, pp. 192–198. [M.A. 10–567.]

LEES (G. M.) and TAITT (A. H.), 1946. The geological results of the search for oil-fields in Great Britain. Quart. Journ. Geol. Soc. London, vol. 101 (for 1945), pp. 255–317.

LUECK, (H.), 1913. Beitrag zur Kenntnis des älteren Salzgebirges. Leipzig, 1913.

MANSFIELD (G. R.) and LANG (W. B.), 1934. The Texas-New Mexico potash deposits. Bull. Univ. Texas, Bur. Econ. Geol., no. 3401, pp. 641–832.

POSNJAK (E.), 1938. The system, $CaSO_4–H_2O$. Amer. Journ. Sci., ser. 5, vol. 35-A, pp. 247–272. [M.A. 7–288.]

—— 1940. Deposition of calcium sulfate from sea water. Amer. Journ. Sci., vol. 238, pp. 559–568. [M.A. 8–87.]

SCHALLER (W. T.) and HENDERSON (E. P.), 1932. Mineralogy of drill cores from the potash field of New Mexico and Texas. Bull. U.S. Geol. Surv., no. 833, 124 pp., 39 pls. [M.A. 5–168.]

TILLEY (C. E.), 1943. Polyhalite from a depth of 4500 feet in a boring at Aislaby, Sleights, near Whitby. Min. Mag., vol. 26, p. lvii.

VAN'T HOFF (J. H.), 1912. Untersuchungen über die Bildungsverhältnisse der ozeanischen Salzablagerungen. Leipzig, 1912.

EXPLANATION OF PLATES XXIX–XXXIV.

Photomicrographs and photographs of evaporites from the lower bed in the Eskdale no. 2 boring, east Yorkshire.

PLATE XXIX.

FIG. 13. Porphyroblasts of sulphur in anhydrite-dolomite-rock. To the right is a patch rich in carbonaceous matter with small clots of sulphur. × 16.

FIG. 14. Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite, showing the edge of a vein-like mass of anhydrite, and patches of anhydrite developing in dolomite (black). × 15.

Fig. 15. Anhydrite-magnesite-rock. The small needle-like crystals are cross-sections of magnesite plates. The crenulated bedding structure is emphasized by carbonaceous impurity. × 11.

Fig. 16. Anhydrite-magnesite-rock. × 25.

Fig. 17. Coarse anhydrite-magnesite-halite-rock, showing plates of magnesite crossing a halite cavity. The groundmass contains a good deal of secondary gypsum. × 16.

Fig. 18. Anhydrite-magnesite-halite-talc-rock, showing a halite cavity crossed by a network of talc plates. Crossed nicols. × 22.

PLATE XXX.

Fig. 19. Talc plates lying along cleavages of halite. The white spots are grains of quartz and anhydrite. Upper evaporite, 3780 feet below surface. Crossed nicols. × 20.

Fig. 20. Halite-anhydrite-polyhalite-talc-rock. Plates of talc lie along halite cleavages, and spear-shaped polyhalite crystals along intergranular boundaries of halite. In the lower part of the photograph, tiny grains of polyhalite are developing at the expense of halite. 4445–47 feet below surface. Crossed nicols. × 10.

Fig. 21. Halite-anhydrite-polyhalite-talc-rock. Pseudomorphs of polyhalite and anhydrite, with centres of halite, after gypsum, embedded in halite. Near the centre is a 'swallow-tail' pseudomorph. A few large twinned polyhalite crystals are enclosed in halite. 4445–47 feet below surface. Crossed nicols. × 19.

Fig. 22. Halite-anhydrite-polyhalite-talc-rock, showing polyhalite-anhydrite-halite pseudomorphs after gypsum. Crossed nicols. × 19.

Fig. 23. Anhydrite-polyhalite-dolomite-rock. The rock is composed largely of anhydrite. Polyhalite is developing along cleavages and intergranular boundaries of the large anhydrite grains at the left-hand side of the photograph. × 25.

Fig. 24. Polyhalite-dolomite-rock. It is believed that the rock was originally composed of anhydrite and dolomite, and that the anhydrite has been completely replaced by polyhalite, the dolomite (black) remaining unchanged and showing indication of original bedding structure. × 16.

PLATE XXXI.

Fig. 25. Polyhalite-anhydrite-rock with pseudomorphs after gypsum. The pseudomorphs are composed largely of anhydrite, which is replaced by polyhalite to a varying degree, especially at the edges. At the top left of the photograph is an elongated pseudomorph with very little residual anhydrite. The interstices between the pseudomorphs are composed of fine-grained polyhalite, which has perhaps replaced halite. × 10.

Fig. 26. Polyhalite-anhydrite-rock showing pseudomorphs of anhydrite, partly replaced by polyhalite, after gypsum. The interstices are composed of fine-grained fibrous polyhalite, probably after halite. × 15.

Fig. 27. Polyhalite-anhydrite-rock with zoned pseudomorphs after gypsum. Some of the pseudomorphs show alternate zones of anhydrite and polyhalite. × 10.

Fig. 28. Polyhalite-rock with pseudomorphs of polyhalite after gypsum. The

polyhalite of the pseudomorphs tends to be nearly equigranular, while that of the interstices shows a fibrous structure. Crossed nicols. × 10.

PLATE XXXII.

FIG. 29. Polyhalite-dolomite-rock with pseudomorphs after gypsum. The edges of the pseudomorphs are marked by aggregates of dolomite granules (black). × 10.

FIG. 30. Polyhalite-anhydrite-rock with pseudomorphs after gypsum. The two pseudomorphs contain corroded and partly detached relics of two large anhydrite crystals, in positions of extinction. The groundmass is composed of polyhalite, which tends to be equidimensional in the pseudomorphs and fibrous in the interstices. Crossed nicols. × 18.

FIG. 31. Polyhalite-dolomite-rock with a large secondary anhydrite porphyroblast. × 20.

FIG. 32. Polyhalite-rock showing coarse polyhalite projecting into halite cavities. Crossed nicols. × 16.

PLATE XXXIII.

FIG. 33. Halite-anhydrite-polyhalite-talc-rock. 4445–47 feet below surface. Nat. size.

FIG. 34. Polyhalite-rock, with a layer of halite cavities lined with polyhalite crystals, and a weathered crust of gypsum. Polished vertical section of core × 1¼ diam.

FIG. 35. Polyhalite-anhydrite-rock with zoned pseudomorphs after gypsum. Many of the pseudomorphs show zones of anhydrite (dark) and polyhalite (light). Polished cross-section of core. × 2 diam.

FIG. 36. Polyhalite-anhydrite-dolomite-rock showing anhydrite porphyroblasts in a matrix of fine-grained polyhalite with dolomite. Weathered gypsum crust. Polished cross-section of core. Nat. size.

FIG. 37. Polyhalite-dolomite-rock, with weathered gypsum crust, probably de-rived from anhydrite-dolomite-rock. Original bedding is indicated by varia-tion in amount of dolomitic and carbonaceous impurity. There is a trace of pseudomorphous structure after gypsum near the top of the specimen. Polished vertical section of core. Nat. size.

PLATE XXXIV.

FIG. 38. Layered polyhalite-anhydrite-rock, with layers rich and poor in pseudo-morphs after gypsum. This is the polished counterpart of fig. 39. The light-coloured layers are composed largely of polyhalite-anhydrite pseudomorphs after gypsum and are believed to have been derived from original gypsum-halite layers. The darker layers consist almost entirely of polyhalite with subordinate dolomite, and are believed to represent original anhydrite-dolomite layers in which a few gypsum porphyroblasts had developed. Polished vertical section of core. Nat. size.

FIG. 39. Counterpart of fig. 38, polished and then etched with water. The poly-halite has developed a thin white decomposition crust of gypsum, while the anhydrite appears darker. It can be seen that the lower pseudomorphous layer is formed largely of 'swallow-tail' twin pseudomorphs after gypsum, showing 'herring-bone' structure marked by alternation of grey anhydrite and white polyhalite (see text-fig. 12). The upper pseudomorphous layer

F. H. STEWART: POLYHALITE-BEARING ROCKS

Plate XXXI.

F. H. STEWART: POLYHALITE-BEARING ROCKS

29

30
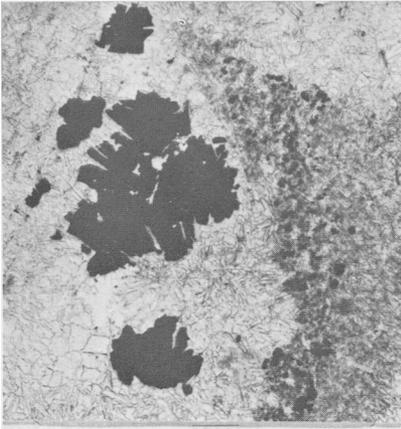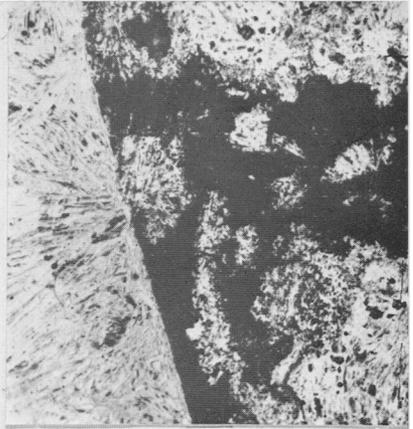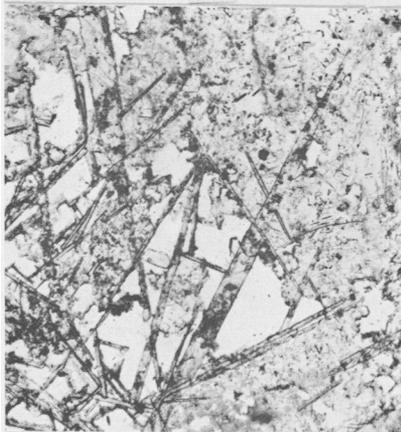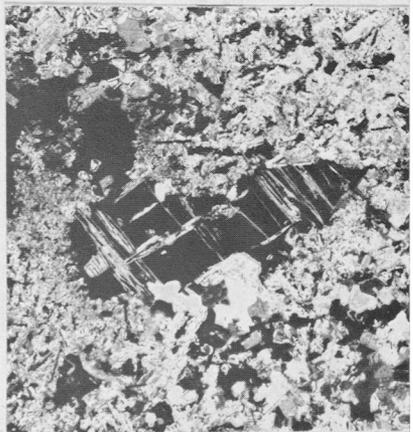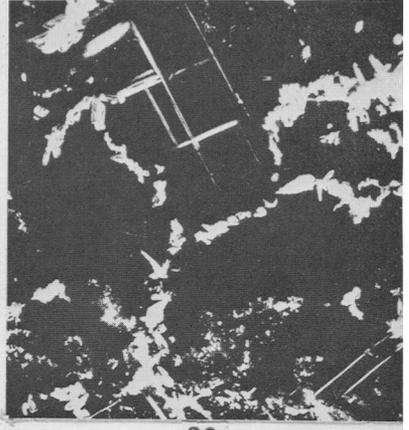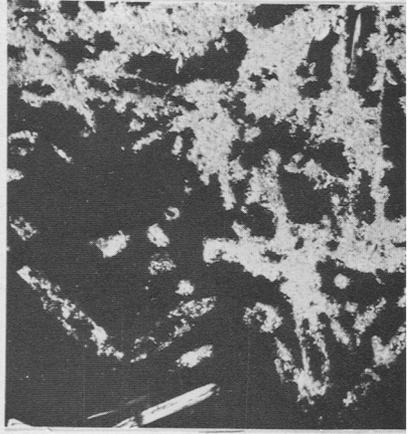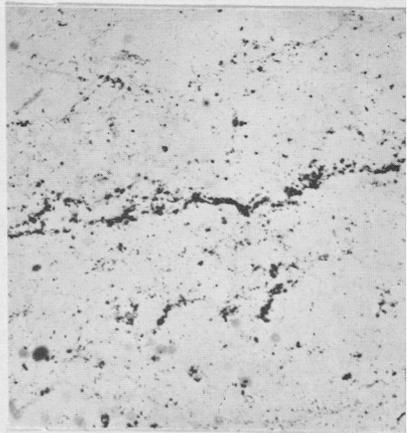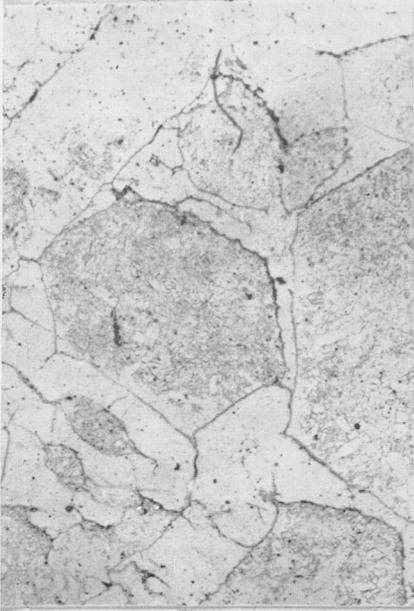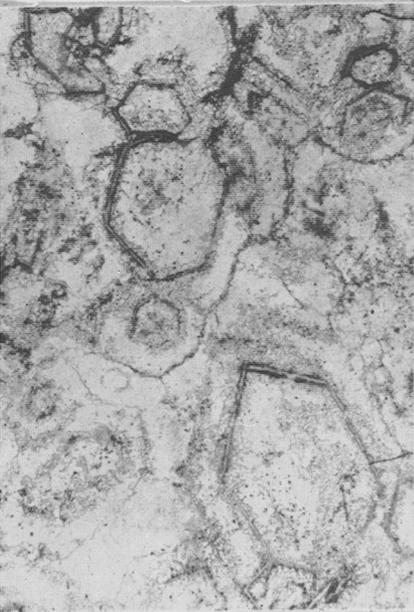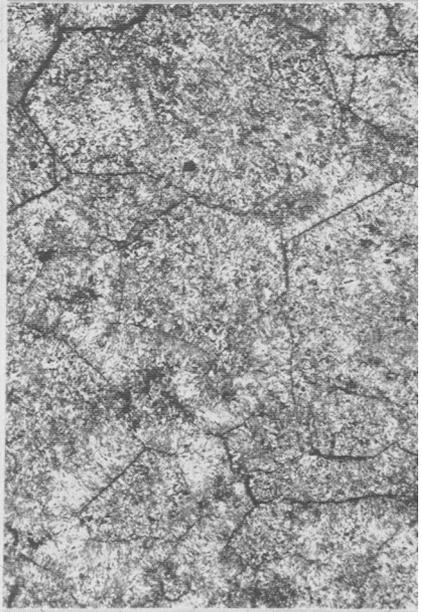
31   32
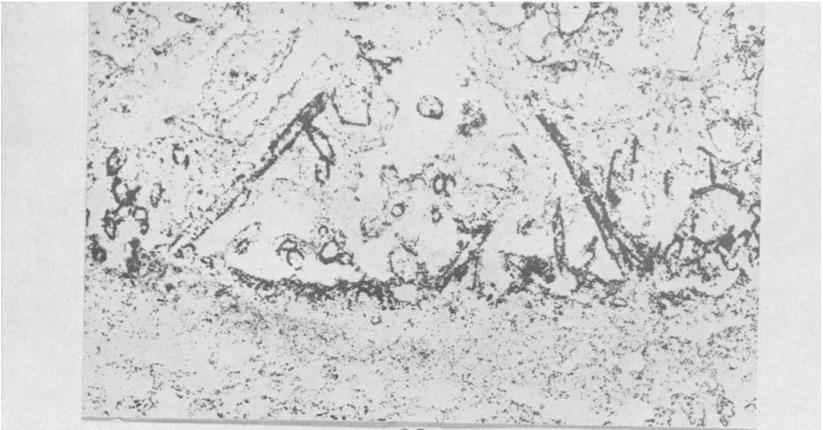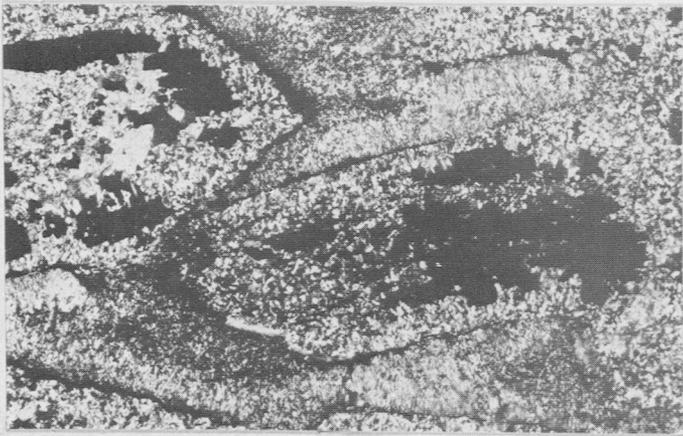
F. H. Stewart: Polyhalite-bearing rocks
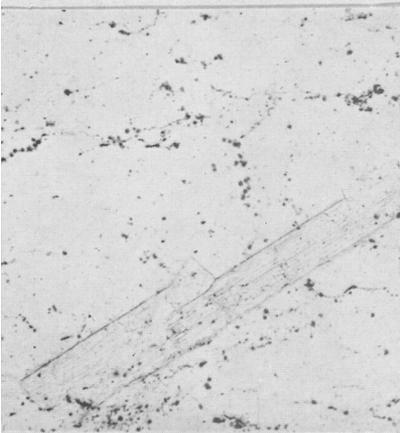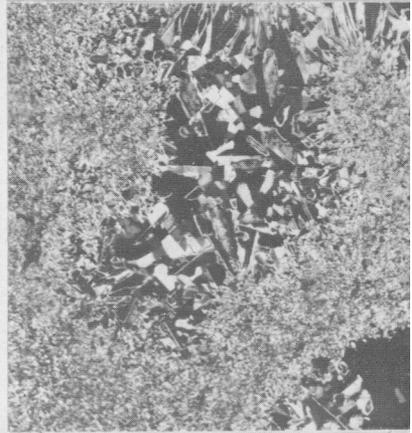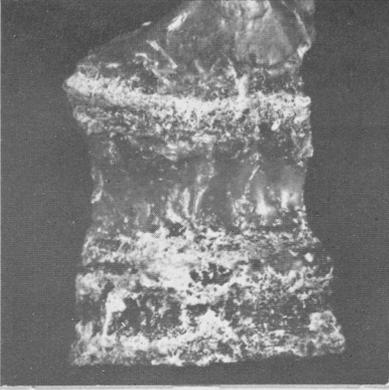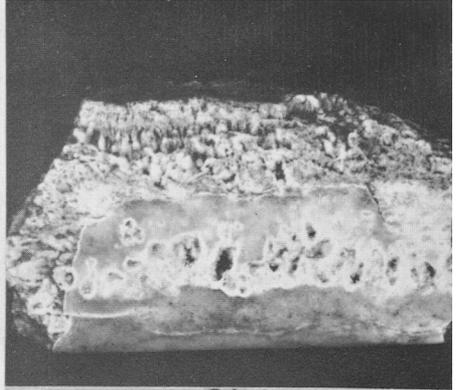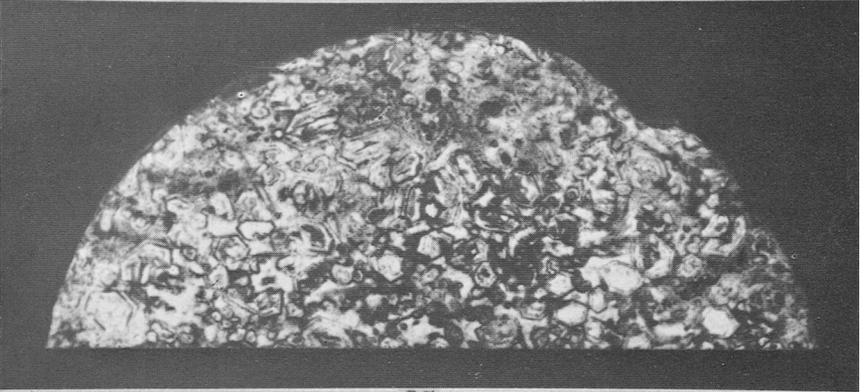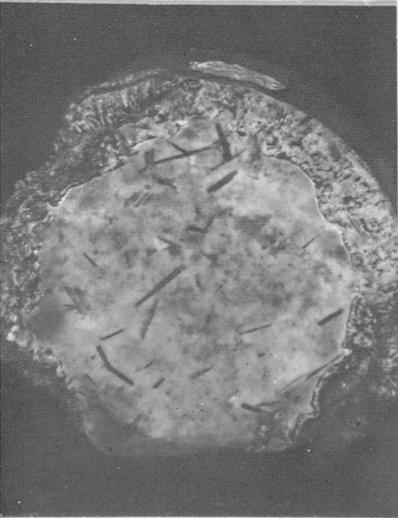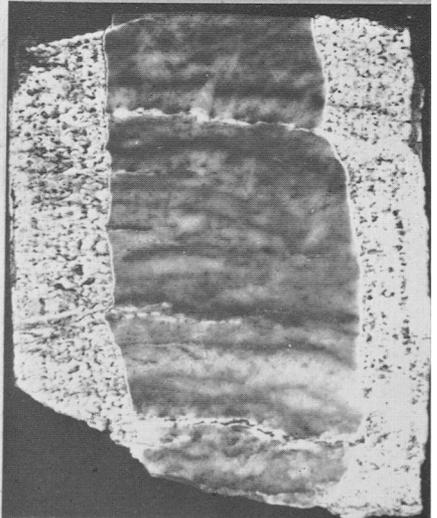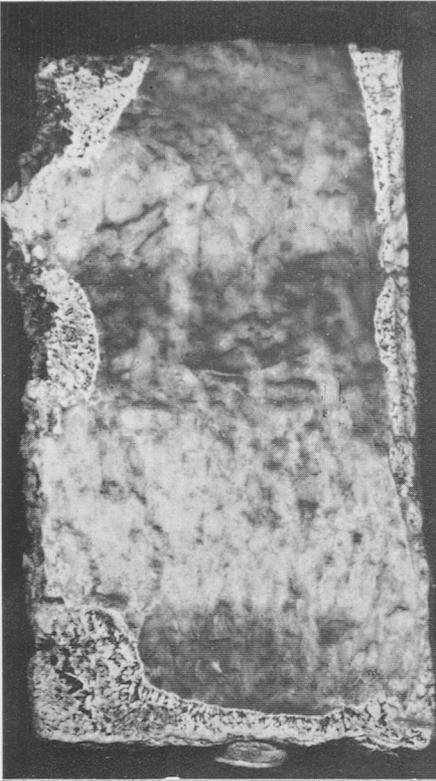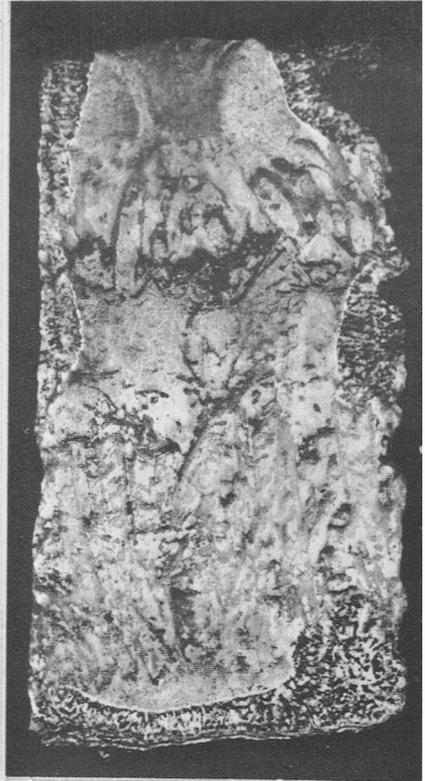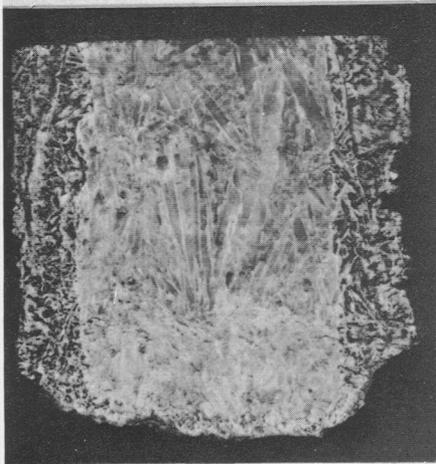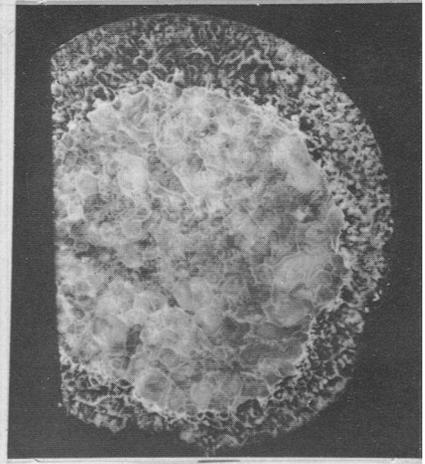
38

39

40

41

F. H. Stewart: Polyhalite-bearing rocks

shows pseudomorphs with outer zones of anhydrite and interiors of poly-
halite. Nat. size.

FIG. 40. Polyhalite-rock with well-developed pseudomorphous structure. The
structure is emphasized by variation in colour of the polyhalite. This rock is
believed to have been derived from an original gypsum-halite-rock. Polished
vertical section of core. Nat. size.

FIG. 41. Polished cross-section of the polyhalite-rock of fig. 39, showing cross-
ctions of pseudomorphs. Nat. size.