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

PART II. *The middle evaporite bed.*

(With Plates IX and X.)

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I. INTRODUCTION AND ACKNOWLEDGEMENTS.

THE D'Arcy Exploration Company's boring, put down in 1938–39 near Aislaby, Eskdale, passed through three Permian evaporite beds. A petrological account of the rocks of the lower evaporite bed has been given in an earlier communication (Stewart, 1949). The present paper deals with the petrography of the middle evaporite bed. The material examined comprises:

Core samples of known depth collected by I.C.I. while drilling was in progress, and consisting of pieces of core, up to 6 inches in length and 4½ inches in diameter, taken at intervals of 2 feet in the following depth ranges: 3910–22, 3950–66, 3970–4008, 4010–32, 4034–46, 4050–64, 4066–68, 4070–84, 4090–4110, 4118–36, 4138–44, 4146–50, 4176–78 feet below surface.

It will be seen that there is a significant gap from 3922 to 3950 feet, from which no core samples were recovered. The range 3950–4150 feet is fairly well represented, but the lower 46 feet of the bed is represented by only one core sample.

Core samples of unknown depth.—A few samples of weathered core were collected in 1942 at the site of the boring. These consist of anhydrite with carbonates. It is not always possible to distinguish with certainty to which of the upper two evaporite beds such samples belong, so they have been largely omitted from this account.

Well cuttings taken at intervals of 5 to 10 feet, covering the whole depth range of the evaporites. These, of course, consist of insoluble residues.

My sincere thanks are due to Imperial Chemical Industries and to the D'Arcy Exploration Company for supplying material for examina-

tion and for allowing me to use data obtained by them. It is indeed fortunate that the D'Arcy Exploration Company, recognizing the possibility of the presence of potassium salts in this part of the salt field, undertook continuous coring throughout the salt series in their boring for oil. The analytical details of KCl percentages were provided by I.C.I., and are quoted with their kind permission. I am indebted to the Durham Colleges for a research grant, and to Mr. G. O'Neill for taking the photographs which illustrate this paper.

II. GENERAL SUCCESSION IN THE MIDDLE EVAPORITE BED.

The general succession is given in the following table. The relative distribution of anhydrite and halite in the lower part of the succession is based partly on data given in the D'Arcy Exploration Company's detailed log of the boring. The rest of the succession is based on a study of the available core samples and well cuttings

	Greenish-grey and red salt clay.	Thickness in feet.
3910 feet		
Upper halite zone	Brown, red, and colourless halite, with greenish-grey clay. (Many patches of blood-red halite, stained by haematite inclusions, in a specimen from 3916–18 feet)	8
3918 feet		
Halite-sylvine zone	Brown halite and sylvine, with greenish-grey clay	4
	No cores available	28
	Brown halite with subordinate sylvine and greenish-grey clay	14
3964 feet		
Halite zone	Brown and pink halite with patches of blood-red halite, the colour being due to haematite inclusions. Subordinate patches of anhydrite and clay, the anhydrite becoming small in amount towards the top. Very scarce sylvine near top	78
	Brown, gray, and colourless halite, with subordinate irregular layers and patches of anhydrite	53
	Alternating halite and anhydrite	3
	Brown halite with streaks of anhydrite	8
4106 feet		
Halite-anhydrite zone	Anhydrite and halite, with layers containing anhydrite-halite pseudomorphs after gypsum	30
	Colourless halite with streaks of anhydrite	4
	Anhydrite and halite	2
	Colourless halite with streaks of anhydrite	4
	Anhydrite and halite	7
	Colourless halite	2

4155 feet Anhydrite zone 4196 feet	Anhydrite with subordinate dolomite	41
	Dolomite and dolomitic marl (Upper Magnesian Limestone).	

It can be seen that the succession is simpler, in general, than that of the lower evaporite bed (Stewart, 1949, p. 625), which is believed to represent the products of several interrupted evaporation cycles. A later stage in the evaporation series, however, has been reached—the formation of potassium chlorides. The absence of a polyhalite zone is striking. The polyhalite zone of the lower evaporite bed, before the formation of secondary polyhalite, was perhaps similar in character to the halite-anhydrite zone of the middle evaporites, with its pseudomorphs after gypsum. The absence of kieserite is also noteworthy, and, indeed, the relative absence of magnesium-bearing minerals other than carbonates. Carnallite is present only in small quantity in the halite-sylvine and halite zones, but, of course, magnesium salts may be present in larger quantity in the large part of the halite-sylvine zone from which no core samples are available (3922–50 feet). Since no special brine was used in the drilling, the very poor core recovery in this range would indicate the presence of highly soluble minerals.

The distribution of potassium.

The following details were provided by Imperial Chemical Industries, and are published with their kind permission. Each 6-inch specimen was cut in half longitudinally, and the material for analysis scraped from the flat surfaces so obtained:

	Depth below surface in feet.	Total KCl percentage.	KCl percentage on water-soluble material.
I.	3910	0·28	0·36
	3912	0·21	0·28
	3914	0·28	0·34
	3916	0·21	0·22
II.	3918	34·0	36·0
	3920	10·1	11·8
	3950	3·28	3·40
	3952	4·85	5·01
	3954	0·71	0·72
	3956	4·20	4·32
	3958	3·94	4·00
	3960	3·66	3·79
	3962	1·89	1·98
	3964	1·44	1·47
III.	3970	0·63	0·64
	3972	1·96	1·99
	3974	0·41	0·42
	3976	0·46	0·47
	3978	0·38	0·40
	3980	0·60	0·61
	3982	0·70	0·70
	3984	0·70	0·70
	3986	1·28	1·34
	3988	0·40	0·41
	3990	0·41	0·42
	3992	0·41	0·42
	3994	0·40	0·41
	3996	0·41	0·42
	3998	0·30	0·31

	Depth below surface in feet.	Total KCl percentage.	KCl percentage on water-soluble material.
III.	4000	0·29	0·30
	4002	0·38	0·39
	4004	0·35	0·35
	4006	0·35	0·35
	4010	0·36	0·39
	4012	0·29	0·30
	4014	0·30	0·31
	4016	0·33	0·34
	4018	0·35	0·36
	4020	0·30	0·31
	4022	0·33	0·34
	4024	0·33	0·36
	4026	0·27	0·31
	4028	0·29	0·39
	4030	0·30	0·32
	4032	0·30	0·32
	4034	0·33	0·34
	4036	0·30	0·33
	4038	0·29	0·30
	4040	0·30	0·31
	4042	0·27	0·28
	4044	0·30	0·32
	4050	0·30	0·31
	4052	0·32	0·34
	4054	0·29	0·30
	4056	0·33	0·35
	4058	0·30	0·31
	4060	0·29	0·32
	4062	0·30	0·32
	4064	0·35	0·35
III.	4070	0·33	0·34
	4072	0·32	0·33
	4074	0·29	0·34
	4076	0·33	0·38
	4078	0·27	0·31
	4080	0·24	0·29
	4082	0·24	0·29
	4090	0·29	0·30
	4092	0·29	0·30
	4094	0·25	0·26
	4098	0·30	0·31
	4100	0·32	0·32
	4102	0·25	0·27
	4104	0·32	0·32
	4106	0·30	0·30
IV.	4108	0·10	0·18
	4118	0·03	0·08
	4120	0·06	0·12
	4122	0·05	0·11
	4124	0·06	0·11
	4126	0·21	0·23
	4128	0·22	0·23
	4130	0·03	0·12
	4132	0·25	0·25
	4134	0·17	0·17
	4138	0·19	0·20
	4140	0·10	0·16
	4142	0·14	0·15
	4144	0·14	0·14

I. Upper halite zone. II. Halite-sylvine zone. III. Halite zone. IV. Halite-anhydrite zone.

Three specimens from the salt clay between the middle and upper evaporite beds gave the following results:

Depth in feet.	Total KCl%.	KCl% in soluble material.
3870	0·28	1·31
3878	1·47	3·99
3898	1·28	5·95

These figures indicate the presence of potassium salts in these marls, but no samples of these were adequately preserved.

III. THE MINERALS.

Anhydrite is generally grey or white in colour. Normally it forms fine-grained aggregates of interlocking grains (0·001 to 0·2 mm.), often showing a tendency to express rectangular habit, and sometimes elongated. Other types are large bluish platy grains up to 2 cm. across, fan-like aggregates of fibrous crystals, and elongated or tabular crystals sometimes showing small dome and pyramid faces. Euhedral grains are very often developed when in contact with chlorides, when replacing dolomite, or when enclosed in clay. The optical properties are normal.

Boracite has been described by E. M. Guppy (1944) from well cuttings from the depth range 4090–4160 feet, with a chemical analysis by C. O. Harvey (see also Harvey, 1943). In the present investigation boracite has been found in small, but nearly constant, quantity in all samples of well cuttings from 3935–4160 feet. A few grains are also present in cuttings from the basal anhydrite zone. About three grams of the mineral have been isolated by hand-picking from the cuttings. It is a striking fact that no trace of the mineral has been found in the core samples, although a thorough search has been made.

The upper limit of a mineral's range can be determined fairly accurately by a study of well cuttings. However, if no special brine is used in the drilling, as was the case with this boring, there is likely to be considerable solution of the salts at the sides of the borehole as the drilling proceeds, and insoluble minerals will tend to be present in well cuttings from beneath the lower limit of their range. It will be noticed that the upper limit, 3935 feet, lies in the gap in the halite-sylvine zone from which no cores were recovered. It is therefore quite probable that the boracite occurs largely, if not entirely, somewhere within the range 3935–50 feet, in the halite-sylvine zone.

The boracite forms small isolated crystals and crystal groups, which are never attached to anhydrite or clay, and were presumably embedded in chlorides. The individual crystals are small (up to 1 mm.) and colourless, pale green, or red. They show pseudo-cubic forms resembling combinations of (100), (110), and (111). Only the very small crystals show nearly plane faces, the larger ones having irregular and curved faces sometimes made up of a large number of individuals in approximately parallel growth. Aggregates of crystals reach $\frac{1}{2}$ inch across. Determinations of optical properties on crushed grains agree with those given by Guppy: for sodium-light, α 1·658, β 1·662, γ 1·668, positive 2V 82°, within the limits of experimental error. The mineral shows complex twinning; often sector twinning with each sector polysynthetically twinned. Owing to overlapping of twin lamellae, only very thin fragments show extinction.

Carnallite occurs in small quantity from 3918 to 4022 feet. The mineral normally forms single grains, and more rarely aggregates of small irregular grains. It is normally light yellow in colour, occasionally black. The largest grain of fresh carnallite seen is 5 mm. in length. The mineral may be detected readily by cutting a flat dry surface on the specimen and observing the development of rings of moisture round the small carnallite grains, due to their rapid deliquescence. The small grains can then be gouged out and determined by optical methods. Under the microscope its very low refractive indices, bright interference colours, and lack of cleavage will distinguish it from any other mineral yet found in these rocks. Many grains show simple twinning or polysynthetic twinning like that of the plagioclase felspars. Crushed fragments deliquesce rapidly and dissolve with the precipitation of small cubes of sylvine. Refractive index measurements gave the values α 1·466, β 1·472, γ 1·496 (for sodium-light). The average of five measurements on the universal stage gave positive 2V 72°.

Dolomite is the carbonate of the lower part of this evaporite bed, giving place to magnesite in the middle of the halite zone. The two carbonates have not been found together. The dolomite normally forms minute rounded granules (0·001 to 0·01 mm.). In the anhydrite zone much larger rhombohedra are also present. Twelve refractive-index measurements show no significant variation from the value ω 1·682.

Gypsum has not been found in this evaporite bed, but layers containing anhydrite-halite pseudomorphs after early gypsum occur in the upper part of the halite-anhydrite zone, from 4106–36 feet.

Haematite inclusions are present in much of the sylvine, some of the halite and boracite, and occasionally in quartz. Haematite occurs from 4042 feet to the top of the evaporite bed. Usually the mineral forms very thin hexagonal plates up to 0·3 mm. in diameter, but occasionally the crystals are rod-like. Mr. E. A. Vincent has kindly confirmed the identification by means of X-ray powder photographs. The mineral gives a uniaxial negative interference figure, and is pleochroic with ω dark brown, ϵ red.

Halite is restricted to interstitial traces in the anhydrite zone, but is by far the most abundant mineral of the rest of this evaporite bed. It forms grains up to several inches in size, normally with irregular margins. It is granular and colourless in the lower part of the halite-anhydrite zone, becoming faintly brown in tinge towards the top of this zone. In the higher zones it is most commonly light brown, but varies from colourless to grey, pink, brick-red, and blood-red, the last variety being full of haematite inclusions. Liquid-filled cavities, often cubic, are common, and are frequently arranged in zones parallel to the cleavages. Strain birefringence has not been observed.

Magnesite occurs from about 4036 feet in the halite zone to the top of the bed. The mineral forms crystals up to 0·5 mm. in size, which are usually combinations of hexagonal prism and base, markedly tabular parallel to (0001). Sometimes rhombohedral faces are developed. Eight refractive-index measurements give ω 1·700–1·702, indicating almost pure magnesite. Chemical tests show the virtual absence of calcium.

Magnetite. Tiny opaque grains have been found in a slice from 4140–42 feet, arranged radially round the edges of small pyrite grains enclosed in halite. Study of crushed material shows that these opaque particles are highly magnetic, and they are therefore provisionally identified as magnetite.

Pyrite. Small quantities of this mineral have been found in three rocks. Irregular grains, up to 0·2 mm. in size, occur enclosed in halite and lying at the contact of halite with anhydrite, in a slice from 4140–42 feet. The pyrite grains are surrounded by tiny radiating particles of magnetite. A single euhedral grain, 3 mm. across, is enclosed in halite in a specimen from 3986–88 feet. Several irregular grains, up to 1 mm. in size, have been found in a halite-sylvine-carnallite-rock at 3920–22 feet, enclosed in halite, and at the contact of halite, sylvine, and clay.

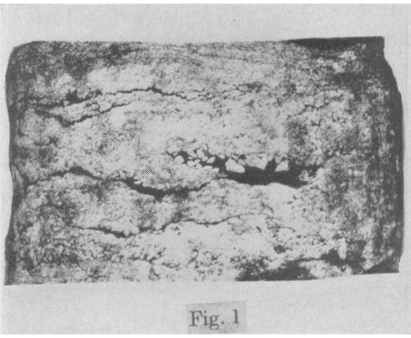
Quartz occurs from 4060 feet to the top of the evaporite bed, increasing in quantity towards the top. The mineral forms doubly-terminated prismatic crystals up to 2 mm. in length, showing the forms $(10\bar{1}0)$, $(10\bar{1}1)$, $(01\bar{1}1)$, $(11\bar{2}1)$, when enclosed in halite or sylvine.

Sylvine (recorded by Lees and Taitt, 1946) occurs in all specimens from the halite-sylvine zone, and in very small quantity in a few specimens near the top of the halite zone. The mineral forms irregular grains occasionally reaching 1½ inches in size. Where free from haematite, it has a translucent milky-white colour, which has not been observed in halite. Much of it, however, is red, due to a multitude of tiny haematite inclusions. The red sylvine can be easily confused with red halite in hand-specimen, but the astringent taste is distinctive. It is readily determined optically by its isotropic character, perfect cubic cleavages, and low refractive index (1·490). It has a much higher surface relief than halite in thin sections. Liquid-filled cavities are not so frequently present as in halite.

IV. ROCKS OF THE ANHYDRITE ZONE.

Samples from 4160 and 4176–78 feet, and a third specimen from the lower part of the zone (4176–94 feet; exact depth unknown) were preserved. Several other specimens of unknown depth, collected at the site of the boring, can be referred to this zone by comparison with the well cuttings.

The specimens and well cuttings show that subordinate dolomite is present throughout this zone, increasing in amount towards the base. The dolomite occurs as two distinct varieties: firstly, aggregates of minute rounded grains up to 0·01 mm. in diameter, coloured black in hand-specimen due to carbonaceous impurity; secondly, much larger clear euhedral rhombohedra, up to 1·5 mm. across, embedded in an anhydrite groundmass. A small quantity of interstitial halite is present in some cases.



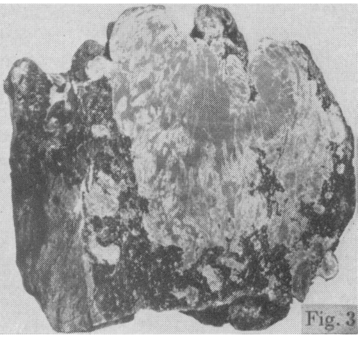


FIG. 1. Anhydrite-dolomite-rock, showing layers of black dolomite partly replaced by anhydrite. Anhydrite zone, 4176–94 feet. ×$\frac{1}{2}$.

FIG. 3. Anhydrite-dolomite-rock with some interstitial halite (white and grey), broken up and partially replaced by halite (black). Ground and chalked surface. Halite-anhydrite zone, 4140–42 feet. ×$\frac{1}{2}$. (Upper surface at right-hand side.)

In the specimen from 4176–94 feet (figs. 1, 2A), fine-grained dolomite (about 20 % of the rock) forms nearly horizontal layers up to 5 mm. thick, alternating with layers composed largely of an interlocking mass of elongated anhydrite grains up to 1 mm. in length. The layering is believed to represent original bedding. In detail, however, the dolomite layers are irregular and patchy, and in slice it is evident that the dolomite has been partly replaced by anhydrite. The layers are broken up by patches and thin veins of anhydrite, and anhydrite crystals have developed inside the dolomite areas. Where the original dolomite was rich in carbonaceous impurity, the replacing anhydrite contains a fine dust of this material, in marked contrast to the clear anhydrite of the anhydrite layers. A few clear dolomite rhombohedra, up to 0·3 mm.

across, are enclosed in the clear anhydrite, but not in the fine-grained dolomite layers.

The rock from 4160 feet (fig. 2B) shows numerous rhombohedral porphyroblasts of dolomite, up to 1·5 mm. across, conspicuous in the hand-specimen. They are embedded in fine-grained anhydrite and enclose small anhydrite grains. There is relatively little residual fine-grained dolomite, broken up into irregular patches full of elongated laths of anhydrite

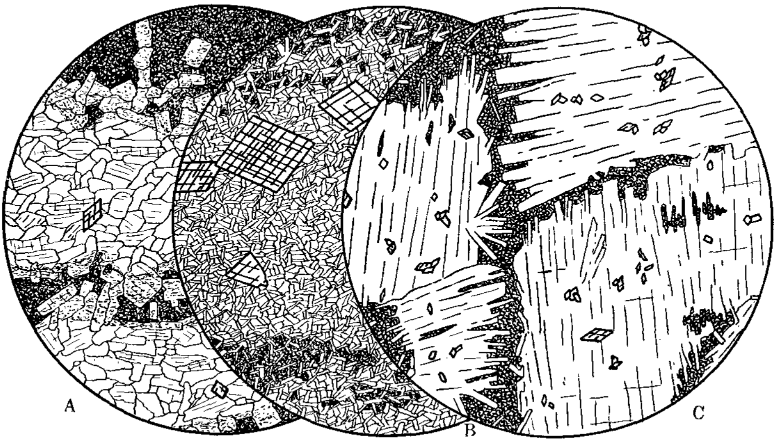


FIG. 2. Anhydrite-dolomite-rocks from the anhydrite zone. × 12.

A. Layers of fine-grained dolomite are partly replaced by anhydrite, the secondary anhydrite containing a dust of carbonaceous impurities. Larger euhedral dolomite grains are also present. 4176–94 feet.

B. Fine-grained dolomite is broken up by anhydrite, and dolomite porphyroblasts are enclosed in an anhydrite matrix. 4160 feet.

C. Coarse anhydrite replaces fine-grained dolomite and encloses euhedral dolomite. 4176–78 feet.

The rock from 4176–78 feet (fig. 2C) resembles the anhydrite-dolomite-rocks with coarse fibro-radiate anhydrite found near the base of the lower evaporite bed. The anhydrite forms large platy grains, with ragged edges, up to 2 cm. across, of slightly bluish tinge. In slice it can be seen that these grains consist of aggregates of fibrous crystals in approximately parallel growth. Many of the plates are broken down, or partially broken down, to masses of small irregular grains. There is about 20 % of dolomite. Between the large anhydrite masses are residual patches of fine-grained dolomite, and from the edges of the anhydrite masses fibrous and lathshaped anhydrite crystals push into the dolomite areas and break them up to form interstitial patches. Independent euhedral anhydrite laths develop inside the dolomite patches. Enclosed in the anhydrite, but not in the residual dolomite, are abundant euhedral dolomite rhombohedra up to 0·1 mm. across.

Some of the specimens of unknown depth are of this general type, showing coarse anhydrite, sometimes in radiate bunches, replacing fine-grained dolomite, with or without the development of euhedral dolomite porphyroblasts. Other specimens contain euhedral dolomite without any of the fine-grained variety, and some of these consist largely of platy anhydrite with rough horizontal platy parallelism.

The apparent bedding of the fine-grained dolomite and anhydrite would indicate that this type of dolomite is a primary precipitate. It seems probable that dolomite and anhydrite formed alternating primary layers, the dolomite being then partially replaced by anhydrite. The larger euhedral dolomite rhombohedra could be due to recrystallization of excess $CaMg(CO_3)_2$ attendant on the replacement (like the anhydrite porphyroblasts found in the polyhalite-bearing rocks of the lower evaporite bed; Stewart, 1949, p. 656).

An alternative view would be that the euhedral dolomite is due to recrystallization of the fine-grained dolomite without replacement. However, in the rock from 4176–94 feet some of the replacing anhydrite is dusted with impurities from the pre-existing dolomite, so that it is possible to make an approximate estimate of the minimum amount of dolomite replaced, and it is found that there is not nearly sufficient euhedral dolomite to account for recrystallization of replaced dolomite. Some dolomite must have been removed.

Whether the replacement was contemporaneous or later is a question which must be left open. It is possible that as each succeeding layer of anhydrite was deposited, the dolomite layer below was in part contemporaneously replaced by anhydrite, and some dolomite taken into solution. In the specimen from 4176–94 feet, more replacement seems to have taken place on one surface of each layer than on the other. If these surfaces are the upper surfaces of the succession, this would indicate contemporaneous replacement, but the evidence from this one 6-inch specimen is not sufficient to justify a definite conclusion.

V. Rocks of the halite-anhydrite zone.

This zone consists of a layered series of bedded anhydrite-dolomite-rocks; halite-rich rocks with subordinate anhydrite; halite-anhydrite-dolomite-rocks with structures indicating movement of halite and replacement of anhydrite and dolomite by halite; and rocks with halite-anhydrite pseudomorphs after gypsum. Apart from the three main minerals, halite, anhydrite, and dolomite, there is only a very small quantity of pyrite and magnetite in some specimens, and a trace of detrital impurity. Fifteen specimens give an average of 0·14 % KCl.

(1) *Anhydrite-dolomite-rocks.*

Layers of compact anhydrite-dolomite-rock, up to a few inches thick, alternate with layers containing much halite. The anhydrite-dolomite-rocks generally show bedding structures due to alternation of layers rich and poor in dolomite. Most of these rocks are fine-grained. The anhydrite forms an interlocking mass of irregular grains (0·001 to 0·1 mm.), sometimes elongated. Tiny granules of dolomite (up to 0·01 mm.) are enclosed in anhydrite or lie between anhydrite grains, some layers containing up to 70 % of the mineral. In most cases, however, dolomite is subordinate in amount. A little interstitial halite is sometimes present, and there is dark dusty impurity in the dolomite-rich layers.

It is likely that the anhydrite and dolomite of these layers are primary precipitates, though some recrystallization of anhydrite may have taken place. In most slices there is no evidence of replacement of dolomite by anhydrite. In a few cases euhedral anhydrite crystals have developed in dolomite-rich areas and broken them up. There has been some replacement of anhydrite and dolomite by halite (pl. X, fig. 16).

(2) *Halite-rich rocks.*

Many layers consist largely of halite, without evidence of early gypsum. In the lower part of the zone, the halite is colourless and forms a granular mass of interlocking grains, up to 1 cm. across. In several specimens of this type the halite grains are flattened and show definite rough platy parallelism, imparting a rude horizontal schistose structure to the rock. There is also in some cases a trace of linear parallelism, the grains tending to lie with their longest dimensions in parallel orientation. This would imply recrystallization under pressure, or movement under the load of the overlying rocks. These structures are not found in the upper part of the zone, where halite of a brownish tinge is often coarsely crystalline, the grains reaching 3 inches in width.

Slices show that some anhydrite is nearly always present, usually as stumpy rectangular euhedral grains, often concentrated along intergranular boundaries of the halite.

(3) *Deformation and replacement of anhydrite-dolomite-rocks by halite.*

The halite-rich rocks of the lower part of the zone frequently enclose contorted and squeezed-out layers of anhydrite-dolomite-rock, and there are all gradations from halite-rich rock to anhydrite-dolomite-rock. Thin anhydrite-dolomite layers are often folded and crenulated, and those enclosed in schistose granular halite are sometimes broken up into elongated patches and lenticles arranged parallel to the schistosity of the halite. Slices show that the bedding structures in the anhydrite-dolomite relics have been deformed so that they are parallel to the edges of the lenticles (fig. 4A), and the anhydrite of the thinner layers has developed a platy parallelism of the grains. The anhydrite tends to become coarser and euhedral when in contact with halite, indicating late recrystallization.

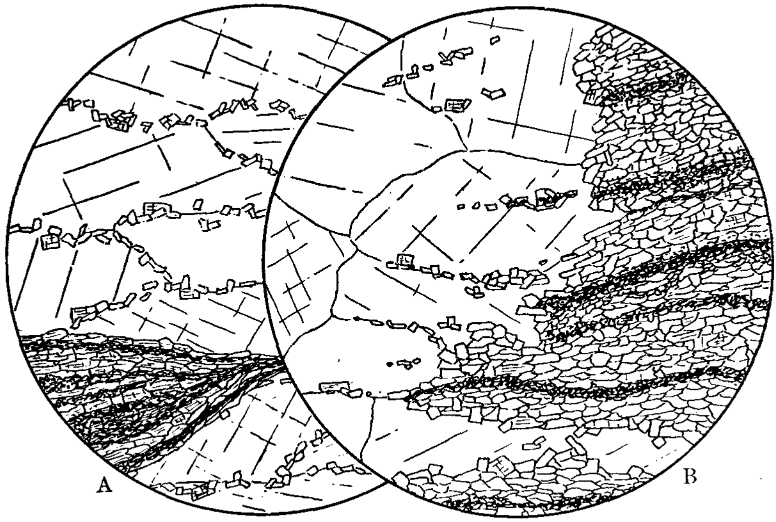


FIG. 4. A. Halite-anhydrite-rock with deformed lenticle of anhydrite-dolomite-rock. The halite grains are markedly flattened. Halite-anhydrite zone, 4142–44 feet. × 14.

B. Anhydrite-dolomite-rock partially replaced by halite, showing recrystallized anhydrite relics. Halite-anhydrite zone, 4140–42 feet. × 14.

The invasion of anhydrite-dolomite-rock by halite is not only mechanical (figs. 3, 4B). Some layers of anhydrite-dolomite-rock come to an abrupt end, cut off by granular halite. The bedding structures are cut off sharply, and not curved round parallel to the edges of the layers.

Sometimes thin relict streaks of anhydrite grains continue from the anhydrite-dolomite layers into the adjacent halite, parallel to the original bedding. Thin veinlets of halite penetrate the anhydrite-dolomite-rock, chiefly following the bedding, but sometimes cutting across it. It appears that halite has replaced both anhydrite and dolomite.

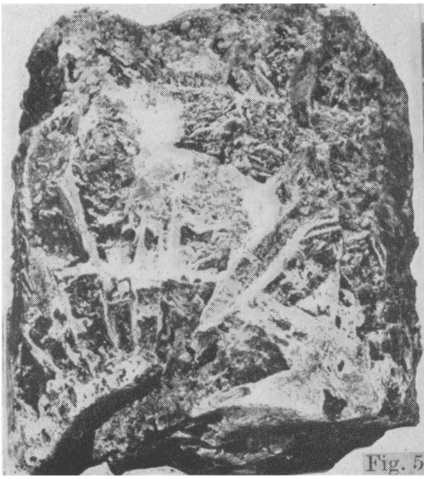
Some of the rocks showing replacement have suffered subsequent deformation, the halite developing a platy or linear parallelism and the bedding of the anhydrite-dolomite-rock becoming distorted. This does not date the replacement as it is possible that deformation under cover may have taken place at various times, either simultaneously with, or both before and after replacement. In one specimen from the upper part of the zone, containing anhydrite-halite pseudomorphs after gypsum, a vein of granular halite, similar in type to that of the rocks described here, cuts through the coarse secondary halite of the pseudomorphs and the anhydrite-dolomite matrix. This indicates that the replacements involving granular halite are later than the development of secondary halite in the rocks with gypsum pseudomorphs.

The relative restriction of evidence of movement of halite to the lower part of this zone is striking. Perhaps the basal anhydrite zone provided a solid and unyielding block against which the halite gave way to pressure by flow, while the upper zones were able to adjust themselves by recrystallization without significant flow.

(4) *Rocks containing pseudomorphs after gypsum.*

Layers containing anhydrite-halite pseudomorphs, which are believed to represent early gypsum crystals, are found in the upper 30 feet of this zone. These layers vary from about an inch to five inches in thickness, and alternate with layers of anhydrite-dolomite-rock and halite-rich rock.

The pseudomorphs are similar in shape to those of the polyhalite zone of the lower evaporite bed, and are very like those described by Schaller and Henderson (1932) from the Texas–New Mexico potash-field. They range from less than an inch to 3½ inches in length, and in some cases reach ¾ inch in width. In most cases they are arranged in an approximately vertical position in the core, although in one specimen pseudomorphs up to 3 inches in length form a radiating fan-shaped group (pl. X, fig. 13). They are irregularly six-sided in cross-section (pl. X, fig. 15) and often show terminations like those of swallow-tail twins of gypsum (fig. 5). A few of these pseudomorphs consist entirely of anhydrite; some have a centre of halite and an outer zone of anhydrite; but most show a well-marked herring-bone structure, consisting of alternate ribs of anhydrite and halite arranged parallel to the swallow-tail twin terminal faces, often with a central vertical partition of anhydrite along the composition-plane of the twin. The relative amounts of halite and anhydrite vary considerably in different pseudomorphs and in different parts of the same pseudomorph, and in many cases the anhydrite ribs are very thin, or broken and discontinuous (pl. X, fig. 14).



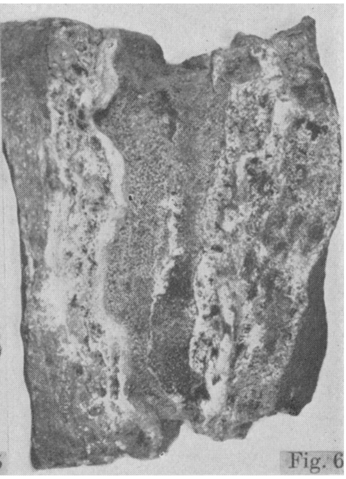


FIG. 5. Halite-anhydrite-rock with pseudomorphs after swallow-tail twins of gypsum. The surface of the core has been etched by the drilling water, the halite (dark) being partially dissolved. Halite-anhydrite zone, 4108–10 feet. $\times \frac{1}{2}$.

FIG. 6. Alternating crumpled layers of halite-anhydrite-rock and anhydrite-dolomite-rock. Etched surface of core. Halite zone, 4096–98 feet. $\times \frac{1}{2}$. (Upper surface at right-hand side.)

In most cases the interstices between the pseudomorphs consist of anhydrite-dolomite-rock, which occasionally shows irregular bedding structure upturned at the edges of the pseudomorphs. It is believed that in such rocks the gypsum crystals grew at the expense of anhydrite, in anhydrite-dolomite-rock, when the latter was in a mushy state, the replacement being an early one (see Schaller and Henderson, 1932, p. 34; Stewart, 1949, p. 653). It is possible that the ribs of anhydrite (which contain some dolomite) in the herring-bone structures represent relics of the original anhydrite-dolomite-rock. Dunham (1948, p. 225, and plate X, fig. 1) has described peculiar zoned porphyroblasts of gypsum containing zones of anhydrite relics in anhydrite-dolomite-rock from the outer part of this salt-field.

The gypsum has been subsequently converted to halite. In slice, it can be seen that this halite encloses euhedral anhydrite crystals, and that while the interiors of the anhydrite ribs consist of fine-grained aggregates of irregular grains, the edges consist of elongated euhedral crystals, up to 0·5 mm. long, projecting into the adjacent halite. It seems likely that recrystallization of anhydrite has accompanied the appearance of secondary halite. The recrystallized anhydrite has cleared itself of impurity, and dolomite and other impurities are concentrated in the centres of the anhydrite ribs (pl. X, fig. 14). Several adjacent pseudomorphs often contain coarsely crystalline halite in common orientation. This feature was noted by Schaller and Henderson (1932, p. 34), and interpreted as indicating that the pseudomorphs may be infiltration pseudomorphs, the gypsum being dissolved, leaving cavities which were later filled with halite. However, they also found evidence indicating a more intimate type of replacement.

In the rocks described above, we have the replacement sequence: anhydrite→gypsum→halite. In other layers, however, the interstices between the pseudomorphs consist of halite, and some of the pseudomorphs consist of anhydrite, others of halite with an outer zone of anhydrite. In these cases it appears likely that the gypsum was a primary mineral, the replacements being: gypsum→anhydrite and gypsum→anhydrite + halite.

The pseudomorphous layers show relatively little evidence of later distortion. Some of the pseudomorphs have been deformed, but there appears to have been little movement in the upper part of the zone.

(5) *General considerations on zones containing evidence of early gypsum.*

The upper part of the halite-anhydrite zone appears to be similar to part of the polyhalite zone of the lower evaporite bed, except that the former contains no polyhalite. A similar zone has been found in the upper evaporite bed. In all three beds, these zones lie in similar positions, above the basal anhydrite and below the chloride-rich zones.

We do not know which were the upper, and which the lower, surfaces of the specimens from the Eskdale boring, so that we cannot give the detailed order of succession of the layers. However, in the Texas–New Mexico potash-field Schaller and Henderson (1932, p. 36) show that in the typical succession a basal layer of clay is succeeded upwards by anhydrite, which is followed by anhydrite with halite pseudomorphs after gypsum, and then by halite. Polyhalite may or may not be present. Evidence of primary gypsum was not found, but it was considered that the gypsum had formed at an early stage in unconsolidated anhydrite mud. The restriction of gypsum to the upper parts of the basal anhydrite layers led the authors to suggest that the gypsum may have been derived from earlier polyhalite.

The presence of these zones of early gypsum in similar positions in all three evaporite beds at Eskdale, and of similar rocks in the Texas–New Mexico deposits, suggests that a zone containing early gypsum may prove to be a normal stage in the formation of many marine evaporites; a stage at which slight rhythmic changes in conditions may cause alternate production of anhydrite-dolomite and halite-gypsum associations.

The following tentative suggestions indicate how the observed rocks may have formed. Take the ideal depositional succession to be: halite—halite-gypsum—anhydrite-carbonate. After precipitation of a basal layer of anhydrite-carbonate-rock (underlain by clay in the Texas–New Mexico case) the changing composition of the brines or some other factor caused halite-gypsum-rock to be deposited. At the same time the anhydrite already formed became unstable in the gypsum-depositing brines, and gypsum crystals grew at the expense of this anhydrite in the unconsolidated upper part of the basal anhydrite-carbonate layer. As the overlying brine changed further in composition, it ceased to deposit gypsum, and formed a layer of halite. The gypsum of the earlier layers, in turn, became unstable and was replaced by halite and anhydrite. A reversal of conditions would cause deposition of anhydrite and carbonate again and a repetition of the sequence. By periodic changes in conditions, a rhythmically layered series of units showing the following sequence would be built up: halite-rock—halite-rock with halite-anhydrite pseudomorphs after gypsum—anhydrite-carbonate-rock with halite-anhydrite pseudomorphs after gypsum—anhydrite-carbonate-rock.

The absence of any particular layer could be explained by postulating re-solution by the overlying brines. The restriction of secondary gypsum to the upper part of the basal anhydrite in the Texas–New Mexico succession could be explained by assuming that the brines responsible for its development percolated from above, and only reached a certain distance into this anhydrite layer. There would be no need to derive the secondary gypsum from earlier polyhalite.

Once again the observed succession does not agree with that expected on experimental grounds. Posnjak (1938, 1940) has shown that gypsum would be expected to form before anhydrite on evaporation of sea-water. We should therefore expect a basal layer of gypsum-carbonate-rock, and anhydrite, if present, should occur above this and in the halite-bearing rocks. There is, however, no evidence that the anhydrite of the bedded anhydrite-carbonate-rocks has been derived from gypsum.

VI. ROCKS OF THE HALITE ZONE.

The lower limit of this thick zone has been fixed at the level where coarse brown halite, with only subordinate anhydrite-carbonate layers, appears, above the highest specimen containing pseudomorphs after gypsum (4108–10). The upper limit is where sylvine first occurs in significant amount. In 59 specimens the average KCl content is 0·39 %. The minerals of the zone are halite, anhydrite, dolomite, magnesite, carnallite, sylvine, quartz, haematite, and pyrite. Greenish clay forms patches in the upper part of the zone.

In the lower part of the zone thin anhydrite-dolomite layers alternate with layers consisting largely of halite. The anhydrite-dolomite layers are similar to those of the zone below, the dolomite forming the usual minute granules. They are frequently contorted and occasionally faulted (figs. 6, 7). The halite-rich layers contain some euhedral anhydrite, but are largely composed of irregular grains of brown, pink, or colourless halite, often varying in size from a few millimetres to several inches in the same specimen. In other specimens the halite is even-grained.

The anhydrite-dolomite layers of the lower part of the zone become much scarcer upwards. They also become more highly contorted, and broken up, and are eventually represented by isolated interstitial patches between halite grains. Throughout the upper part of the zone halite forms over 80 % of the rocks, and the other minerals (except the chlorides), with detrital impurities, are largely confined to these interstitial patches. The halite tends to develop crystal boundaries against these aggregates, although the individual grains of the other minerals are euhedral towards halite. It would appear that recrystallization of halite has pushed the impurities into the interstices (figs. 8, 9A, 10A).

The upper part of the zone is mineralogically more complex than the lower. Halite becomes very coarse in places. Anhydrite varies from aggregates of irregular grains to spherulitic groups of elongated crystals, and platy crystals. Magnesite is the carbonate (dolomite being absent), and has been detected in most slices above 4036 feet. It is normally present in very small quantity, but larger amounts are associated with anhydritic clay towards the top of the zone. It is mainly found in the interstitial areas, but some isolated crystals and crystal groups are enclosed in halite. It forms small tabular crystals or rhombohedra, up to 0·2 mm. diameter, and is euhedral towards all the other minerals. Quartz has been found in most slices above 4060 feet, and is present only in small quantity in the lower part of its range, but forms about 1 % of some slices in the upper part. It forms excellent doubly terminated crystals up to 0·5 mm. in length, when enclosed in halite. It is especially concentrated in, and at the edges of, interstitial areas, where crystals moulded on anhydrite and magnesite, towards which it is anhedral, project into halite (figs. 9B, 10A). This suggests late crystallization. Some of the silica may have been derived by solution of the detrital material with which it is so often associated.

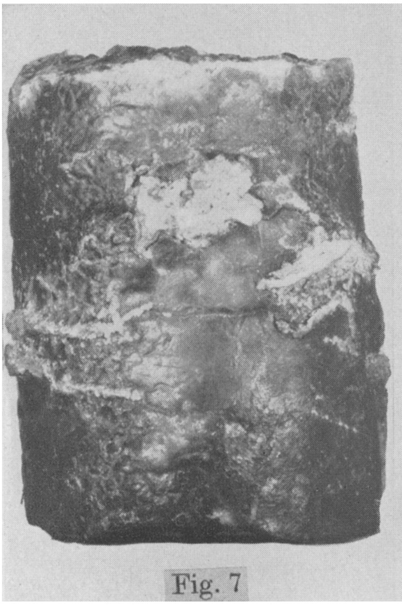


Fig. 7

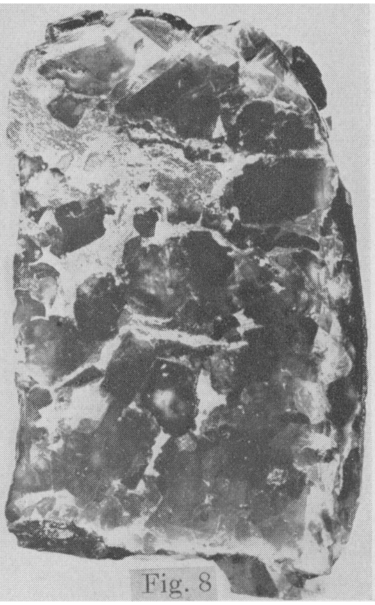


Fig. 8

FIG. 7. Anhydrite layers faulted and contorted due to recrystallization of adjacent halite. Etched surface of core. Halite zone, 4094–96 feet. $\times \frac{1}{2}$.

FIG. 8. Coarse halite with interstitial patches of anhydrite and clay. Polished surface. Halite zone, 4034–36 feet. $\times \frac{2}{3}$.

Carnallite is present in most specimens from 4022 feet upwards, in very small quantity, as small rounded or irregular grains or aggregates enclosed in halite. It has not been found in contact with any other mineral. Sylvine has been observed in a few specimens near the top of the zone, where it forms grains up to about 5 mm. across, showing irregular boundaries against halite.

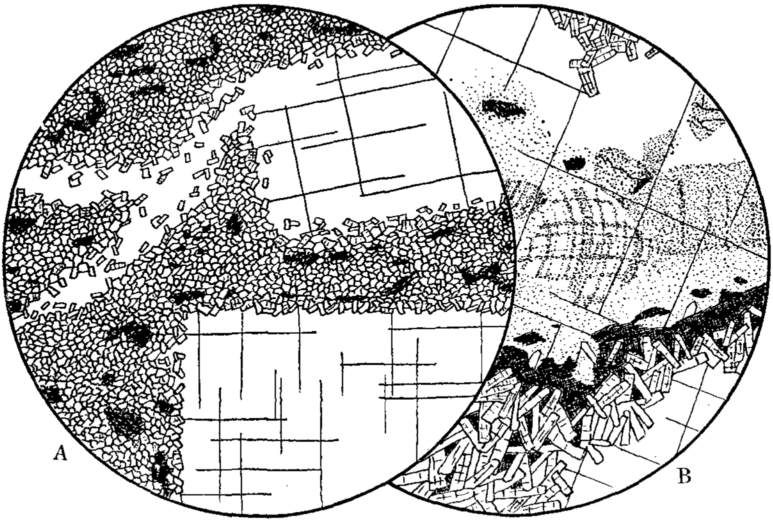


FIG. 9. Rocks from the halite zone. × 14.

A. Halite-anhydrite-rock with carbonaceous impurities. The halite shows crystal boundaries against anhydrite aggregates, although individual anhydrite crystals are euhedral towards halite. Veinlets of halite traverse the anhydrite area. 4078–80 feet.

B. Halite-anhydrite-rock with dark clay, and a dust of haematite inclusions in parts of the halite. A few euhedral quartz crystals project from the clay into halite. The arrangement of haematite inclusions suggests either that the large halite grain has formed by recrystallization of a number of smaller grains, or that halite has replaced smaller grains of some other mineral. 3978–80 feet.

The sylvine tends to have red margins, due to haematite inclusions, but most of the haematite of this zone is enclosed in halite, colouring it blood-red (fig. 9B). The haematite forms very thin hexagonal plates and rods, usually extremely small, but occasionally reaching 0·1 mm. across. At 4042 feet, small patches of blood-red halite, crowded with countless inclusions, make an appearance, and these get more numerous towards the top of the zone, reaching about a centimetre in size. The inclusions are sometimes arranged in zones parallel to the halite cleavages, but this zoning is commonly distorted, and all stages are found between cubic zoning and irregular wavy bands of haematite. The mineral is often concentrated round interstitial patches of greenish-grey clay, and is enclosed in any halite present within these patches. Perhaps iron oxide has been leached out of the clay and precipitated as haematite with the neighbouring halite (Schaller and Henderson, 1932, p. 24). On the other hand, clay is not always present in the haematite-rich patches. Some of the quartz enclosed in red halite encloses haematite, zoned parallel to its crystal faces.

Recrystallization and replacement.

The above details show that there has been large-scale recrystallization of halite in this zone. The evidence includes contortion and faulting of anhydrite-carbonate layers in the lower part of the zone; breaking up of the layers to form interstitial patches, often showing streaking out of impurities, between halite grains throughout the upper part of the zone; ejection of detrital material with magnesite, &c., from halite into the interstices; distortion and disruption of the zoning of haematite inclusions. It is believed that recrystallization of halite has taken place throughout the zone. None of the halite shows linear or platy parallelism of the grains.

The faulting of anhydrite layers shows that recrystallization took place when the anhydrite was sufficiently solid to yield by fracture. That recrystallization took place at various times is shown by the occurrence of aggregates of clay, anhydrite, and other minerals, having the angular shape of interstitial patches, completely enclosed in large grains of halite formed by later recrystallization (fig. 10B). A similar thing is seen in the case of haematite inclusions, where the later light-coloured halite has failed to re-orientate the inclusions in the earlier angular red patches enclosed in it.

Some recrystallization of anhydrite has taken place, giving rise to euhedral crystals cutting a finer-grained anhydrite matrix, and euhedral crystals projecting into halite from the edges of anhydrite layers and patches. In one slice (pl. X, fig. 17) interstitial aggregates of small elongated anhydrite grains show a honeycomb network of detrital impurities, suggesting simultaneous recrystallization of anhydrite from a number of centres, the impurities being pushed out and concentrated between the areas of recrystallization.

Some replacement of anhydrite by halite is indicated by irregular veinlets of halite cutting anhydrite areas. In a few cases anhydrite grains have been found to be broken up into several pieces, with common optical orientation, by invading halite.

The haematite of other salt deposits tends to be concentrated particularly in the magnesium and potassium minerals, and in the Eskdale evaporites it is found in sylvine and boracite, as well as in halite. It is perhaps possible that the haematite of this halite zone has been derived from some pre-existing magnesium- or potassium-bearing salt which has been replaced by halite (fig. 9B is suggestive). No residual patches of such a mineral have been found in the halite zone, but the widespread recrystallization of halite would tend to destroy most of the evidence of early replacements in this zone.

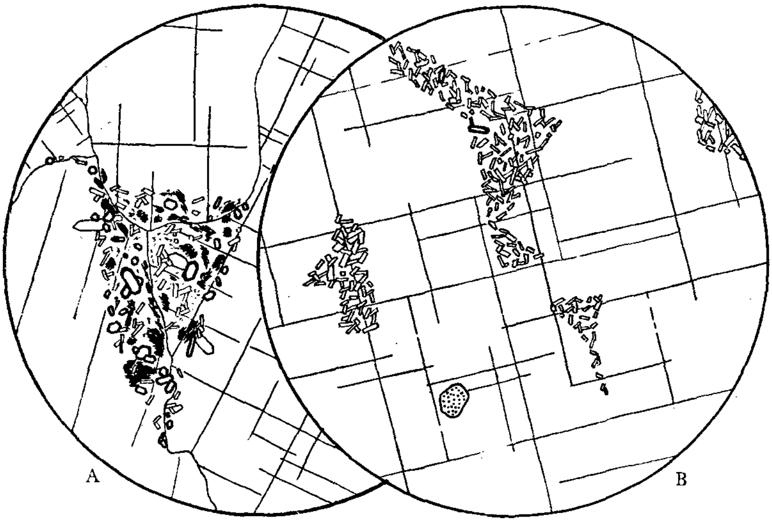


FIG. 10. Rocks from the halite zone. ×14.

A. Halite-anhydrite-magnesite-quartz-rock, showing large grains of halite, and an angular patch containing small elongated rectangular anhydrite crystals, magnesite plates (heavy boundaries), a few quartz crystals, and some detrital material. 3992–94 feet.

B. Halite-anhydrite-carnallite-rock with scarce magnesite. A carnallite grain (stippled) is enclosed in halite. The anhydrite is aggregated in angular patches enclosed in a large halite grain, indicating recrystallization of halite. 4016–18 feet.

VII. ROCKS OF THE HALITE-SYLVINE ZONE.

Ten samples from this zone are available. There are two sylvine-rich samples from near the top of the zone (3918–20 feet, 34 % KCl; 3920–22 feet, 10·1 % KCl). Below this level there is a gap of 28 feet from which there are no available specimens. This is followed by 14 feet represented by eight specimens with an average KCl content of 3 % (maximum 4·85 % KCl, minimum 0·71 % KCl). The poor core recovery may well be due to the presence of highly soluble potassium and magnesium chlorides, leading to solution and disintegration of the core. The well cuttings give no information on the soluble minerals, so that we do not know what lies between 3922 and 3950 feet. They show, however, that boracite (not found in the core samples) appears at 3935 feet.

Most of these rocks show no layered structure, and consist largely of a coarse-grained mixture of halite and sylvine, showing evidence of widespread recrystallization. In such rocks the small amount of greenish-grey clay present is concentrated in interstitial patches, together with the accessory minerals other than carnallite and haematite. There are, however, some layers rich in clay, and there the chlorides tend to occur in smaller grains, about $\frac{1}{4}$ inch or less, with a tendency to aggregate in lenticular patches, elongated horizontally. This imparts a rough lamination to the rock.

The minerals of this zone are halite, sylvine, carnallite, anhydrite, magnesite, quartz, haematite, and pyrite. All these minerals may occur in the same rock. Apart from clay, halite and sylvine form over 90 % of all the specimens. Sylvine is most abundant in the uppermost specimen (3918–20 feet), where a three-inch layer consists of halite and sylvine in nearly equal proportions, with about 1 % of carnallite and only traces of magnesite and anhydrite.

The halite varies from colourless to reddish-brown, and the grains sometimes reach 2 inches in size. The sylvine is either translucent milky-white, or bright-red due to haematite inclusions. One grain of sylvine reaches $1\frac{1}{2}$ inches in size (3958–60 feet), but most are much smaller. Commonly the sylvine encloses tiny rounded inclusions of halite. The two minerals normally show interlocking irregular boundaries. In one slice of the specimen from 3918–20 feet they are intergrown in common orientation, the cleavages passing continuously through both minerals (fig. 11A). It is interesting that in this case the sylvine contains haematite, but the halite is clear. In several slices and hand-specimens a replacement relationship is seen, where sylvine grains have been broken up into residual patches with common orientation (fig. 12A). Colourless halite often replaces sylvine with haematite inclusions, showing that the solutions responsible for the replacement were capable of removing haematite as well as sylvine (fig. 12C). More rarely the haematite inclusions persist in the secondary halite, occasionally in sharp-edged areas marking the boundaries of the original sylvine grains (fig. 12B).

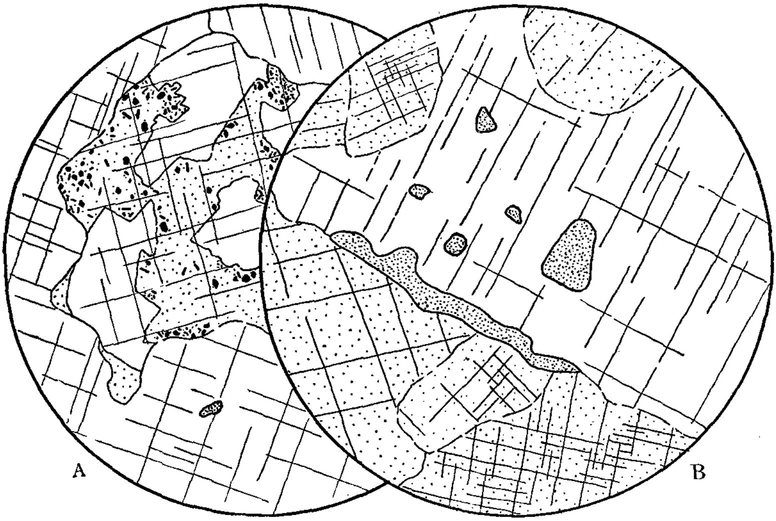


FIG. 11. Halite-sylvine-carnallite-rocks from the halite-sylvine zone. 3918–20 feet.

A. Sylvine (lightly stippled) is intergrown with halite in common orientation, the sylvine containing plates and rods of haematite, while the halite is clear of inclusions. A small grain of carnallite (heavily stippled) is enclosed in halite. ×14.

B. A large carnallite grain lies between halite and sylvine, and several smaller carnallite grains are enclosed in halite. The shape of the carnallite grains suggests corrosion, but there is no definite evidence of replacement since the grains have different optical orientations. ×7.

Late veinlets and patches of halite in these rocks are normally colourless. Halite and sylvine may enclose any of the other minerals, showing irregular boundaries towards carnallite and pyrite, and being anhedral towards anhydrite, magnesite, and quartz.

Carnallite occurs only in small quantity (1 % or less), but is present in all specimens. Small single grains of the mineral, with irregular or rounded margins, are enclosed in halite, and more rarely sylvine, or lie between halite and sylvine grains (fig. 11). No definite evidence of a replacement relationship between carnallite and the chlorides has been observed, and the mineral has not been found in contact with anhydrite, magnesite, or quartz.

Anhydrite is very scarce in the upper two rocks, only a few rectangular crystals being found. In the lower part of the zone it is more plentiful, but not abundant. In the lowest rocks, interstitial aggregates of small grains, like those of the halite zone, are found, but these give place higher up to radiating fan-like groups of elongated crystals up to 0·5 mm. in length. Sometimes these groups are aggregated together in shapes suggesting that they have been derived by recrystallization of interstitial patches. There is some evidence of replacement of anhydrite by halite, crystals of anhydrite being broken up into residual corroded relics (fig. 12A).

Magnesite is fairly abundant in the layers rich in clay (e.g. 3920–22 feet), but only a few small grains are found elsewhere. It forms thin hexagonal plates, tabular parallel to (0001), like the magnesite of the lower evaporite bed. These plates are rod-like in cross-section, and occasionally reach 0·5 mm. in diameter. Magnesite is euhedral towards all other minerals.

Quartz is especially associated with clay, and is abundant in layers rich in clay (fig. 12). It forms well-shaped crystals in contact with halite and sylvine, and is anhedral towards anhydrite and magnesite. Its special association with clay would suggest that the silica has been at least partly derived by leaching of the clay.

The distribution of haematite and the origin of sylvine.

Plates and rods of haematite, generally minute, but occasionally reaching 0·3 mm. in size, are found in most of the sylvine, and very little of the associated halite. The inclusions are usually unorientated, but are occasionally arranged in zones, often distorted, inclined to the cleavages of their host. Some small sylvine grains are crowded with minute inclusions, uniformly distributed, but most often the inclusions are concentrated near the borders of the grains, the centres being clear, and in these cases the inclusions are usually larger and fewer in number. Sometimes they are concentrated near the centres as well as at the edges of sylvine grains (pl. X, fig. 19), and they are frequently concentrated round foreign inclusions such as quartz, magnesite, and anhydrite grains (fig. 12C). They are not, however, enclosed in these minerals, except rarely in quartz. Occasionally a sylvine grain, with an outer zone of relatively large haematite flakes, contains a sharply bounded central area crowded with minute haematite inclusions arranged in criss-cross sets of zones inclined to the cleavages (fig. 12c and pl. X, fig. 18). This suggests either that there are two generations of sylvine, or that the central area of sylvine has been derived from some other mineral. There is sometimes a tendency for haematite to be concentrated in interstitial areas like those of the halite zone, but this is not marked. Sylvine and halite tend to be more deeply coloured in rocks rich in clay than in other rocks, but even in layers containing practically no clay the sylvine normally contains some haematite.

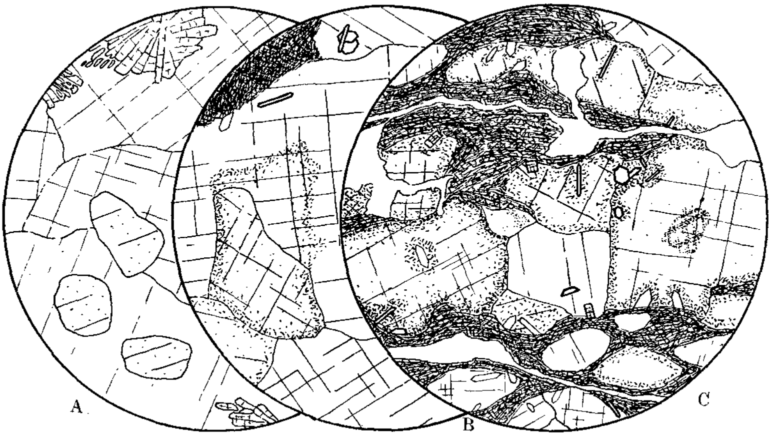


FIG. 12. Rocks from the halite-sylvine zone. × 12.

A. Halite-sylvine-anhydrite-rock, showing three corroded relics of sylvine (stippled) in halite, and replacement of anhydrite (top left) by halite. 3962–64 feet.

B. Halite-sylvine-rock with magnesite, quartz, and clay, showing replacement of sylvine by halite. A zone of haematite inclusions marks the original boundary of the sylvine grain. 3918–20 feet.

C. Halite-sylvine-rock, with magnesite, quartz, anhydrite, haematite, and a considerable amount of interstitial clay. The edges of sylvine grains are crowded with haematite inclusions, which are also concentrated round foreign crystals included in sylvine. To the right is a sylvine grain with haematite-rich edges and a sharply bounded central area rich in zoned haematite inclusions, the zones being inclined to the sylvine cleavages. This suggests replacement of some pre-existing mineral by sylvine. Halite is practically free from haematite, and late veinlets and areas of halite have replaced sylvine and removed haematite. Magnesite plates (thick boundaries) and quartz (thin boundaries) are fairly abundant, and a few rectangular crystals of anhydrite are present. 3920–22 feet.

In the Texas–New Mexico field haematite is stated to be largely confined to the potassium-bearing minerals (Schaller and Henderson, 1932; Mansfield, 1930; Phillips, 1947), being present in polyhalite, carnallite, leonite, langbeinite, and sylvine. It is also present in glauberite and to a very small degree in halite. Schaller and Henderson suggest that it may have a bacteriological origin, and also suggest that there are two generations of sylvine, the red variety replacing the colourless along intergranular boundaries, cracks, and cleavages. They never found the red variety surrounded by the colourless.

Johnsen (1909) ascribes orientated haematite inclusions in the Stassfurt carnallite to the oxidation of carnallite which contained some $FeCl_2$ as an isomorphous replacement of $MgCl_2$. Leonhardt and Tiemeyer (1938) record sylvine from Wathlingen, Hanover, in which the (0001) faces of haematite lie on the (100), $(\bar{1}11)$, and (110) planes of sylvine. They conclude that the preferred orientation of the haematite shows that the mineral crystallized simultaneously with sylvine, and that therefore the sylvine and haematite were not derived from earlier carnallite.

In the Eskdale evaporites the concentration of haematite at both centres and margins of sylvine grains, and round foreign inclusions, would suggest recrystallization of sylvine with partial ejection of haematite, and not replacement of colourless by red sylvine. Secondary clear halite has replaced sylvine, but it is most unlikely that all the clear halite of this zone is secondary, and if sylvine is a primary mineral it must almost certainly have been deposited together with halite. In this case there would appear to be no reason why haematite should not be present in both minerals, unless the iron preferred to go into solid solution only in sylvine, and later separated as haematite. However, it seems unlikely that any appreciable amount of iron could be contained in solid solution in either sylvine or halite.

This raises the suggestion that the red sylvine found with colourless halite may have been formed by replacement of some pre-existing magnesium salt, such as carnallite. If Fe-Mg-carnallite were replaced by sylvine under oxidizing conditions, the iron oxide might well be precipitated as haematite on replacement, and the haematite might sometimes form orientated inclusions in the secondary sylvine. All of the red potassium salts of the Texas–New Mexico field, except sylvine, contain magnesium. Iron could perhaps replace magnesium in these salts, and calcium in glauberite, and separate later by oxidation and ex-solution as haematite.

It is, of course, not claimed that haematite cannot be deposited directly from salt solutions under certain circumstances, but it is suggested that red sylvine associated with other colourless primary salts such as halite may well be secondary. However, more decisive evidence is needed in the present case.

VIII. ROCKS OF THE UPPER HALITE ZONE.

The four available specimens from this 8-foot zone have an average KCl content of only 0·25 %. They consist largely of halite, with a considerable quantity of clay. Magnesite and quartz are more abundant than in the lower zones, quartz forming about 3 % of some slices (pl. X, fig. 21). Anhydrite is scarce. Sylvine and carnallite are absent. The minerals have the usual relations to one another. Some anhydrite grains are partially replaced by halite, but no other direct evidence of replacement has been found.

The halite is relatively fine-grained (about 1 mm. to 1 cm.). Quartz crystals reach 2 mm. in length. Magnesite crystals are combinations of short hexagonal prisms with rhombohedra and base, up to 0·3 mm. in width. The halite is brick-red in colour in the upper three specimens. The lower specimen (3916–18) lies 2 feet above the specimen with 34 % KCl in the halite-sylvine zone. It contains only 0·21 % KCl, and consists of light brown halite (about 50 %), angular patches of blood-red halite full of haematite inclusions (about 45 %), and small quantities of quartz, magnesite, and anhydrite (about 5 %). The angular aggregation of haematite inclusions and distortion of zones of inclusions indicate recrystallization of halite (pl. X, fig. 20).

It seems likely that the haematite has in this case been derived from earlier sylvine or some earlier potassium or magnesium salt, although no relics of such a mineral have been found. It would be expected that with the incoming of the clastic material which sealed off the top of the evaporite bed, or with later percolation of ground-water through the clastic cover, there would be leaching of the more soluble salts in the upper part of the evaporite bed. This upper halite zone is believed to be such a 'cap' zone. Kainite, which is commonly formed by reaction of sylvine or carnallite with kieserite in the 'cap' zones of the German deposits, has not been found here, but the absence of kieserite would account for this.

IX. SUMMARY AND CONCLUSIONS.

The evaporite bed is 286 feet thick, and is underlain by dolomite and overlain by salt clay. It has been divided into the following five zones: Upper halite zone, 8 feet; Halite-sylvine zone, 46 feet; Halite zone, 142 feet; Halite-anhydrite zone, 49 feet; Anhydrite zone, 41 feet.

The following minerals have been found: anhydrite, boracite, carnallite, dolomite, haematite, halite, magnesite, magnetite, pyrite, quartz, and sylvine. The major constituents are halite, anhydrite, carbonates, and sylvine. Quartz is unusually abundant. Dolomite is restricted to the lower part of the succession, and magnesite, quartz, carnallite, sylvine, and haematite to the upper part. Some of the silica and iron oxide necessary to the formation of quartz and haematite may have been derived by solution of detrital material.

Petrographic descriptions of the rocks are given. The following replacements have been recorded: Dolomite→anhydrite; Dolomite→halite; Anhydrite→halite; Anhydrite→gypsum→halite; Gypsum→anhydrite±halite; Sylvine→halite.

Replacement of dolomite by anhydrite has taken place in the anhydrite zone, and to a small extent in the halite-anhydrite zone. The formation of dolomite porphyroblasts has apparently accompanied the replacement. There is no definite evidence to date this replacement.

Replacement of anhydrite-dolomite-rock by halite has taken place in the halite-anhydrite zone, and some of the secondary halite has suffered subsequent deformation. This replacement is probably later than those involving gypsum.

Halite has replaced some anhydrite in all the upper four zones. Some of this replacement appears to have taken place during or after recrystallization of halite, and after earlier recrystallization of anhydrite. It seems that halite has replaced anhydrite at several different times.

The replacements involving gypsum took place in the upper part of the halite-anhydrite zone. It is considered that some of the gypsum was primary, and some derived from anhydrite in unconsolidated anhydrite-dolomite-rock, all of it being later converted to halite and anhydrite, probably contemporaneously with the formation of this zone. There is no evidence of early gypsum in the anhydrite zone.

The presence of zones containing early gypsum in all three Eskdale evaporite beds, and of similar rocks in the Texas–New Mexico potash-field, suggests that such a zone may prove to be a normal stage in the formation of many marine evaporites; a stage during which slight rhythmic changes in conditions may cause alternate deposition of halite-, gypsum-halite-, and anhydrite-dolomite-rocks, with metasomatism of each earlier layer during the deposition of the one above it.

Replacement of sylvine by halite has been found in the halite-sylvine zone, and some of this appears to have taken place after recrystallization of halite and sylvine. Whether sylvine was primary or not cannot be decided. There is no direct evidence that it has replaced any pre-existing mineral, but the widespread recrystallization in the chloride zones would tend to destroy evidence of earlier replacements. The distribution of haematite suggests that the sylvine has been derived from some pre-existing magnesium-bearing salt, such as carnallite, containing ferrous chloride in solid solution, the latter separating as haematite during the replacement.

In the lower part of the halite-anhydrite zone, directional and deformational structures indicate recrystallization and 'flow' of halite under pressure, above the solid and unyielding anhydrite zone. There is evidence of wholesale recrystallization of halite, without directional structures, in the greater part of the chloride zones. Much recrystallization of anhydrite has taken place.

These evaporites provide the first record of significant quantities of potassium-bearing chlorides in Britain, and of the occurrence of sylvine, carnallite, and boracite.

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Explanation of Plates IX and X.

Photograph and photomicrographs of evaporites from the middle bed in the Eskdale no. 2 boring, east Yorkshire.

Plate IX.

Fig. 13. Anhydrite-dolomite-halite-rock with radiating group of distorted pseudomorphs after gypsum. The pseudomorphs show irregular 'herring-bone' structure, and consist of halite (black), and anhydrite and dolomite (white and grey). The interstices consist of anhydrite and dolomite. A late vein of halite is present near the base of the specimen. The surface has been ground with coarse carborundum, the halite polished with a wet cloth, and the specimen rubbed with chalk, which adheres to anhydrite and dolomite but not to halite. Halite-anhydrite zone, 4108–10 feet. Natural size.

Fig. 14. Part of large 'herring-bone' pseudomorph after gypsum. Irregular ribs of anhydrite (grey) and dolomite (black) alternate with halite areas. Halite-anhydrite zone, 4108–10 feet. × 10.

Fig. 15. Anhydrite-dolomite-halite-rock, showing cross-section of pseudomorph after gypsum. The gypsum crystals probably grew at the expense of anhydrite in anhydrite-dolomite-rock, pushing the dolomite (black) into the interstices. The gypsum was later replaced by anhydrite (grey) and halite (white). Halite-anhydrite zone, 4124–26 feet. × 10.

Plate X.

Fig. 16. Anhydrite-dolomite-rock showing replacement of dolomite (dark) by halite which has euhedral tendencies. A thin vein of late halite is also present. Halite-anhydrite zone, 4120–22 feet. × 15.

Fig. 17. Halite-anhydrite-rock with fine-grained anhydrite interstitial to large halite grains. Detrital impurities form a honeycomb network in the anhydrite area, probably due to recrystallization of anhydrite from a large number of centres, with ejection of impurities. Halite zone, 3978–80 feet. × 7.

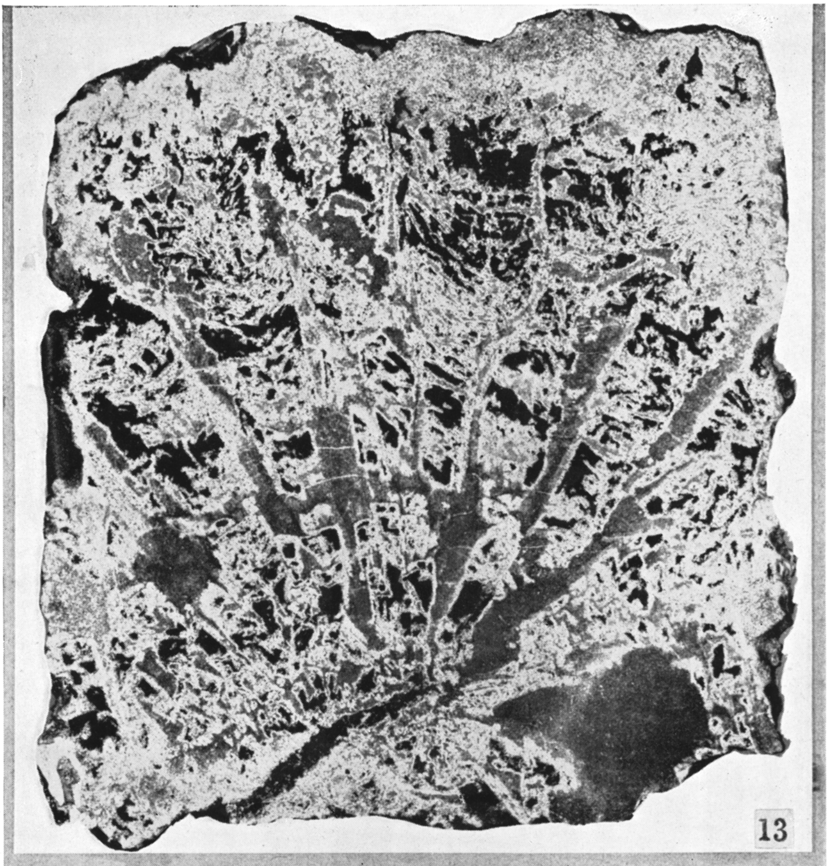
Fig. 18. Halite-sylvine-rock with haematite. A large sylvine grain shows a dark border full of haematite inclusions, and a sharply bounded central area in which haematite inclusions are arranged in two sets of zones inclined to the sylvine cleavages. Dark clay and colourless halite are present. Halite-sylvine zone, 3920–22 feet. × 22.

Fig. 19. Halite-sylvine-rock, showing a large sylvine grain which encloses haematite at its centre and edges. Halite-sylvine zone, 3918–20 feet. × 20.

FIG. 20. Halite-rock with haematite. The dark patches are composed of halite crowded with minute haematite inclusions showing distorted zoning. Upper halite zone, 3916–18 feet. ×7.

FIG. 21. Halite-quartz-rock with clay. The nicol prisms are inclined at an angle of 85° to each other, so that the clay is black and the halite dark. The birefringent grains are mainly quartz, which is associated with the clay. A few grains of magnesite and anhydrite are also present. Upper halite zone, 3910–12 feet. ×15.

Postscript.—Since this paper was written and read to the Society, a paper by Dr. A. Fleck (1950) has been published, and gives details of the results of three recent borings put down by Imperial Chemical Industries in the Yorkshire potash-field. Permission for the publication of the present paper has now, therefore, been given by I.C.I. In Fleck's paper details are given of the thickness and KCl content of two main beds of sylvine and halite; one in the middle evaporite bed and one in the upper evaporites. From the results given it would seem reasonable to conclude that a substantial part of the range from which no cores were recovered in the halite-sylvine zone of the Eskdale no. 2 boring has a high content of sylvine, and not much carnallite. The scarcity of magnesium minerals here is very odd. An upper halite zone is present in the I.C.I. borings, and its very variable thickness adds support to the view that this is a zone of leaching. Fleck mentions the presence of rinneite and a considerable amount of carnallite in the salt clay above the middle evaporites. These would explain the analytical results given on p. 448.



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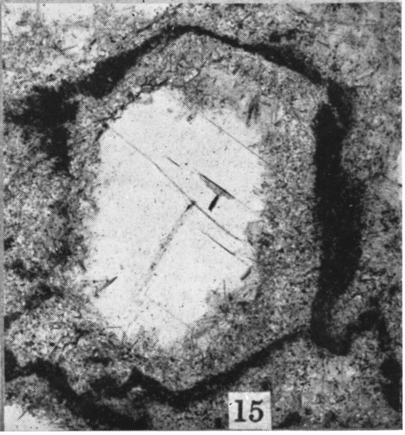

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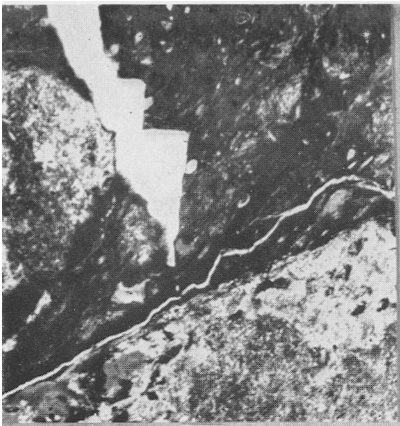

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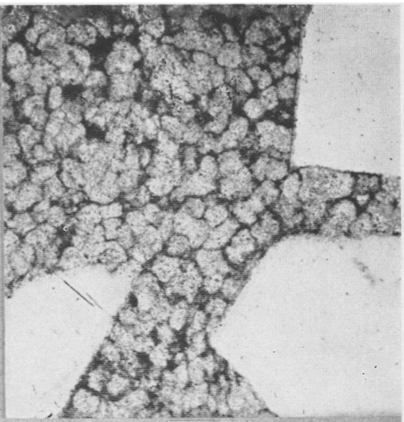

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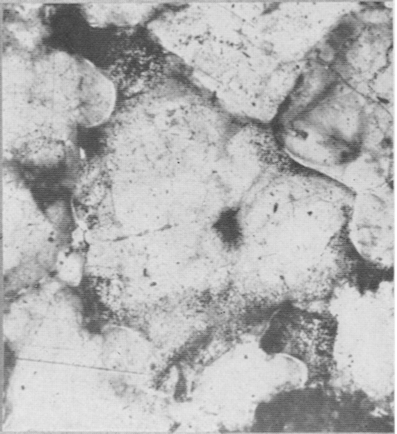

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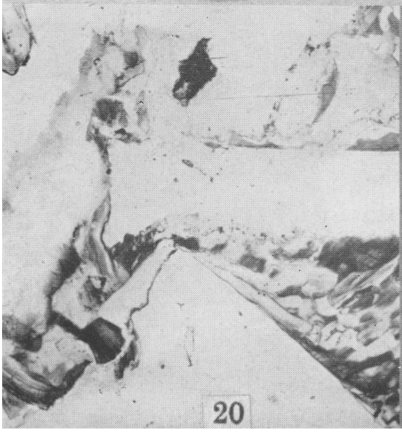

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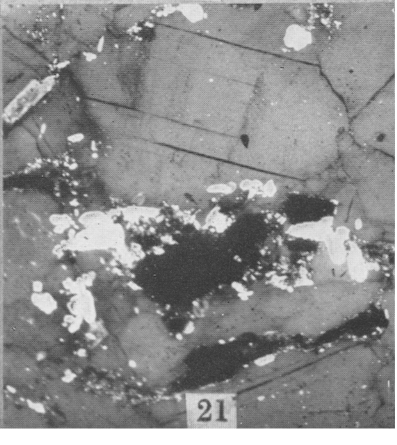

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