

*The paragenesis of sylvine, carnallite, polyhalite, and  
kieserite in Eskdale borings nos. 3, 4, and 6,  
north-east Yorkshire.*

(With Plate XXV.)

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INTRODUCTION.

THE confirmation of the presence of potassium salts in the Permian evaporites beneath the Whitby district, first found in the D'Arcy Exploration Co.'s Eskdale no. 2 (Aislaby) boring (G. M. Lees and A. H. Taitt, 1945), and the discovery by Imperial Chemical Industries in their Eskdale no. 3 (Sleights), no. 4 (Sneaton), and no. 6 (Upgang) borings that these salts exist in workable quality and quantity, has been recorded in a recent historic paper by Dr. A. Fleck (1950). The successful outcome of this boring campaign may well lead to the outstanding development of the present century in economic mineralogy in Britain.

In the course of the exploration the Geological Survey has examined in detail the cores obtained, and every facility has been granted by Imperial Chemical Industries for the removal of specimens from the cores for preservation in the national collection at the Geological Museum. The Petrographical Department of the Geological Survey has, on its side, provided reports on the mineralogy of the cores. The present brief summary of these reports, with some additional chemical, X-ray, and petrographical data, is published by permission of the Director of the Geological Survey and with the approval of Imperial Chemical Industries, Limited.

Core-examination was carried out by Mr. G. Armstrong of the Newcastle Unit, successively under the direction of Dr. T. Robertson and Mr. W. Anderson; and by Prof. Dunham and Dr. Sabine of the Petrographical Department who were, respectively, responsible for the optical

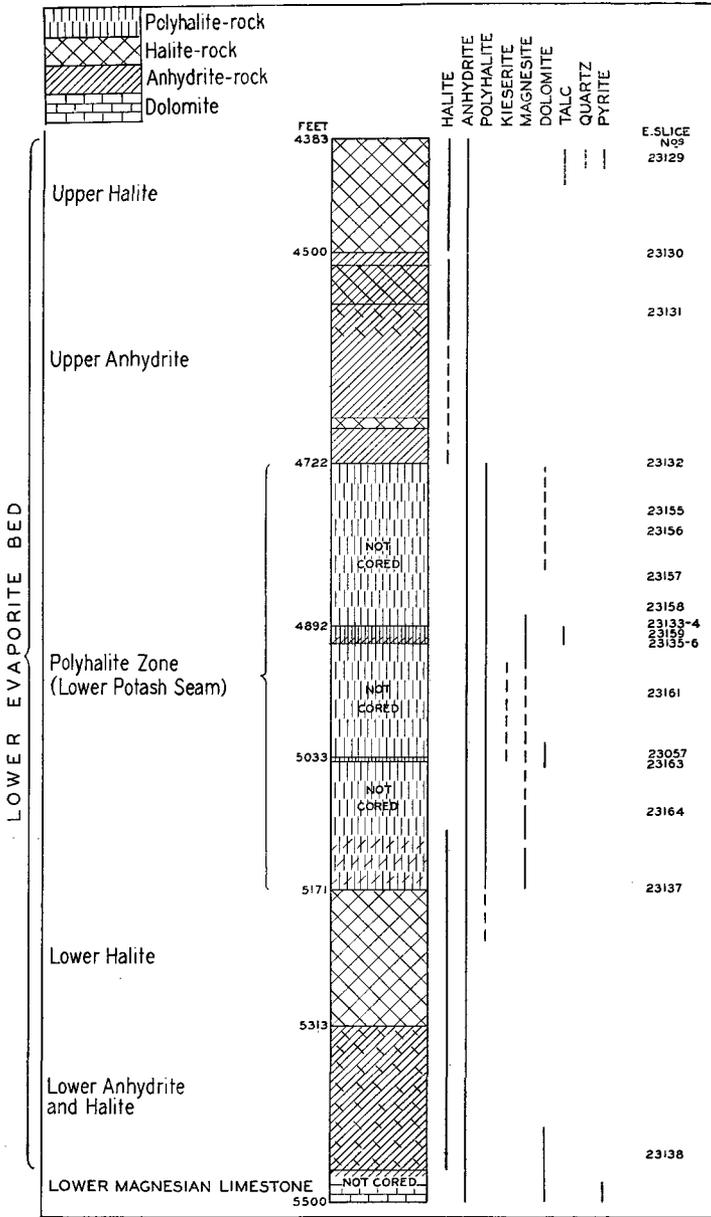


FIG. 1. Section of the lower evaporite bed of Eskdale no. 3 (Sleights) borehole, to show approximate ranges of minerals.

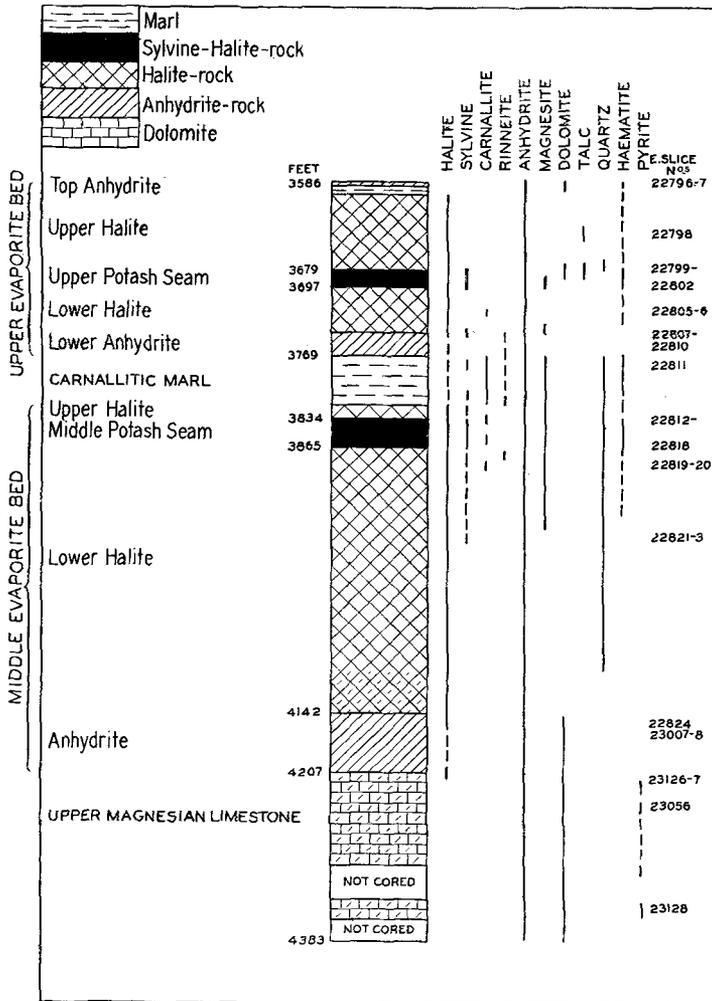


FIG. 2. Section of the upper Magnesian Limestone, middle and upper evaporite beds, and carnallitic marl at Eskdale no. 3 (Sleights) borehole, to show approximate ranges of minerals.

and X-ray investigations. Chemical investigations were the work of Mr. Harvey and Mr. Waters. The assistance of Dr. J. A. C. McClelland of the Government Laboratory, who made the spectrographical determinations, is gratefully acknowledged.

We are indebted to Mr. W. R. Madel and Dr. O. B. Westcott, successively in charge of the boring campaign under Mr. J. Hughes, Technical Manager of the Wilton Works of Imperial Chemical Industries, for much kindness; also to the late Mr. L. H. Barker, to Mr. B. T. James, as well as to Mr. L. R. Raymond and Mr. M. E. Pease, respectively geologist and mineralogist in the Research Department, I.C.I., Billingham.

The first published record of a potassium salt in Britain is due to C. E. Tilley (1943), who identified polyhalite in a core from Eskdale no. 2 boring submitted to him by W. G. Fearnside. A log and description of this boring were published by G. M. Lees and A. H. Taitt (1945). Miss E. M. Guppy (1944), discovered boracite in cuttings from Eskdale no. 2 boring. More recently in a notable series of papers, F. H. Stewart (1949, 1951 *a, b*) has described the petrography and petrology of the evaporites. The results of our examination of the material from the more recent borings in a great measure confirm the conclusions reached by Stewart; attention is therefore concentrated here upon new features. These include (1) the identification of kieserite from the polyhalite zone; (2) a description of the rich middle sylvine zone, possibly represented by material lost in solution at Aislaby; (3) an account of the carnallite-bearing marl overlying this zone; (4) a description of the sylvine-halite seam in the upper evaporite bed.

The difficult task of making the 150 thin sections used in our investigations was carried out by Mr. D. Hepple; Mr. J. Rhodes took the photomicrographs.

#### THE PERMIAN EVAPORITE SUCCESSION.

The sub-divisions of the Permian evaporite succession in the Whitby area are tabulated below.

Upper evaporite bed 150-215 feet	{ Top anhydrite (p. 687) Upper halite (p. 687) Upper potash seam (p. 685) Lower halite (p. 684) Lower anhydrite (p. 684)
Carnallitic marl (p. 681) 40-55 feet	
Middle evaporite bed 239-383 feet	{ Upper halite (p. 681) Middle potash seam (p. 677) Lower halite (p. 676) Anhydrite and banded anhydrite-halite zones (p. 676)

Upper Magnesian Limestone	
183 feet	
Lower evaporite bed	} Upper halite (p. 675) Upper anhydrite (p. 674) Polyhalite and kieserite zone (lower potash seam) (p. 672) Lower halite (p. 672) Lower anhydrite and halite (p. 671)
1098 feet	
Lower Magnesian Limestone	

#### LOWER MAGNESIAN LIMESTONE.

The lower Magnesian Limestone and the overlying lower evaporite bed was reached in only one of the three borings (Eskdale no. 3), and in these beds 'the rock was so hard that coring became too laborious and expensive to continue, and even straight drilling became a very slow process' (Fleck, 1950, p. s11) at the depth reached, 4383–5500 feet.

Some 22 feet of the lower Magnesian Limestone were penetrated at the bottom of the hole, and of this the last 4 feet were cored. The rock (E.23058)<sup>1</sup> is a buff laminated dolomite-rock containing discrete rhombs of dolomite and lenticles carrying dolomite, pyrite, and gypsum in a matrix of cryptocrystalline dolomite. It is uncertain whether the gypsum is of primary or secondary origin. Thin carbonaceous shaly partings occur in the rock.

#### LOWER EVAPORITE BED.

A comparison of the details of this bed in Eskdale no. 3, summarized by Fleck (1950, p. s10) with that given by Stewart (1949, p. 625) for Eskdale no. 2, reveals the following significant differences: (1) the total thickness is much greater in the recent boring—1098 feet—as compared with 460 feet; (2) the lower anhydrite in Eskdale no. 3 is poorly developed, its place being largely taken by halite-rich strata; (3) the polyhalite zone is more than five times as thick in Eskdale no. 3 as in Eskdale no. 2. The significance of the differences is not yet clear.

*Lower anhydrite and halite.*—Anhydrite-rock enclosing some halite occurs above the Magnesian Limestone; occasional black shaly films occur and, at 5465 feet depth, veinlets filled with halite traverse the rock. Occasional thin beds of fine-grained dolomite-rock are found; in one of these (E.23138) the carbonate, with  $\omega$  1.682, has a platy habit especially in coarser layers where it is associated with anhydrite. Between 5438 and 5464 feet depth, the anhydrite-dolomite-halite-rock

<sup>1</sup> Numbers in brackets refer to specimens in the sliced rock collection of the Geological Survey.

shows traces of distorted bedding. Above 5438 feet dark halite predominates up to 5313 feet, but an open mesh of anhydrite is present. It is probable, as Stewart has suggested, that this texture is inherited from the replacement of coarse primary gypsum by halite, the pseudomorphs being surrounded by anhydrite with a little dolomite.

*Lower halite.*—Above 5313 feet the cores up to 5171 feet consist essentially of halite having a predominantly grey colour, possibly due to carbonaceous inclusions. Halite crystals up to 2.5 cm. across are common. There are suggestions of gypsum pseudomorphs between 5250 and 5215 feet depth. A little polyhalite begins to appear towards the top of this zone, and at 5173 feet (E.23137) the presence of magnesite crystals about 0.005 mm. diameter was noted. These have centres, possibly of dolomite, of markedly lower refringence than the rest of the crystal. In the halite tiny hair-like needles, showing negative elongation, occur in bunches. It was considered possible that these might be the borate pinnoite, but their refractive index appears to be too high; further investigation is necessary.

*Polyhalite and kieserite-bearing rocks (lower potash seam).*—Of the 449 feet (5171–4722 feet depth) assigned to the polyhalite zone in Eskdale no. 3 boring, cores were taken for 21 feet only. Only one significant addition can be made to Stewart's account (1949) of the petrography of this zone: the presence of the mineral kieserite  $MgSO_4 \cdot H_2O$ , of which this constitutes the first record in Britain. The solubility of this mineral is such that it may well have been destroyed before the relevant portion of the core of the earlier boring was investigated.

The core from 5033 feet 6 inches depth in no. 3 boring (E.23057, 23057A) is a buff, semi-transparent rock with large white patches. The most abundant mineral present is polyhalite showing the characteristic polysynthetic twinning (see, for example, Shaller and Henderson, 1932, p. 72), optically negative with medium 2V, refractive indices  $\alpha$  1.550,  $\beta$  1.562,  $\gamma$  1.568. The polyhalite forms a mosaic of closely interlocked xenomorphic crystals. The white patches (pl. XXV, fig. 4), up to 2.5 cm. across, prove to be kieserite, optically positive with 2V near 60°, and high birefringence as indicated by the refractive indices  $\alpha$  1.524,  $\gamma$  near 1.580. Many cleavages are visible in thin section, and striking polysynthetic twinning is displayed. The large kieserite crystals are considered to be porphyroblasts, for at their margins they appear to have replaced polyhalite, and they enclose many relics of polyhalite, reminiscent of the anhydrite relics often found in gypsum. Trains of tiny hexagonal or rounded carbonate crystals occur in the rock, similar

to those described from the main anhydrite and salt-field of SE. Durham (Dunham, 1948). Refractive index measurements indicate that both magnesite (with  $\omega$  1.703) and dolomite ( $\omega$  1.682) are present. Small pods containing halite, more coarsely crystallized than the polyhalite, and very little anhydrite are present, and these appear to have been affected by polyhalite. Thus in this rock the sequence of replacements seems to have been: anhydrite, halite  $\rightarrow$  polyhalite  $\rightarrow$  kieserite.

The presence of kieserite was confirmed by X-ray powder photography, the interplanar spacings computed agreeing well with those given for  $MgSO_4 \cdot H_2O$  in the 'Index of the American Society for Testing Materials' (no. I-1580).

An analysis of the rock, with a calculated proximate mineral composition, is given in table I. Although a noteworthy amount of strontium is revealed, no separate strontium mineral was found, and it is surmised that this element may substitute for calcium in polyhalite.

TABLE I. Partial analysis of polyhalite-kieserite-rock.  
No. 3 (Sleights) boring, 5033 feet 6 inches.

Soluble in dilute HCl:			Determined spectrographically:	
Ca	...	10.95	Li	not detected, less than 0.01
Mg	...	5.36	Rb	" " " 0.1
K	...	11.05	Cs	" " " 0.1
SO <sub>4</sub>	...	56.82	Ba	not detected
Cl	...	0.77	Pb	not detected
CO <sub>3</sub>	...	3.63	Mn	slight trace
Total H <sub>2</sub> O + 105° C.	...	6.25	Sr	0.9
		94.83	B	0.02 (approximate)
			Tl	not detected

Proximate mineral composition:

Polyhalite (strontium-bearing)	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	...	85.2
Kieserite	$MgSO_4 \cdot H_2O$	...	3.6
Magnesite	$MgCO_3$	...	4.4
Dolomite	$CaMg(CO_3)_2$	...	0.2
Halite (from excess chlorine)...	NaCl	...	1.3
Difference (siliceous matter) ...	—	...	5.3

100.0

Analyst, W. F. Waters, Geological Survey and Museum, Lab. no. 1542 (1949).  
Spectrographical determinations by J. A. C. McClelland (1950).

The next higher core-samples were taken in the range 4892–4910 feet (E.23133–6). Here the rocks are greyish-white and contain in order of abundance, anhydrite, polyhalite, magnesite, dolomite, halite, and talc. The polyhalite forms a hypautomorphic-granular aggregate of elongate

crystals 0.01–0.06 mm. long, with, in places, larger individuals up to 2.0 mm. across. This aggregate appears to have invaded, mainly along vertical directions, somewhat coarser anhydrite-rock. Magnesite ( $\omega$  1.701) occurs as tiny hexagonal crystals, forming streaks in the rock. Some of these have centres of markedly lower refringence, which may be dolomite (E.23136). In some rocks, the anhydrite has probably recrystallized to form coarse poikilitic areas which may have formed contemporaneously with equally coarse polyhalite.

The continuity of the occurrence of polyhalite through the extensive uncored portion of the polyhalite zone was established by Imperial Chemical Industries' laboratories by the determination of potash-content in the drill-cuttings, both radiometric and chemical methods of analysis being employed. For our microscopical examination, cuttings were mounted in bakelite and sectioned, using the technique successfully developed at the Geological Museum in connexion with the D'Arcy Exploration Company's boring programme. The sections (E.23155–23164) show polyhalite, anhydrite, and magnesite in the fragments; the presence of clear primary kieserite was established in cuttings from 4946 feet, but some fine-grained, dusty-looking kieserite in specimens from other depths was considered to be either an alteration of polyhalite during drilling, or else a recrystallization product. All the fragments were more or less completely coated with secondary gypsum.

At the top of the polyhalite zone, at 4722 feet depth (E.23132) there occurs a rock rich in anhydrite which encloses lenticular wisps of fine-grained magnesite. Interlayered with the magnesite is a pale brown isotropic mineral, showing no cleavages and having refractive index appreciably below that of halite, and close to 1.530. It is believed that this may be langbeinite,  $K_2SO_4 \cdot 2MgSO_4$ , but the very meagre quantity of the material precludes satisfactory identification. A careful watch for this mineral, which is abundant in the New Mexico potash-field, is desirable as investigation of the British field proceeds. Halite has to some extent replaced the anhydrite in this rock, and coarse polyhalite appears to have been the latest mineral to crystallize here. X-ray data on polyhalite are given on p. 688.

*Upper anhydrite.*—Predominantly anhydrite-rocks, with some halite, especially near the top, range from 4722 up to 4556 feet. At 4566 feet (E.23131) lenticular masses of anhydrite are bordered with very fine-grained carbonate; here there is a suggestion of dips up to  $20^\circ$ . At 4637 feet finely banded white anhydrite seems to have been folded, contorted, and invaded by halite. A horizontal lineation appears in a

bed of grey halite between 4676 and 4684½ feet, beneath which apparently contorted anhydrite is again seen. The possibility of movement involving flowage of halite may perhaps be envisaged at this level.

*Upper halite.*—The topmost division of the lower evaporite consists of banded halite-anhydrite-rock overlain by massive halite. A crude lineated or schistose texture is seen in places between 4423½ and 4500 feet, while between 4530 and 4556 feet the halite encloses apparently broken-up anhydrite-rock fragments showing dips up to 25°. At higher levels clear rock-salt shows thin bands of dark pigmentation dipping at about 20°. Talc is a prominent constituent at 4410¼ feet and again at 4403 feet, as silvery-looking plates up to 3.5 mm. across. The other constituents at 4403 feet (E.23129) are halite, anhydrite, scarce euhedral quartz crystals, and pyrite. The talc lies, as Stewart has described, along cleavages in the halite, and some crystals also occur along what may be bedding-planes in the rock.

#### UPPER MAGNESIAN LIMESTONE.

Dolomite reappears in force at 4383 feet, and dolomite-rock extends up to 4207 feet. In places the rock is shaly, with layers containing clay minerals and carbonaceous matter. Anhydrite is generally present in small amount and usually with poikiloblastic habit or in a form indicative of porphyroblastic growth. Pyrite is also widespread in small amounts, in places edging the anhydrite areas. Remains of the fossil *Filograna ?permiana* (King) were found at 4237–4248 feet, and again at the top of the division, from 4207–4210 feet (E.23126). The remains consist of tubes up to 0.75 mm. across, and up to 3.0 mm. long. In cross-section they now consist of alternating layers of dolomite and anhydrite, giving evidence of former metasomatic changes (Dunham, 1948, pl. X, fig. 3). This fossil<sup>1</sup> has been accepted elsewhere as evidence of an Upper Zechstein age (C. J. Stubblefield, in discussion on Dunham and Rose, 1949, p. 40). The identification in this case was made by Dr. Stubblefield (E.18374).

#### MIDDLE EVAPORITE BED.

This bed was penetrated in all three borings; it was completely cored, with excellent recovery, in Eskdale no. 3 boring, while in Eskdale no. 4 the coring was discontinued before the basal anhydritic zone was reached. In no. 6 borehole the base of the bed was not reached.

<sup>1</sup> The fossil also occurs in Eskdale no. 2 borehole at a similar horizon, at 4218 feet depth.

*Anhydritic and banded anhydrite-halite zones.*—In no. 3 boring anhydrite, with dolomite and occasional low-dipping, black, shaly partings, extends from 4207 up to 4195 feet. Above this, layers not more than a few inches thick of anhydrite and halite alternate up to 4184 feet. It is tempting to regard these as 'annual' layers such as have been recorded from the German evaporite field, in which anhydrite is believed to have been deposited during the warmer season and halite during the cooler part of the year, in conformity with temperature-coefficients of solution of the minerals (J. D'Ans, 1949). Whether this is so or not, the rocks almost certainly represent primary precipitates. Evidence of disturbance of anhydrite layers and their enclosure in halite (probably recrystallized) is found at intervals from 4184 up to 4164 feet; dips in anhydrite-rock fragments as high as 20° may be seen in this range. Between 4164 and 4162½ feet a buff-grey porcellanous rock (E.23007-8) is a dolomite-siltstone in which the carbonate averages 0.005 mm. in grain-size, and the rock encloses a few detrital quartz grains. In section, groups of rounded areas, filled with anhydrite or halite, suggest the possible former presence of a fossil such as *Filograna*. Wavy markings traversing the rock may be the remains of ripple-marks.

At slightly higher levels, arborescent growths of anhydrite in halite occur, a texture probably inherited from the replacement of early gypsum (see Stewart, 1951 *a*, for a full discussion of comparable textures at similar levels in Eskdale no. 2 boring). Banded rocks continue up to 4114 feet, but the halite bands in the upper part of this zone are markedly thicker than those of anhydrite.

*Lower halite.*—This zone ranges from 4114 up to 3865 feet in no. 3 boring, where it was cored throughout. In no. 4 boring the range was 4386 up to 4245 feet 10 inches, cores being taken only above 4330 feet. The zone was penetrated in no. 6 borehole from 4055 down to 4215 feet, below which anhydrite bands were found.

Halite is the dominant mineral, with anhydrite as a persistent accessory. In the lower part of this zone as exposed by no. 3 boring, the halite is nearly colourless, or has a greyish shade, probably due to small amounts of carbonaceous pigment. Higher up, the salt is pink, with, rarely, a few bright red individual halite crystals (e.g. at 4036 feet in Eskdale no. 3 boring). A few partings of dark shaly material occur apparently undisturbed.

Automorphic quartz crystals make their appearance, as in the Aislaby boring (Stewart, 1951 *a*, p. 451) low down in this zone, at 4000 feet depth in no. 3 boring, and occur in all the powders and slices examined up to

its summit. Cuttings from no. 4 boring at the base of the zone, some of which probably came from higher levels (E.23704) include quartz euhedra up to  $1.0 \times 0.2$  mm., fragments of quartzite-like rock composed of clear interlocked hypautomorphic quartz crystals enclosing anhydrite crystals, and also fragments showing the poikilitic enclosure of magnesite and anhydrite by quartz.

Magnesite, as automorphic hexagonal plates, flattened parallel to (0001), and with  $\omega$  1.701–1.703, first appears, according to our observations, at 3952 feet in no. 3 boring and at 4300 feet in no. 4. It continues sporadically to the top of the zone.

From 4000 feet depth in no. 3 boring upwards, occasional occurrences of sylvine have been noted. Owing to the greater solubility of the potassium chloride, the former presence of sylvine is revealed by conspicuous deep etching on the outsides of the cores. The mineral occupies irregular gashes and pockets, and this mode of occurrence, in conjunction with microscopical evidence of replacement of halite by sylvine (E.22819 23) makes it likely that potassium penetrated into this zone beneath the rich middle seam. Carnallite occurs as rounded crystals or groups of crystals enclosed in halite (E.23701–3). These have the appearance of primary constituents, but, as the extent to which the salt has recrystallized is uncertain, such appearances must be treated with caution.

*Middle potash seam.*—The paragenesis sylvine-halite-magnesite-quartz-anhydrite-(carnallite), which first makes its appearance in the halite zone, reaches its maximum development in the middle potash seam. The depth-ranges of this seam have been given by Fleck (1950, fig. 10): 3865–3834 feet in no. 3 boring; 4245 feet 10 inches–4213 feet in no. 4 boring; 4055–4043 feet in no. 6 boring. Sylvine occurs: (1) as red crystals wholly pigmented with haematite inclusions in the form of rods and hexagons, individually visible in many specimens only at the highest magnifications; (2) as crystals marginally red, but with white centres; (3) as milky-white crystals. In thin section the sylvine is readily distinguished from halite by its much lower refractive index (1.490, from which no detectable variation was found in numerous determinations). Smoothly curving boundaries separate the sylvine from adjacent halite. Much of the middle seam as exposed in no. 3 boring consists of a phanocrystalline aggregate of red sylvine intergrown with halite, which is mainly dark grey probably due to associated carbonaceous material. On the other hand, red pigmentation is conspicuously lacking from most of the sylvine in this seam in no. 4 boring. The grain-size in both cases is coarse, individual crystals reaching 1–3 cm. across.

Enclosed in the chlorides there are automorphic anhydrite crystals of very variable size, and euhedra of magnesite and quartz. Some clay is generally present, and in some, though not all, cases quartz and magnesite crystals cluster round the clay inclusions, or occur with clay which occupies an interstitial position among the chlorides. A fringe of haematite pigmentation in chlorides sometimes surrounds clay inclusions, as if ferric oxide had diffused from the marl into the chlorides. Such pigmentation is not capable of resolution into separate haematite crystals, even at the highest magnifications.

Carnallite is probably not much more abundant in the seam than in the upper part of the halite zone, and its mode of occurrence is similar, generally as rounded or crudely hexagonal inclusions in halite. On cores from the top of the seam in no. 3 boring, an efflorescence which formed on the outside was found to consist largely of carnallite. This may be the product of reactions involving the boring fluid, or carnallite may be soluble in the fluid, but capable of redeposition.

From no. 3 boring a sample was taken for chemical analysis in Geological Survey and Museum laboratories, the first object being to investigate the bromine- and iodine-contents; subsequently full analyses were made of water-soluble and insoluble portions. The sample consisted of small chips removed from the core of the seam at regular intervals of 3 inches, the partially dissolved outside of the core being avoided in taking the chips, or removed from them. This method of sampling is less satisfactory than that later adopted by I.C.I. for sampling the cores of no. 4 and subsequent borings, when a diamond-impregnated cutting disk was used to make a longitudinal cut. This explains some discrepancies between the result obtained by I.C.I. and by us, to which Fleck (1950, p. s11) makes reference. The results of the Geological Survey analysis are given in table II, together with one possible calculation—not, of course, a unique solution—of the mineral composition.

Bromine was found to be present in the water-soluble portion of the core, but iodine was not detected, the method used being sensitive to 0.001 %. Comparison of the bromine-content of the middle seam (0.104 %) with that of the upper seam (0.014 %, p. 686) suggests a correlation with total KCl-content rather than with amount of carnallite present, which is approximately the same in both seams. This may, however, be accidental, and in calculating the mineral composition it has been assumed that the bromine occurs as a substitution for chlorine in carnallite.



the insolubles both from this seam and the upper seam spectrographically, and found no indication of the following elements: Sb, Zr, Nb, Ta, W, Ga, Ge, In, Yt, Eu, La, Ce, Th, Ni, Mo, Bi, Be.

Both in the halite zone and the middle seam a search was made for boracite, but without success. It will be recalled that Miss Guppy's (1944) discovery of this mineral was in cuttings, the residue from extensive solution of chlorides. Examination by Dr. McClelland of insoluble residues from five samples from no. 3 boring at the depths shown below gave the following approximate boron-contents:

Depth, feet.	B %.
4036 ... ..	0.01-0.05
4046 ... ..	trace
4090 ... ..	0.05-0.10
4110 ... ..	0.01-0.05
4131 ... ..	0.01-0.05

In the insolubles from the middle seam the boron was of the order of 0.1 %. Though a concentration of boracite in the middle seam, such as Stewart thought might be possible (1951 *a*, p. 449), has not been confirmed, a little more boron appears to be present than in the halite zone.

The middle seam as exposed by no. 4 (Sneaton) boring shows alternations of halite-rich and sylvine-rich layers. It is strikingly different in appearance from the Sleights material, being predominantly white or grey rather than red and black. Fleck (1950, p. s11) has given the KCl-content of the various beds. In the table below, proximate mineral compositions, based by kind permission on I.C.I. analyses, are given:

Proximate mineral compositions, middle seam, no. 4 (Sneaton) boring.

Depth. (Feet/inches).	Thickness. (Inches).	Halite.	Sylvine.	Carnallite.	Insoluble.
4213-4214/2	14	59	37	1	1%
4214/2-4215/2	12	78	2	5	10
4215/2-4217/3	25	38	58	1	1
4217/3-4221	45	50	4	5	33
4221-4230/11½	119½	58	38	1	2
4230/11½-4241	120½	95	2	1	1
4241-4245/10	58	57	38	1	2

The next 96 inches below the seam showed 96 % halite; sylvine and carnallite 1 % each. The high carnallite-contents of the fourth and sixth beds of the seam are confirmed by microscopical examination. The mineral occurs in close association with clay present as thin beds or inclusions in the seam.

In no. 6 (Ufgang) borehole the middle seam is only 12 feet in thickness and contains greater quantities of marl than in boreholes E3 and E4. Rinneite occurs at 4047 feet and carnallite at 4052 feet depth.

Alternations of sylvine-rich layers are present as in borehole no. 4. Proximate mineral compositions, based by kind permission on I.C.I. analyses are given below. Complete recovery of the core was not obtained and precise depths are not therefore stated.

Proximate mineral compositions, middle seam, no. 6 (Ufgang) boring.

Portion of core		Halite.	Sylvine.	Carnallite.	Insoluble.
4041-4051 feet.					
First 17 inches	...	75	< 1	3	19%
Next 7 "	...	84	2	1	4
" 11 "	...	67	6	5	15
" 35 "	...	41	42	1	10
" 10½ "	...	32	19	1	34
" 13 "	...	33	37	3	17
" 9 "	...	40	17	1	28
4051-4062 feet.					
First 17 inches	...	54	31	1	7

The Geological Survey Museum slices of material from the middle seam include the following: no. 3 borehole E.22812-8; no. 4 borehole E.23694-23701; no. 6 borehole E.24292-7.

*Upper halite.*—In nos. 3 and 6 borings, the middle potash seam is overlain by a thin bed of halite, almost colourless, but enclosing some black and green marl and traces of bright red sylvine. There is a suggestion of veining or steep banding at this level in the Sleights core (3821-3834 feet). In no. 4 boring, the middle seam is overlain directly by the carnallitic marl.

#### CARNALLITIC MARL.

In no. 2 (Aislaby) boring, a bed of marl was recorded above the middle evaporite bed, at 3861-3920 feet. This bed, which has proved to be a persistent one, shows some unusual features in the more recent borings. Fleck (1950, pp. s9, s11) has recorded that the presence of carnallite was established here both by I.C.I. laboratories and at the Geological Museum. More recently a specimen of the marl from Messrs. Fisons' Robin Hood's Bay no. 1 boring has been exhibited by Hollingworth and Stewart (1950).

In no. 3 boring recovery was poor, only centres of cores, partly fragmented, being obtained with a mass of loose material. Carnallite, as grains with low refringence but high birefringence ( $\alpha$  1.468,  $\gamma$  1.493,

optically positive, 2V near 70°, occasionally showing polysynthetic twinning) proved to be common among the marl fragments, accompanied by halite, anhydrite, quartz, haematite, and clay minerals (E. 22811). The presence of carnallite as a main constituent was considered to have been the reason for the disintegration of the marl during drilling. The occurrence of rinneite was also suspected. This mineral, first found by Stewart (1949) in the upper evaporite bed at Aislaby, yields on decomposition sylvine and limonite of a conspicuous yellow colour. Such material was first noted in the marl at 3769 feet by Mr. L. R. Raymond.

In no. 4 boring the recovery from this bed was again poor, but here an average sample covering the range 4173–4213 feet was taken for analysis in the Geological Survey laboratory. The results are given in table III. There are too many uncertainties to make possible a calculation of the proximate mineral composition at this stage. It is, however, possible to state that the carnallite content is of the order of 10 % (a figure corroborated by later I.C.I. analyses on cores from no. 6 boring) and that sylvine amounts to about 0.4 % and halite 17.0 %. Among the insoluble constituents, magnesite probably amounts to 2.7 %, but a large residue of magnesia (5.28 %) is left unaccounted for. As in the case of the insolubles in the middle potash seam, magnesia is exceptionally high, implying, it is suggested, the presence of talc or magnesian chlorite or both. Among the clay constituents, the potash figure is normal and no doubt represents white mica, probably with an illite-type mineral. The soda could be accounted for by montmorillonite. Considerable amounts of kaolin must be present.

In no. 6 boring much greater success was achieved with coring the carnallitic marl. The rock is a consolidated salt-clay, dull red except near the base, where the coloration changes to yellowish or olive-green. In this section (E.24103–5, 24112–27) it is seen to be full of tiny ramifying veinlets, some more or less horizontal, spaced at intervals of 0.05–1.0 mm. apart, linked by steep, nearly vertical veinlets. These veinlets seldom exceed 0.1 mm. in width.

Oblique veins, up to 3 cm. wide, carrying pink and white salts also occur, though at wide intervals. The minerals in the largest veins include halite, carnallite, sylvine, and rinneite, with in places some anhydrite, euhedral quartz, and magnesite (pl. XXV, fig. 3). In the tiny veinlets, carnallite seems to be the dominant mineral, but determination is difficult in the smallest ones. The clay also encloses cubic pseudomorphs after halite—now partly replaced by or occupied with quartz

TABLE III. Analysis of carnallitic marl, No. 4 (Sneaton) boring.  
4173-4213 feet.

Water-soluble matter.				Water-insoluble matter.			
						I.	II.
Mg	...	...	0.88	SiO <sub>2</sub>	...	56.05	35.83
Ca	...	...	1.99	Al <sub>2</sub> O <sub>3</sub>	...	16.37	10.47
Na	...	...	6.72	Fe <sub>2</sub> O <sub>3</sub>	...	3.54	2.28
K	...	...	1.62	FeO	...	1.16	0.74
SO <sub>4</sub>	...	...	2.77	MgO	...	10.32	6.59
Cl	...	...	15.69	CaO	...	0.33	0.21
Br	...	...	0.041	Na <sub>2</sub> O	...	0.26	0.17
I	...	...	n.d. < 0.001	K <sub>2</sub> O	...	2.70	1.73
Mn*	...	...	trace	ign.†	...	5.67	3.62
CO <sub>2</sub>	...	...	n.d.	TiO <sub>2</sub>	...	0.82	0.52
B*	...	...	n.d.	P <sub>2</sub> O <sub>5</sub>	...	0.15	0.10
Ba*	...	...	n.d.	CO <sub>2</sub>	...	2.20	1.42
Sr*	...	...	trace	SO <sub>3</sub>	...	0.22	0.14
Pb*	...	...	trace	B <sub>2</sub> O <sub>3</sub> *	...	about	about
Li*	...	...	trace			0.2	0.1
Rb*, Cs*	...	...	n.d.	FeS <sub>2</sub>	...	0.06	0.04
Tl*	...	...	n.d.	Cr <sub>2</sub> O <sub>3</sub>	...	0.02	0.01
			— —	BaO	...	0.03	0.02
			29.71	SrO	...	trace	trace
Water-insoluble matter			64.0	Li <sub>2</sub> O	...	0.03	0.02
Total H <sub>2</sub> O—105° C.			5.6			— —	— —
			— —			100.13	64.0

I. Water-insoluble matter as analysed.

II. Water-insoluble matter recalculated to 64.0 %.

The two portions were analysed separately; analysts, W. F. Waters and K. L. H. Murray, Geol. Surv. Lab. nos. 1563, 1564 (1950).

\* Semi-quantitative spectrographic determination by J. A. C. McClelland.

n.d., not detected.

† Matter volatile on ignition, other than CO<sub>2</sub> and S; mainly H<sub>2</sub>O : 105° C.

(E.24126)—and pseudomorphs showing the characteristic outline of gypsum, replaced by halite and anhydrite (E.24115-17). From the fact that carnallite veinlets follow the sides of the halite pseudomorphs, it is concluded that introduction of carnallite occurred after their replacement (E.24127). Polyhalite occurs in the marl in the form of small rounded aggregates, partly coated with clay (E.24113, 24125).

The clay minerals are too much mixed with haematite to permit optical study except in the basal layers of the bed. Here attempts to determine the refractive indices suggested that these are abnormally low, but the presence of secondary fine-grained gypsum complicates the

investigation of this material. The possibility that montmorillonite might be present (Fleck 1950, p. s12) was suggested to explain the swelling and breaking-up of the clay in water, but X-ray determinations of glycerol-treated material have failed to substantiate the presence of a mineral of this group. Possibly the breaking-up can be explained sufficiently by the solubility and deliquescence of carnallite and rinneite. Examination by X-ray powder methods, after repeated extraction of soluble salts with water, of a specimen from the carnallite marl of bore-hole E6 (4016 feet depth) shows the clay fraction to consist of quartz and illite with possibly a member of the kaolinite group.

This clay formation, as seen at the present early stage of investigation, has evidently had a complex history. Gypsum and halite, and perhaps also polyhalite, seem to have been deposited with the clastic constituents; later brines brought in anhydrite, quartz, and further halite. Subsequently carnallite and rinneite were introduced along veins which show evidence of still later attack by anhydrite, halite, sylvine, quartz, and magnesite.

#### UPPER EVAPORITE BED.

*Lower anhydrite.*—The uppermost evaporite sequence is initiated by anhydrite with some layers of dolomite containing angular detrital quartz grains (e.g. 3975 feet in no. 6 boring, E.24111). Pink halite is sporadically present, occurring in the form of striking pseudomorphs after early gypsum (E.24109 10), such as Stewart has described. These occur in a matrix of anhydrite which appears, from the vagueness of the halite-anhydrite margins, to have crystallized during or after the metasomatism of the gypsum. Veins carrying halite, sylvine, and yellow limonite (probably after rinneite) cut through the anhydrite, for example at 3752 feet in no. 3 boring. The anhydrite zone is very consistent in the three borings, the thicknesses being respectively 26, 28, and 26 feet. Towards the top of the lower anhydrite in both no. 3 and no. 6 bore-holes, there is a subsidiary development of sylvine. This sylvine (pl. XXV, fig. 5) is often pigmented by haematite, contains automorphic crystals of anhydrite, and displays sinuous boundaries against associated halite, e.g. from 3957 to 3959 feet depth in Eskdale no. 6 (E.24298; E.24109).

*Lower halite.*—Above the anhydrite, flesh-pink halite, corresponding to Stewart's 'granular halite' zone, appears. A little anhydrite is mixed with it in the form of oblique wisps and veinlets. In the main this salt is unusually pure, but at its base there is a continuation of the sylvine

zone which develops towards the top of the underlying anhydrite. This sylvine zone ranges up to 3724 feet in Eskdale no. 3, and cores from this borehole show a strong yellow coloration of the sylvine at 3766–3769 feet depth. Although no rinneite was found here, it seems certain that this variety of sylvine arises from a decomposition of rinneite into sylvine, halite, and yellow limonite. In no. 6 borehole at 3953 feet 3 inches to 3955 feet 5 inches this sylvine zone is represented by a bed of coarse clear granular halite with anhydrite inclusions and opalescent sylvine crystals, and includes a 4-inch band of pure sylvine. In Eskdale no. 4 there are traces of sylvine at 4144–5 feet immediately above the lower anhydrite.

*Upper potash seam.*—The position of this seam appears to be between Stewart's 'granular halite' and halite zones, but it does not seem to be represented in the Aislaby boring. It represents a recrudescence of the mineral assemblage which first appears in the middle seam. Sylvine, halite, anhydrite, quartz, and subordinate carnallite are the principal constituents. Three important features distinguish the upper from the middle seam: (1) the presence of substantial amounts of salt-clay intermixed with the upper seam; (2) the abundance of coarse talc as a replacement of halite in the upper half of the seam; (3) the paucity of magnesite in it. Texturally the two seams have, nevertheless, much in common.

A general sample, taken by the same method as the analysed sample of the middle seam (p. 679), gave on analysis the results in table IV.

Thin sections in the Geological Survey collection of the upper potash seams include the following: no. 3 boring, E.22801–4; no. 4, E.23688–91; no. 6, E.24128–38. Red pigmentation of the sylvine, marginal or complete, is displayed, and it is noteworthy that the colouring matter in adjacent halite has a brown or greyish-brown appearance by comparison. The occurrence of red pigmentation along the courses of veinlets filled with talc may indicate that some of the colouring is secondary (E.24132). The clay occurs as apparently broken up fragments, and is also found in the interstices between chloride crystals, which have evidently been able to push it aside.

It should be noted here that no potash minerals are present at this position in the Aislaby borehole (Eskdale no. 2) where, from general stratigraphic and thickness considerations, the upper potash seam might be expected to occur. At this position, talc, the presence of which is a feature of the upper potash seam in the later borings, occurs in association with halite at 3778–3782 feet depth. The first appearance of potash in the Aislaby borehole is at 3798 feet depth where colourless halite

TABLE IV. Analysis of the upper potash seam.  
No. 3 (Sleights) boring, 3679-3697 feet.

Water-soluble matter.				Water-insoluble matter.			
						I.	II.
Mg	...	...	0.09	SiO <sub>2</sub>	...	57.8	5.91
Ca	...	...	0.82	Al <sub>2</sub> O <sub>3</sub>	...	14.6	1.49
Na	...	...	29.16	Fe <sub>2</sub> O <sub>3</sub>	...	3.3	0.34
K	...	...	6.73	FeO	...	1.9	0.19
SO <sub>4</sub>	...	...	1.81	MgO	...	9.7	0.99
Cl	...	...	50.94	CaO	...	0.2	0.02
Br	...	...	0.014	Na <sub>2</sub> O	...	0.2	0.02
I	...	n.d.	< 0.001	K <sub>2</sub> O	...	5.9	0.60
P <sub>2</sub> O <sub>5</sub>	...	...	n.d.	ign.†	...	5.0	0.51
Mn*	...	...	n.d.	TiO <sub>2</sub>	...	0.8	0.08
CO <sub>2</sub>	...	...	n.d.	P <sub>2</sub> O <sub>5</sub> (qual.)	...	trace	trace
B*	...	...	n.d.	MnO*	...	trace	trace
Ba*	...	...	n.d.	CO <sub>2</sub>	...	0.9	0.09
Sr*	...	...	trace	B <sub>2</sub> O <sub>3</sub> *	...	trace	trace
Pb*	...	...	trace	SO <sub>3</sub>	...	trace	trace
Li*	...	n.d.	< 0.01	Cl (qual.)	...	trace	trace
Rb*, Cs*	...	n.d.	< 0.1	FeS <sub>2</sub>	...	trace	trace
Tl*	...	...	n.d.	Cr <sub>2</sub> O <sub>3</sub>	...	n.d.	n.d.
			89.56	V <sub>2</sub> O <sub>5</sub> *	...	trace	trace
Water-insoluble matter			10.24	BaO*	...	trace	trace
Total H <sub>2</sub> O + 105° C.			0.25	SrO*	...	trace	trace
				Li <sub>2</sub> O	...	n.d.	n.d.
			100.05			100.3	10.24
Proximate mineral composition:				I. Water-insoluble matter as analysed.			
Halite	...	...	74.1	II. Water-insoluble matter recalculated to 10.24%.			
Sylvine	...	...	12.5	† Matter volatile on ignition, other than CO <sub>2</sub> and S, mainly H <sub>2</sub> O + 105* C.			
Carnallite	...	...	1.0				
Anhydrite	...	...	2.6				
Magnesite, dolomite	...	...	0.1				
Talc	...	...	2.9				
Silicate minerals	...	...	6.8				
Ilmenite	...	...	0.1				
Haematite	...	...	0.3				
			100.4				

The water-insoluble matter was analysed separately by semi-micro methods. Analyst, C. O. Harvey, Geol. Surv. Lab. nos. 1537, 1538 (1949).

\* Semi-quantitative spectrographic determination by J. A. C. McClelland.  
n.d., not detected.

contains a small proportion of pink sylvine. At 3804-3805 feet the core is remarkable for the presence of pockets of a bright yellow mineral which proves to be sylvine mixed with finely divided limonite, which are probably the decomposition products of rinneite. Thus the potash zone in the upper evaporite bed at the Aislaby borehole bears a marked

similarity and has a comparable position to the subsidiary potash zone at the base of the lower halite in the upper evaporite bed at Eskdale no. 3 borehole. It is considered possible, therefore, that the upper seam has died out completely before reaching the site of the Aislaby borehole, or else that it is present in the uncored portion of the hole between 3653 and 3738 feet.

*Upper halite.*—Halite, without potassium minerals, but enclosing streaks and layers of clay, is the next upward division in all three borings. Anhydrite is present in variable amount with, towards the top, some dolomite. The clay is the dull red type found also in the saliferous marl which forms the uppermost division of the Permian here, and occasional bluish or greenish 'eyes' are to be seen in it, where it is included in the halite. Some 'schistose' halite was noted at 3607 feet in no. 3 boring. Talc continues in small amount in this zone (E.22798).

*Top anhydrite.*—The topmost bed of the evaporite succession is a thin but persistent layer of anhydrite, composed of interlocked automorphic and hypautomorphic crystals averaging about 0.05 mm. Thin red films of haematitic clay enclose lenses of still finer-grained anhydrite which are engulfed within the main mass of the rock (E.22796).

The saliferous marl, mainly an anhydritic siltstone with detrital micas, quartz, clay minerals, and fine-grained dolomite, immediately succeeds the anhydrite (E.22794-5, 23686-7).

#### X-RAY DATA.

As X-ray powder data for carnallite do not appear to have been published, a standard photograph, details of which are given (table VI, no. 1) of Stassfurt material, was prepared. In a number of photographs sylvine was always found to be present as an impurity and is therefore also shown in the table (no. 2). It should be noted that the relative intensities of sylvine and carnallite are likely to vary. In the Stassfurt specimen the ratio of the intensities of the strongest lines of carnallite and sylvine was 1:1.3. Powder data for polyhalite are shown in table VI, no. 3. Intensities expressed numerically in the table were measured with a microphotometer and are given relative to unit intensity for the strongest line.

#### SUMMARY.

1. An account is given of the Permian evaporite succession revealed by the three Imperial Chemical Industries borings, with ranges of minerals as determined by optical methods. A lower polyhalite zone and one subsidiary and two main sylvine beds are described.

TABLE VI. X-ray powder data for evaporite minerals.  
( $\lambda = 1.5418 \text{ \AA}$ ., 9-cm. camera.)

1, Carnallite.		2, Sylvine.		3, Polyhalite.			
$d(\text{\AA}.)$	<i>I.</i>	$d(\text{\AA}.)$	<i>I.</i>	$d(\text{\AA}.)$	<i>I.</i>	$d(\text{\AA}.)$	<i>I.</i>
4.65	0.5	3.13	vs	5.94	0.18	1.693	0.11
3.77	0.5	2.21	ms	4.77	< 0.05	1.584	0.06
3.56	0.5	1.808	mw	4.08	0.06	1.550	0.05
3.30	1.0	1.568	w	3.78	< 0.05	1.510	0.05
3.01	0.30	1.392	mw	3.47	< 0.05	1.453	0.10
2.92	0.7	1.282	w	3.39	0.19	1.434	< 0.05
2.83	0.33	1.108	vw	3.17	0.9	1.403	< 0.05
2.37	0.23	1.047	vw	2.90	1.0	1.377	< 0.05
2.33	0.31			2.54	< 0.05	1.354	0.06
2.12	0.27			2.50	< 0.05	1.327	< 0.05
2.00	0.34			2.41	< 0.05	1.303	0.05
1.975	0.43			2.33	0.05	1.267	< 0.05
1.886	0.10			2.21	0.17	1.231	0.08
1.865	0.11			2.03	< 0.05	1.215	< 0.05
1.458	0.20			1.984	0.09	1.197	< 0.05
				1.936	0.09	1.179	< 0.05
				1.891	0.12	1.152	< 0.05
				1.861	0.12	1.112	0.07
				1.805	0.15	1.059	0.06
				1.766	0.09	1.041	< 0.05
				1.725	0.08	1.021	< 0.05

1, Carnallite, Stassfurt, Germany (Film no. X55).

2, Sylvine, occurring with carnallite, Stassfurt (X55).

3, Polyhalite, Eskdale no. 2 borehole, Yorkshire (X147).

2. Kieserite accompanies polyhalite in the lower potash seam, where it appears to have been the last mineral formed, replacing polyhalite which had itself replaced anhydrite.

3. In the middle evaporite bed, the mineral assemblage in the middle potash seam includes sylvine, halite, minor amounts of carnallite, anhydrite, euhedral quartz, and magnesite. Chemical analysis reveals an abundance of magnesia in the water-insoluble portion of this seam.

4. The carnallitic marl is a salt-clay containing pseudomorphs after gypsum and halite. It is traversed by veins and veinlets carrying carnallite, rinneite, halite, sylvine, anhydrite, quartz, and magnesite. A little polyhalite, possibly of early formation, occurs in the clay. Carnallite forms 10 % of the rock.

5. The upper potash seam, at or near the junction of Stewart's 'granular halite' (with scarce rinneite) and halite zones, contains halite, sylvine, subordinate carnallite, anhydrite, and quartz. Talc is abundant in the upper part of the seam.

6. The water-insoluble portions in analysed samples from the middle

and upper seams and from the carnallitic marl are alike in the abnormally high MgO/CO<sub>2</sub> ratio they show. This points to the presence of magnesium silicates such as talc (which is conspicuous in the upper seam) or magnesian chlorite or both.

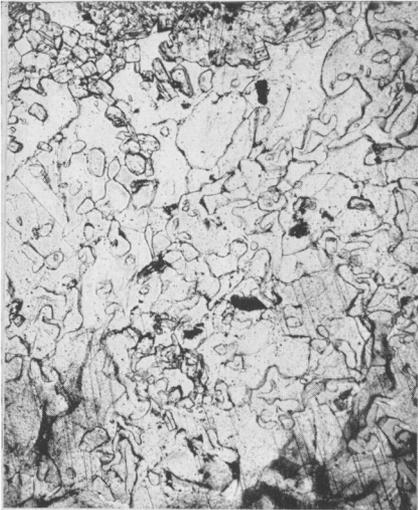
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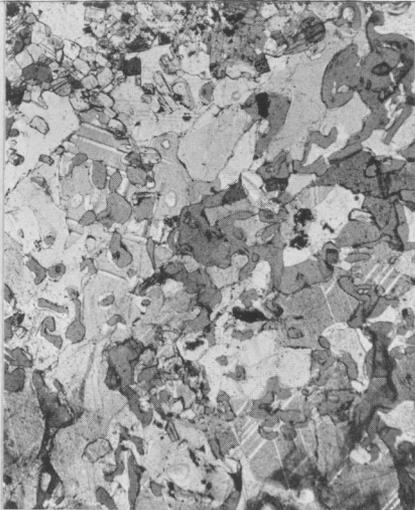
EXPLANATION OF PLATE XXV.

Photomicrographs of potash-salt rocks from NE. Yorkshire.

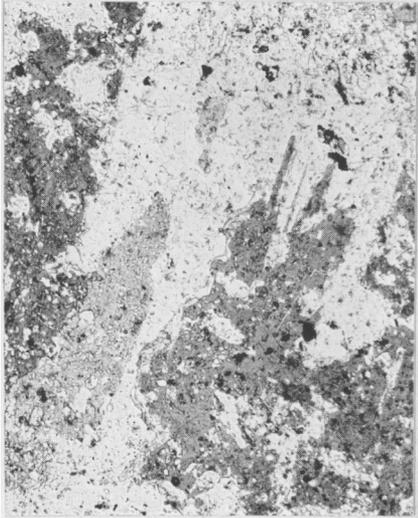
- FIG. 3. Carnallite vein. Carnallite is distinguished by intersecting sets of twin lamellae. Halite shows sinuous boundaries against the carnallite. Small anhydrite euhedra occur at the top of the photograph. Eskdale no. 6 borehole, 4000 feet, E.24114. (*a*) Ordinary light, (*b*) nicols slightly uncrossed.  $\times 12$ .
- FIG. 4. Kieserite-polyhalite-rock. Kieserite, showing complicated twinning, encloses abundant grains of polyhalite. Eskdale no. 3 borehole, 5033 feet 6 inches, E.23057. Crossed nicols.  $\times 57$ .
- FIG. 5. Sylvine-anhydrite-halite-rock. Sylvine (cloudy) and subordinate halite (clear) enclose abundant small automorphic prisms of anhydrite. Eskdale no. 6 borehole, 3957 feet, E.24298. Ordinary light.  $\times 14$ .



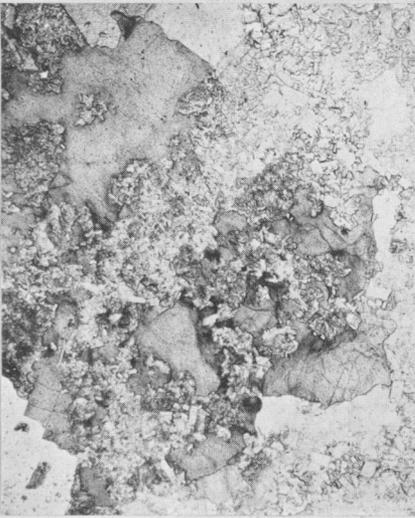
3a



3b



4



5

G. ARMSTRONG *ET AL.*: PHOTOMICROGRAPHS OF POTASH-SALT ROCKS FROM NORTH-EAST YORKSHIRE