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*The origin of some Manganese oxide ores: with
special reference to the deposits of Sinai*

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Secrets come to light in the wilderness.

Frontispiece

THE ORIGIN OF SOME MALGANESE OXIDE ORES,
with special reference to the deposits of Sinai.

being a thesis for
the degree of Doctor of Philosophy

submitted in
December, 1957

by

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P A R T I

THE OXIDE ORES OF MANGANESE.

(1) THE MANGANESE OXIDE MINERALS.

These minerals may be divided into four fundamental groups, according to the state of oxidation of the manganese. The pure oxides symbolising these groups are, in ascending order of oxidation, manganosite (MnO), hausmannite (Mn_3O_4), bixbyite (Mn_2O_3) and pyrolusite (MnO_2). Manganese in higher states of oxidation is not found preserved in natural environments. These minerals will be described here with analagous minerals containing essential ions of other metals, and the hydrous oxide minerals.

(i) Manganous oxide group.

(a) Manganosite.

The formula is given as MnO , but Fe, Mg and Zn may substitute for Mn. The crystal system is cubic, hexoctahedral class ($4/m \bar{3} 2/m$), and the space group is $Fm \bar{3} m$. The length of the a axis is 4.436 A, unit cell containing Mn_4O_4 .

The colour is green on fresh surfaces, turning to black on exposure. The streak is brown and the hardness $5\frac{1}{2}$. The specific gravity is calculated at 5.36, artificially prepared material varying between 5.0 and 5.4. The mineral is transparent, with a vitreous lustre. In polished section manganosite appears grey and isotropic, with emerald green internal reflections. In transmitted light the colour is emerald green. The refractive indices and dispersion are high (n green 2.19, n red 2.16).

Manganosite is unstable under atmospheric conditions, altering to the higher oxides. It alters more readily under alkaline conditions, yielding the hydrous oxide pyrochroite ($Mn(OH)_2$) and eventually manganite ($MnOOH$). The compound forms solid solutions at high temperature with other RO oxides, and has been found in ex-solution intergrowths with zincite (ZnO) and periclase (MgO). The melting point is 1785° , (Hay, Howat & White, quoted by Mason, 1943).

Manganosite was named and first described from Langban by Blomstrand in 1874. It occurs as small grains in dolomite, formed by the metamorphism of calcium, magnesium and manganese carbonates, the latter breaking down to manganosite and carbon dioxide at a relatively low temperature (Mason, *ibid*).



(b) Pyrochroite.

The formula is given as $\text{Mn}(\text{OH})_2$, but Hg, Zn and Fe may substitute for Mn. The crystal system is trigonal, scalenohedral class ($32m$) and the space group is $C 3m$. The unit cell contains $\text{Mn}(\text{OH})_2$, the dimensions being $a = 3.34\text{A}$, $c = 4.68\text{A}$.

The colour is pale greenish blue on fresh surfaces, altering to brown and finally to black on exposure. The mineral is transparent in thin plates, with a pearly lustre on cleavage surfaces. The hardness is $2\frac{1}{2}$ and the specific gravity is calculated at 3.25.

In transmitted light thin sections are colourless, becoming brown on alteration, and pleochroic with absorption $O > E$. The mineral is uniaxial negative, with indices: $nO = 1.723 - 1.733$, and $nE = 1.681 - 1.693$.

(ii) Mangano-manganic oxide group.(a) Hausmannite.

The formula is Mn_3O_4 , or $\text{Mn}^{2+}\text{Mn}^{3+}_2\text{O}_4$. The mineral belongs to the ditetragonal dipyramidal class of the tetragonal system ($4/m2/m2/m$), and is regarded as having a deformed spinel structure. The space group is $I4/amd$. The unit cell contains $\text{Mn}_4\text{Mn}_8\text{O}_{16}$ and the dimensions are $a = 8.14\text{A}$, $c = 9.42\text{A}$ (Mason, *ibid*), but these are quoted as $a = 5.75\text{A}$, $c = 9.42\text{A}$ by Fleischer (1944).

The colour of hausmannite is described by Fleischer as brownish black to reddish, giving a reddish brown streak. Material from Om Bogma, Sinai is a metallic grey. The mineral is paramagnetic. The hardness is 5 to $5\frac{1}{2}$ and the specific gravity varies between 4.7 and 4.9, being calculated at 4.84.

Thin sections of hausmannite appear deep reddish brown and non-pleochroic in transmitted light. The mineral is uniaxial negative with indices: $nO = 2.46 \pm 0.06$, $nE = 2.15 \pm 0.02$. In polished section it appears grey-white with low reflectivity (between 10% and 20%) and slight reflection pleochroism ($O > E$). The plane of polarisation is rotated through 2° . Anisotropy is distinct, with brown and grey to blue colours. Deep red to brownish internal reflections appear in some sections. Lamellar twinning

is reported to be typical, but this was not seen in material from Om Bogma.

The d spacings and estimated intensities of the lines in an x-ray powder photograph of a specimen from Om Bogma are as follows: (08|15) (Fe radiation, Mn filter, taken with a 9cm. camera).

no.	d	I
1	4.9	40
2	4.1	50 (goethite?)
3	3.07	40
4	2.75	60
5	2.47	100
6	2.35	5
7	2.03	5
8	1.79	5
9	1.57	3
10	1.54	20
11	1.44	5

Hausmannite is the most stable oxide of manganese at high temperatures, and can be produced by heating any of the other oxides in air at about 1000° (Mason, *ibid*). The melting point is given as 1560° .

First recognised by Werner, hausmannite is of widespread occurrence but of comparatively minor importance as an ore of manganese. Besides high temperature associations it also occurs in deposits showing no other sign of thermal activity, as in Fiji.

(b) Solid solution relationships.

The naturally occurring mineral is generally almost pure Mn_3O_4 , but it has been found with 6.91% of Fe_3O_4 , which appears to be close to the limiting replacement at ordinary temperatures, and 8.6% of ZnO - apparently a connecting link with heterolite ($ZnMn_2O_4$). Verwey and van Bruggen (1935) reported the preparation of a series of solid solutions of Mn_3O_4 with Fe_2O_3 . There was a gradual change in the axial ratios with increasing Fe content, from $c/a = 1.16$ to $c/a = 1.00$ at a composition of Mn : Fe = 60 : 40, mixtures with more than 40% Fe_2O_3 having a cubic structure comparable to γFe_2O_3 . Mason (1943), without reference to the above work, reported a similar series between the end members Mn_3O_4 - Fe_3O_4 , with a similar change from tetragonal

to cubic structure at 60% Mn_3O_4 . The work appears to have been duplicated with a different interpretation of the valency state of the iron present. The essential point is that the deformation of the spinel structure is caused by the larger size of the manganese ions, but it appears to be the smaller trivalent ion (the largest trivalent ion in the iron family) which causes the deformation rather than the larger di-valent ion as suggested by Goldschmidt (1954). Thus the minerals jacobite (ideally $\text{Mn}^{2+}\text{Fe}^{3+}_2\text{O}_4$) and galaxite (ideally $\text{Mn}^{2+}\text{Al}^{3+}_2\text{O}_4$) have normal spinel structures, while hetaerolite ($\text{Zn}^{2+}\text{Mn}^{3+}_2\text{O}_4$) has a tetragonal lattice resembling that of hausmannite, although all the other zinc spinels are cubic.

(c) Hydrohausmannite.

This mineral has been described by Brondel (1953) and Wadsley (1955). The structure is similar to that of hausmannite with a slightly larger unit cell, compared with the dimensions of Fleischer (ibid): $a = 5.79\text{\AA}$, $c = 9.49\text{\AA}$. The unit cell contains $(\text{Mn}^{2+}, \text{Mn}^{3+})_{12-6} (\text{O}, \text{OH})_{16}$.

The colour is iron-black to brownish black with a brown streak. The refringence is less than that of hausmannite, $n_0 = 2.055$, $n_E = 1.95$. The mineral is dichroic in brown, with $E > 0$.

(iii) Manganic oxide group.

(a) Bixbyite.

The ideal formula for bixbyite is $\alpha\text{Mn}_2\text{O}_3$, iron is practically always present, substituting for manganese. The mineral belongs to the diploidal class of the cubic system ($2/m\bar{3}$), space group Ia $\bar{3}$. The unit cell contains $(\text{Mn}, \text{Fe})_{32}\text{O}_{48}$. Gruner (1943) reported a variation in cell size according to the Mn : Fe ratio: artificial Mn_2O_3 $a = 9.42\text{\AA}$, 17.25% Fe_2O_3 $a = 9.39\text{\AA}$, c. 40% Fe_2O_3 $a = 9.35\text{\AA}$. Mason (ibid.), however, found the cell edge of pure Mn_2O_3 to be $9.400 \pm 0.005\text{\AA}$, and that of a sample with 60% Fe_2O_3 to be $9.386 \pm 0.005\text{\AA}$. The structure is that of the C type of sesquioxides, (cf. the rare earth oxides) with octahedral co-ordination. The large size of the trivalent manganese ion (0.73\text{\AA}) prohibits the ~~tetrahedral~~ co-ordination of the corundum type of structure, cp. $\alpha\text{Fe}_2\text{O}_3$ (ionic size of $\text{Fe}^{3+} = 0.70\text{\AA}$).

The colour of bixbyite is dark brown to black, and the streak is dark brown. The hardness is $6\frac{1}{2}$ and the specific gravity 4.74 to 5.1, calculated at 5.01. The mineral is opaque with a metallic to sub-metallic lustre. It is weakly magnetic, being infusible before the blowpipe but becoming strongly magnetic on alteration to $(\text{Mn,Fe})_3\text{O}_4$.

Bixbyite is the stable oxide of manganese between 530° and 940° . It occurs in pneumatolytic deposits and in metamorphosed manganese ores, often in well-formed cubic crystals. Mason (ibid.) demonstrated that Fe_2O_3 is soluble in bixbyite to the extent of about 20% at ordinary temperatures, rising to nearly 70% at 1000° . The composition of the bixbyite occurring in the presence of haematite thus gives an indication of its temperature of formation.

(b) Braunite.

The formula is $3\text{Mn}_2\text{O}_3 \cdot \text{MnSiO}_3$. Braunite belongs to the ditetragonal dipyramidal class of the tetragonal system ($4/m2/m2/m$), and the space group is $I4/acd$. Mason (ibid.) reports the unit cell dimensions as $a = 9.41\text{A}$, $c = 18.64\text{A}$, but they are given in "Dana's System of Mineralogy" as $a = 13.44\text{A}$, $c = 18.93\text{A}$ for a unit cell containing $(\text{Mn,Si})_{128}^{O}_{192}$.

The colour of the mineral is dark brownish black and the streak blackish brown. The hardness is 6 to $6\frac{1}{2}$ and specific gravity 4.72 to 4.82, being calculated at 4.83. Braunite is weakly magnetic and opaque with a submetallic lustre. In polished section it appears greyish white and anisotropic, with a reflectivity of 15% to 20%.

Normally braunite contains little foreign material in solid solution, but small amounts of iron are commonly present. Hewett & Schaller (1937) reported a specimen with 81% $3\text{Mn}_2\text{O}_3 \cdot \text{MnSiO}_3$ and 19% $3\text{Fe}_2\text{O}_3 \cdot \text{MnSiO}_3$, but this is an exception and a wide range of solid solution seems unlikely. Fermor (1909) reported an analysis corresponding to the formula $3\text{Mn}_2\text{O}_3 \cdot (\text{Mg,Ca})\text{SiO}_3$, and this was confirmed with an artificial product by Mason (ibid.).

Braunite is probably more common than bixbyite, and locally forms an important ore of manganese, as in some of the Moroccan deposits.

(c) Manganite.

The formula is $\text{MnO}(\text{OH})$, manganite being a member of the prismatic class of the monoclinic system ($2/m$). The structure was determined by

Buerger (1936) who assigned to it the space group $B2_1/d$. The unit cell contains $Mn_8O_8(OH)_8$, the dimensions being $a = 8.86A$, $b = 5.24A$, $c = 5.70A$, $\beta = 90^\circ$. The manganese is in octahedral co-ordination.

Manganite is dark grey to black, with a chocolate brown streak. The hardness is 4 and the specific gravity 4.2 to 4.4, being calculated at 4.38. The lustre is sub-metallic, the mineral being transparent only in the thinnest splinters.

In transmitted light manganite appears red-brown and faintly pleochroic, (X and $Y > Z$). The optic plane $= 010$, $Z = c$ ($\pm 4^\circ$) and $2V$ is small and positive. Dispersion is very strong, red $>$ violet. The refractive indices in lithium light are: $nX = 2.25$, $nY = 2.25$ and $nZ = 2.53$.

In polished section manganite is grey-white with a brownish tint. It is faintly pleochroic and anisotropic with blood red internal reflections. The reflectivity is between 10% and 20%.

(d) Groutite.

The formula of groutite, described by Gruner (1945), is $HMnO_2$. It is orthorhombic (space group $Pbmm$), and a member of the diaspore - goethite group. The unit cell dimensions are $a = 4.58A$, $b = 10.76A$, $c = 2.89A$.

The colour is jet-black, the hardness 3.5 and the specific gravity 4.14.

(iv) Manganese dioxide group.

(a) Pyrolusite.

MnO_2 , pyrolusite, also formerly named polianite, belongs to the ditetragonal dipyramidal class of the tetragonal system ($4/m2/m2m$); the space group is $P4/mrm$. The unit cell contains Mn_2O_4 and the dimensions are: $a = 4.48A$, $c = 2.86A$.

Pyrolusite is opaque and iron grey to black in colour, with a black streak and metallic lustre. The hardness is 6 to $6\frac{1}{2}$ but as the mineral rarely occurs in good individual crystals and is often in the form of soft minutely crystalline masses the hardness has been recorded as 2. The specific gravity for the pure mineral is 5, but values between 4.7 and 4.9 are commonly observed.

In polished section pyrolusite appears creamy white and weakly pleochroic, with reflectivity 25% to 35%. Anisotropy is distinct.

The d spacings and estimated intensities of the lines from an x-ray powder photograph of a specimen from Oja Bogma (OB/65) follow:
(Fe radiation, Mn filter, taken with a 9 cm. camera).

no.	d	I
1	7.1	2
2	4.29	5
3	3.38	30
4	3.14	100
5	2.42	25
6	2.12	20
7	1.63	30
8	1.55	5
9	1.30	15

Pyrolusite is probably the most abundant manganese mineral, being the stable form of manganese under normal atmospheric conditions. It is of very widespread occurrence, in small amounts in many rocks within the zone of weathering and in concentrations forming the most valuable ore deposits. It is found in both primary and secondary deposits.

(b) Ramsdellite.

The formula is MnO_2 ; ramsdellite is a dimorph of pyrolusite. This mineral is orthorhombic, with unit cell dimensions: $a = 4.5A$, $b = 9.2A$, $c = 2.83A$. It is iron-grey to black in colour, with a black streak. The hardness is 3 and specific gravity 4.7.

This mineral was first described by Ramsdell in 1932 and was named by Fleischer and Richmond (1943). It is a very rare mineral. γ MnO_2 is a more reactive compound and therefore of special use in the battery trade. It may be a poorly crystalline form of ramsdellite or a form intermediate between ramsdellite and pyrolusite. It is more widespread in occurrence than ramsdellite, (Cole, Wadsley & Walkley, 1947, Wadsley & Walkley, 1951).

(c) The alpha dioxides.

This term includes a group of minerals, cryptomelane, hollandite and coronadite, containing essential ions other than manganese. The ratio

O : Mn is always less than 2, being in the range 1.83 - 1.90. The group was shown to be isostructural by Frondel & Heinrich (1942), Richmond & Fleischer (1942) and Gruner (1943). It has since been investigated by Bystrom & Bystrom (1950), who proposed the general formula: $A_{2-y} B_{8-z} X_{16}$, where A represents large ions, Ba^{2+} (hollandite), K^+ (cryptomelane) or Pb^{2+} (coronadite); B represents small or medium-sized ions, Mn^{4+} , Fe^{3+} or Mn^{2+} ; X represents O^{2-} or OH^- . They (Bystrom & Bystrom, 1951) have since modified this to include water which may possibly occur within the lattice: $(Ba,K,Pb)_{2-y}(H_2O)_u(Mn,Fe)_{8-z}(O,OH)_{16}$, where y is always close to 1, but less in coronadite, u is probably always small and must be less than 1, and z is nearly 0. Maxwell, Butler & Thirsk (1952) studied artificial MnO_2 with other foreign ions.

These minerals are tetragonal or pseudotetragonal (monoclinic) with β within 0.5° to 1.5° of 90° . The space group of the tetragonal cell is $I4/m$ and the cell dimensions are $a = 9.8A$, $c = 2.86A$. The manganese is in octohedral co-ordination.

The colour is steel grey to black, with a metallic to sub-metallic lustre and a dark brownish black streak. The hardness is 6 and the specific gravity in the range 4.2 to 5.6, being low for cryptomelane and higher for coronadite.

In polished section the minerals of this group appear white and weakly pleochroic, but strongly anisotropic. The reflectivity is in the range 20% to 30%. Chemical tests are necessary to distinguish the individual members of the group.

These minerals are of widespread occurrence, cryptomelane being by far the most common.

(d) Psilomelane.

This name was previously applied to a broader group of minerals, including the three species described above. Psilomelane was originally described from Schneeberg in 1831 by Haidinger. It was investigated by Vaux (1937), using x-ray methods, and more fully studied by Wadsley (1952a and 1953).

The formula is $(\text{Ba}, \text{H}_2\text{O})_2\text{Mn}_5\text{O}_{10}$. Psilomelane is monoclinic, space group $A2/m$. The unit cell contains: $\text{Ba}_{1.28}(\text{Mn}, \text{R})_{10}\text{O}_{20} \cdot 2.72\text{H}_2\text{O}$, $\text{R} = \text{Mn}^{2+}$ and traces of other ions substituting for Mn^{4+} . The unit cell dimensions are: $a = 9.56 \pm 0.02\text{A}$, $b = 2.88 \pm 0.02\text{A}$, $c = 13.85 \pm 0.02\text{A}$, $\beta = 92^\circ 30' \pm 20'$.

The colour and streak are black, and the mineral is opaque with a sub-metallic lustre. The hardness is 6 and the specific gravity 4.4 to 4.7, being calculated at 4.82.

In polished section psilomelane appears greyish white and generally fine grained or amorphous, with moderate reflectivity (lower than the reflectivity of pyrolusite). The reflection pleochroism and anisotropy are strong. Some specimens show brown internal reflections (Uytenbogaart, 1951), but these were not seen in specimens from Om Bogma.

The Sinai material suspected of being psilomelane or related minerals did not give good x-ray powder photographs. It was identified on the basis of its optical properties as belonging to this type, the composition of the ore (Chapter 6, (i), (b)) suggesting that all of these minerals (psilomelane, cryptomelane, hollandite and coronadite) are represented.

Psilomelane is one of the commonest manganese minerals. It loses water on heating, taking it up again on exposure to air for several days. At 550° it alters to its dehydration product, hollandite (Wadsley, 1953). All the manganese dioxides become unstable at about this temperature, altering to bixbyite (Gruner, 1943), but the change is apparently not rapid until a higher temperature is reached, as in D.T.A. both psilomelane and pyrolusite show strong endothermic reactions above 600° , but little reaction below this temperature (Heystek & Schmidt, 1954).

(e) Wad.

Poorly crystalline, generally soft and earthy, forms of hydrous manganese oxides are generally classed as "wad". In recent years some of this and other material has been investigated and a number of distinct minerals are now recognised. This material is generally unimportant as ore: the minerals will merely be briefly listed here.

Cesarolite	$PbMn_3O_7 \cdot H_2O$	
Chalcophanite	$(Mn, Zn) Mn_2O_5 \cdot 2H_2O$	(Wadsley, 1955a)
Lithiophorite	$LiMn_3Al_2O_9 \cdot 3H_2O$	(Wadsley, 1952b)
Quenselite	$Pb_2Mn_2O_5 \cdot H_2O$	
Ranciéite	$(Mn, Ca) Mn_4O_9 \cdot 3H_2O$	(Richmond & Fleischer, 1942a)
Woodruffite	$(Zn, Mn)_2 Mn_5O_{12} \cdot 4H_2O$	(Brondel, 1953)

(2) THE PROBLEM OF ORE-GENESIS.

In the past the genesis of some of the oxide ores of manganese has been rather an enigmatic subject. The larger deposits of these ores typically occur as more or less conformable masses of the higher oxides of manganese, occurring either alone or accompanied by varying (and often enormous) amounts of the higher oxides of iron. Seldom do any other elements occur in more than very minor proportions.

There has been a tendency among many geologists to ascribe an epigene origin to the manganese oxides, the ore deposits being classified as sedimentary, residual or metamorphic, the latter being formed by the alteration of the two former types. This approach is epitomised in "Kutley's Mineralogy" (Read, 1948), probably one of the most widely used reference books among economic geologists and others having frequent contact with manganese ores:

"It will be seen that all deposits of manganese oxides have been formed by the breaking up of the manganese bearing minerals of igneous and metamorphic rocks."

The point was also made by Lindgren (1933):

"Manganite, pyrolusite, psilomelane and wad are always secondary, formed under the influence of weathering."

In the extreme case even the formation of veins of manganese oxides has been regarded as being by the filling of a previously open fissure by material of superficial origin (Neltner, 1933).

In support of the sedimentary marine origin the deposits forming on the floor of the deeper parts of the ocean are sometimes cited. These are, however, forming extremely slowly, in the almost total absence of other deposition. Disregarding the theory of the permanence of the oceans, if such deposits were to be raised up to be exposed in a land-mass they would present lithological associations quite unlike those of many of the larger known manganese ore deposits.

It is more usual to suggest deposition in shallow coastal waters, by analogy with the sedimentary iron ores. The deposits of Chiatury, probably the largest in the world, are quoted as an example of this. The problem here is one of concentration, or more particularly of relative

concentration. To produce a workable iron ore body containing 40% of the metal the average concentration of iron in the crust (about 5%) has to be increased eight times, but to form a manganese ore of comparable tenor the average concentration of manganese (about 0.1%) must be increased 400 times. For an ore with equal proportions of iron and manganese the natural processes of concentration of the latter must be 50 times more effective than for the iron. It must be remembered that, excluding biological factors, conditions which are favourable to the concentration of manganese are generally also favourable to the concentration of iron. This relative concentration could best be effected at the source (i.e. during weathering), as the manganous ion is leached more easily than the ferrous ion (Goldschmidt, 1954). There is still concentration relative to the normal sediments of a neritic environment to be considered; owing to the usually very small proportion of manganese in the rocks of the crust its accumulation in the sea as a result of the weathering of those rocks would necessarily be slow. Where an ore deposit is associated with detrital sediments (as at Chiatary) further concentration by secondary processes may have to be invoked.

Very special conditions would be required for the formation of large sedimentary deposits of manganese ore, but large oxide ore bodies of remarkable purity occurring in many varied types of rock formation have been classed as of sedimentary origin in the past.

Bog ores and lake deposits of manganese oxide are being formed in many places at present, but they are generally of small size, amounting to some tens of thousands of tons. This mode of formation does not apply to any of the larger manganese ore deposits.

Residual and lateritic deposits can also be seen forming at the present time. Accumulation in this manner is common, since manganese is readily oxidised in atmospheric conditions to the insoluble trivalent or tetravalent ions. The proposed residual origin of some ores, however, is not entirely satisfactory. In some cases the "oxidised zone" of a deposit has been found to extend well below the present water table, and so it has been impossible to attribute this oxidation to weathering in the present cycle of erosion (Fermor, 1909).

The oxides of manganese are not easily accommodated in the normal

sequence of hydrothermal mineral deposits associated with deep-seated igneous intrusions. They have not been recorded in any appreciable quantity in the paragenesis of the hydrothermal deposits at any stage, except the zone of secondary alteration where they are sometimes found as oxidation products of the carbonate and silicate minerals, rhodochrosite, mangano-siderite and rhodonite. The iron and manganese oxide deposits are "foreign" to this primary hydrothermal environment on two counts: these are the high state of oxidation of these metals and the usual paucity of gangue, or any minerals other than the oxides of iron and manganese.

The occurrence of many of the manganese oxide deposits in association with, or in proximity to volcanic or minor intrusive rocks has led Westerveld (1948) to infer that they are genetically connected with this igneous activity. He proposed a scheme of classification for the manganese deposits, associated with the Alpine orogenic belts including oxide, carbonate and silicate minerals of both hydrothermal and sedimentary origin, arriving at the following conclusion (1951):

"Le schéma suppose que presque la majeure partie des gîtes de manganèse des régions alpines a reçu ce métal de sources hypogènes, même le grand dépôt de Tchiaturi. Les concentrations tout à fait sédimentaires, dérivées de roches décomposées par alteration superficielle ou formées par latéritisation de roches basiques, ne paraissent jouer qu'un rôle très secondaire; quand celles-ci obtiennent quelque importance, il s'agit le plus souvent de remaniements de matériaux provenant d'une source profonde."

The object of this thesis is to explain the origin of some deposits of manganese oxide ore.

P A R T I I

THE MANGANESE AND IRON DEPOSITS OF SIMAI.

(1) INTRODUCTION.(i) Location.

Sinai is a roughly triangular area with south-pointing apex situated at the junction of Asia and Africa. It is bounded to the north by the Mediterranean coast-line; to the west by the Suez Canal crossing the Isthmus of Suez; and to the east it merges into the Negev Desert (Israel). The southern part, the Sinai Peninsula, is bounded by the two northern arms of the Red Sea - the Gulf of Suez to the south-west and the Gulf of Aqaba to the south-east.

Om Bogma is situated about midway between Suez and Ras Mohammed, the southern point of the peninsula, seventeen kilometres from the shore of the Gulf of Suez and 700 metres above sea-level. (Lat. 29° N., Long. $33^{\circ} 20'$ E.).

(ii) Physical Features.

The topography of Sinai is very varied, from the mud-flats and low sand dunes round the Bay of Pelusium in the north, through white chalk hills and the Cretaceous escarpment of the central portion, which is known as the Gebel el Tih and forms an almost unbroken barrier over 1,000 metres above sea-level across the middle of the peninsula, to the extremely rugged country of Pre-Cambrian crystalline rocks of the south. Gebel Katharina, the highest peak of Mount Sinai, situated in the latter area, rises to an altitude of 2,646 metres (Ball, 1916) Om Bogma is on a strongly faulted and deeply dissected plateau of sandstone resting on a basement of the crystalline rocks. The lower parts of the two principal drainage channels of this area, the Wadi Baba and the Wadi Shellal, which cut through the uplifted granites of the basement, are very narrow and deep box-canyons. The upper parts of these wadis are wider, sand-filled valleys. Many of the hills are bounded by near-vertical cliffs. The nature of the terrain makes transport a difficult and costly proposition.

Plate I

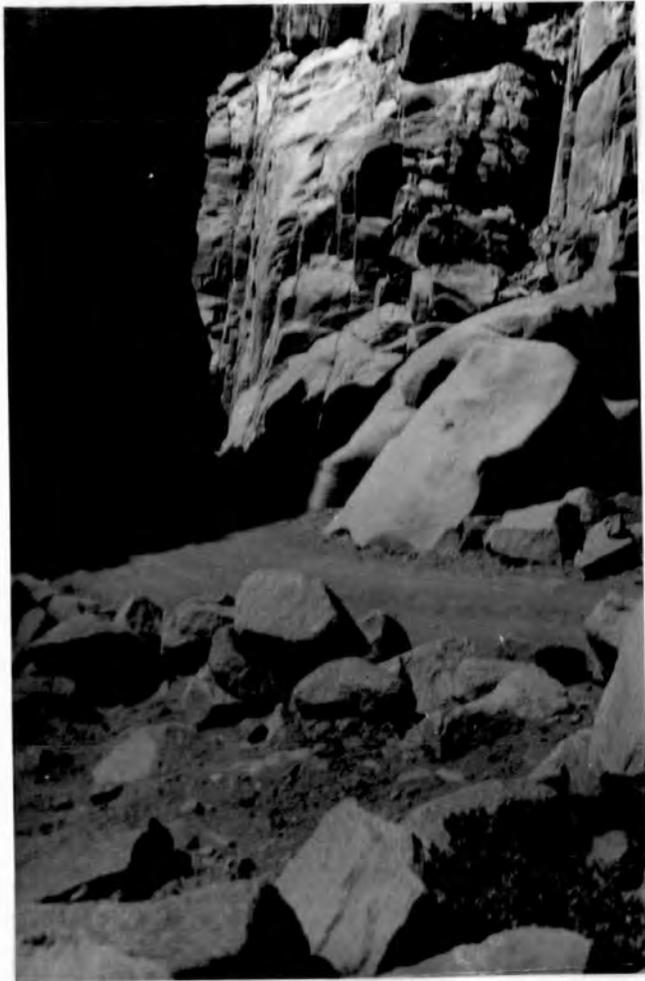
The lower parts of the courses of the main drainage channels, where they cut through the granitic rocks of the basement complex, are narrow box canyons.

Lower part of Wadi Shellal, $3\frac{1}{2}$ kms. south-west of Om Bogma.

Plate II

The upper parts of these wadis, traversing the sediments at a smaller gradient, are wider, sand-filled valleys.

Upper part of Wadi Baba, looking north-east from Bir Rekeis.



Limestone Series →

Lower
Sandstone



← Limestone Series
Lower
Sandstone

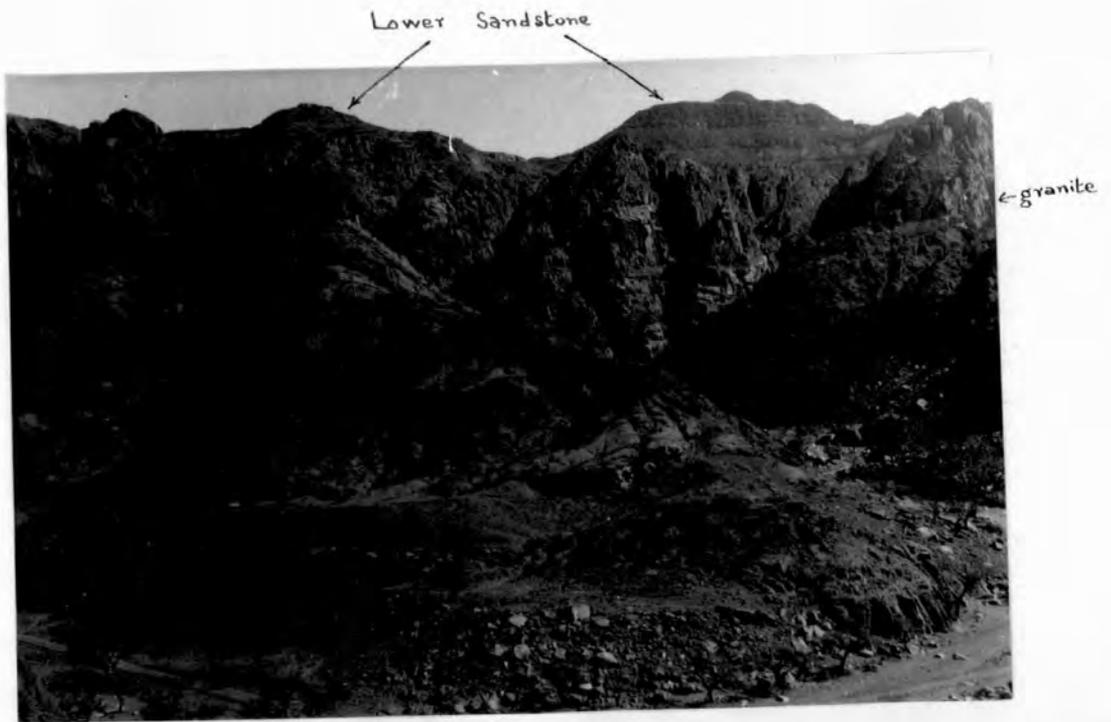


Plate III

The nature of the terrain makes transport a difficult and costly proposition.

The motor road leading down to Wadi Shellal from the Om Bogma hills.

Plate IV

A dissected plateau of sandstone resting on the uplifted granites of the basement.

Looking north-east from the downthrow side of one of the major faults in Wadi Shellal.

(iii) The Mining Areas.

The principal mining operations are carried out on the properties of the Sinai Mining Company Limited. These fall naturally into two parts: the older mines of Om Bogma itself, and the Nahman Areas to the east and north-east of them. The Om Bogma have provided virtually all / mines the production of this company to date. They are situated on four groups of hills, described by Ball as the Central, North, East and South hills but better known at the mines as "Lease 10", "Lease 8", "Lease 9" and "Ras el Homara" respectively. The Nahman Areas, named after Enrico Nahman, the engineer who took out the first mineral prospecting licences in them, are considerably larger, extending some five kilometres eastwards to the Wadi Nasib and Wadi el Lahian and for several kilometres to the north.

The surrounding areas, to the north of Wadi Baba, east of Wadi Nasib and south of Wadi el Sahu, as well as the lower part of the Wadi Shellal (the continuation of Wadi el Sahu), have been worked for smaller deposits of manganese dioxide. This activity has increased considerably in recent years.

(iv) Climate and Vegetation.

The climate is dry, with a few inches of local rainfall in the winter months. Winter temperatures are usually in the $40^{\circ} - 50^{\circ}$ (F) range; frost is of rare occurrence except on the higher mountains. Summer indoor temperatures are in the range $85^{\circ} - 95^{\circ}$, but shade temperatures have been recorded up to 125° (F). Midday temperatures in the deep wadis during the summer are very high as there is very little shade or movement of air.

The most important agent of erosion has been running water. Although rain only falls on two or three days in the year a good deal of the water flows away as surface run-off, there being virtually no soil or vegetation to hold it. The result is that in the normally dry wadis there suddenly appear torrents of water which can move quite coarse material in their path. Probably the very deep erosion of the higher ground took place during the Pleistocene Pluvial period, but there are

Plate V

Wind erosion in the sandstones; examples of honeycomb weathering, enlarging to windows and undercut ledges.

Lower Sandstone on the eastern slope of the North Hill.

Plate VI

Erosion in the basement rocks is largely controlled by joints and other structure lines.

Wadi Shellal, 3 kms. southwest of Om Bogma.

Plate VII

The dolomites of the Limestone Series typically form flat-topped hills (mesas) and plateaux.

Central Hills, seen from the middle of the North Hills. Prominent cliff of Lower Sandstone, with a lesser scarp of Upper Dolomite nearer the top of the hill.



m-
ands



Pavement →



Upper Dolomite
Limestone Series
Pavement
Lower Sandstone

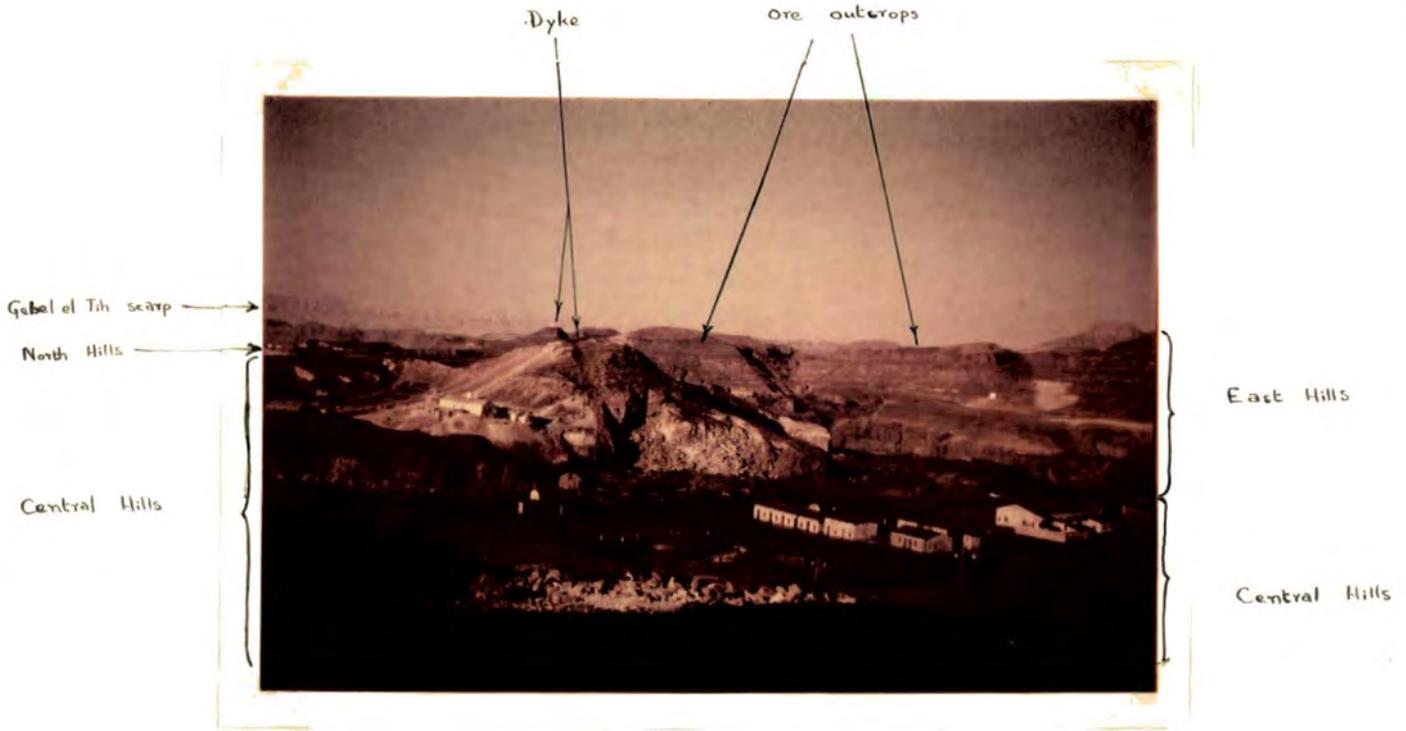


Plate VIII

View to the north-east from Om Bogma. Central Hill in the foreground, with the North Hills beyond with prominent outcrops of dark ore and East Hills to the extreme right. The Cretaceous Scarp of Gebel el Tih can be seen in the far distance. The Om Bogma Dyke cuts through the conical hill in the foreground and continues through the similar hill (surmounted by an aluminium painted water tank) in the background.

Plate IX

View to the north from the North Hill. Gebel Hazbar, at the head of Wadi Kharig, can be seen on the right in the middle distance, with the sandy tract of Debbet el Qeri beyond. The scarp of Gebel el Tih is in the background.

signs of more recent rejuvenation in the form of terraces of gravel and conglomerate.

Wind erosion has had a striking effect on the sandstones, which show perfect examples of honeycomb erosion enlarging into windows and undercut ledges.

Vegetation is very sparse and consists of small groups of date-palms, forming oases where the water which trickles beneath the sand in the wadi-bottoms is brought close to the surface by the configuration of the bed-rock, and scattered acacia trees. Numerous smaller plants appear after the rains, only to disappear again after a few weeks drought.

(v) Occurrence of the manganese ores.

The only manganese ore deposits in the Middle East which have been worked commercially on a large scale are those of Om Bogma, but there are other deposits of manganese in and around Sinai. These are relevant to the subject as their presence suggests that the region may be a metallogenetic province with regard to manganese.

(a) Om Bogma ores.

The ores consist of a heterogeneous mixture in varying proportions of the higher oxides of manganese and iron. They outcrop intermittently at a single geological horizon in the hillsides; this is usually near to the tops of the hills. The individual outcrops vary from a fraction of a metre up to several hundred metres in length. Owing to the dissected nature of the terrain the total aggregate length of outcrop is very considerable, and access is possible to the ore deposits at a great many places.

(b) Deposits of the Wadi el Arabah area.

The Wadi el Arabah is that part of the Rift between the head of the Gulf of Aqaba and the southern end of the Dead Sea. In the Wadi Menayeh, some thirty kilometres north of Aqaba on the west side of Wadi el Arabah, (in Israel), there is a deposit of manganese and iron oxides. Another deposit has been described in Wadi Dana, farther to the north and to the east of Wadi el Arabah, (i.e. in Jordan). Both of these deposits have much in common with those at Om Bogma.

(c) Wadi el Akhdar.

In a tributary near the head of the Wadi el Akhdar ("the green valley"), about 45 kilometres E.S.E. of Om Bogma and almost at the centre of the Sinai peninsula, a vein of manganese dioxide has been found cutting the Pre-Cambrian basement rocks. This ore has been worked to a depth of about ten metres, but as there was no improvement with depth the workings were abandoned.

(d) Other occurrences.

Occurrences of "float" manganese ore have been reported from the neighbourhood of Ras Mohammed, the southern tip of the peninsula and from near Noweiba on the Sinai shore of the Gulf of Aqaba, but no workable deposits are known at these places.

Hume (1901) described a conglomerate at Sherm, in eastern Sinai, which is cemented with "hydrous black oxide of manganese". The deposit is up to four metres thick and overlies strata with "red ferruginous ochre". Hume also recorded that the S.S.Pola expedition found manganiferous deposits forming on the floor of the Gulf of Aqaba, which (unlike the Gulf of Suez) is 1,400 metres deep. (Ball, 1911).

(vi) History of the Om Bogma ore-deposits.(a) Ancient workings.

A number of excavations containing ancient implements have been found in outcrops of both rich manganese ore and of the lower grade iron ore. Ball (1916) believed that malachite was the ore sought by the ancient miners on Gebel Um Rinna and in Wadi Kharig. Evans (1929) believed that the manganese ore must have been locally cupriferous and was accordingly smelted for copper. Large heaps of furnace slag, much of it with green copper stains, occur at a number of places, suggesting that a good deal of ore was smelted in ancient times. Both Ball and Evans recorded the finding of copper artifacts among the slag at Bir Nasib.

Blake (1939) reported the presence of heaps of slag in Wadi Dana, which he says was an ancient centre for copper smelting.

Although the manganiferous ore and the country rocks at Om Bogma do contain traces of copper (amounting to less than 0.1% in the ores) no concentrations of copper minerals of sufficient size to justify extraction of the metal, even on a very small scale, have been found in the modern workings. It is possible that some of the ancient excavations in deposits of rich manganese dioxide were made to obtain "kohl", powdered pyrolusite used by the ancient Egyptians as a cosmetic - and still sold in the Cairo bazaars for the same purpose.

(b) Discovery in modern times.

The deposits of iron and manganese ores were discovered by Thomas Barron of the Geological Survey of Egypt, who made a reconnaissance of some 3,500 square miles of Western Sinai in the winter of 1898-99. The area soon became the centre of some commercial interest because of the rising demand for manganese in the steel industry.

(c) Development and mining.

Before the outbreak of the first World War a German company had leased the biggest deposits at Om Bogma and some development work was in progress on some of the hills there. An aerial rope-way was under construction to carry the ore for 9 kilometres over mountainous terrain to a depot on the coastal plain which was connected by a light railway to the deep water anchorage at Abou Zenima. Prospectors were also at work near Bir Rekeis and in other outlying areas.

After the war the assets of the former company were bought from the Controller of Enemy Property by the present Sinai Mining Company Ltd., who have been responsible for the entire production of ferruginous manganese ore (amounting to some three and a half million tons) and a high proportion of the manganese dioxide from Sinai. The pace of operations increased after the second World War, the rate of production of ferruginous ore rising to nearly a quarter of a million tons a year in 1956. Production of manganese dioxide, both by the Sinai Mining Company and by smaller operators in the outlying areas also increased considerably in this period. At the same time a great deal of development work was done, between ten and fifteen kilometres of underground workings being driven and mapped in detail, while many kilometres of new access roads were made on the surface.

(vii) Geological research.

(a) Ball (1916).

The most comprehensive geological survey of this area was made by Dr. John Ball, of the Geological Survey of Egypt, in the two winter seasons of 1912/13 and 1913/14. He mapped the topography and geology of an area of 1,000 square kilometres with considerable accuracy on a scale of 1 : 50,000. His account of the survey includes a description of the stratigraphy, including the palaeontology of the Carboniferous formations, the tectonics and a detailed description of the more important groups of ore deposits, with his interpretation of their probable origin.

(b) Barthoux (1923).

In 1923 J. Barthoux published a comparison between the manganese ores of west Sinai and those of the lower Mesozoic rocks of Morocco, with some remarks on their respective origins. He gave a succession for Sinai with three distinct "beds" of manganese ore, a description which does not tally with my own field observations, or with any other recorded description. He also stated that the marine transgressive deposits overstepped on to the ancient eruptive rocks, a statement which does not appear to be borne out by the field evidence.

(c) Evans (1929).

Dr. J. W. Evans examined the ore deposits in the area surrounding Om Bogma on behalf of the Sinai Mining Company. His report has not been published, but Groves (1938) reported his suggestions that the ore had been squeezed from beneath the superincumbent strata to appear at the hill sides. This analogy with valley bulges is quite unjustified by the physical state of the ore, which is typically very hard and compact, and has been disproved by underground development.

(d) Fenine (1930).

Professor Alexandre Fenine made a study of the ore deposits being worked between Wadi Baba and Wadi Shellal, near to their junction, and presented his results to the Institute of Egypt. He was particularly concerned with deposits of manganese dioxide and he made a rather confused attempt to explain the relative concentration of manganese in relation to iron.

(e) Recent research.

After resuming bulk production following the second World War the Sinai Mining Company consulted Dr.G.A.Schnellmann, who made a close examination of the mines and outlying areas in 1951. He confirmed the opinion of the Company's Technical Director, Mr.Donald Gill, that the deposits were epigenetic in origin and largely due to hydrothermal metasomatic replacement of carbonate rocks. He also stressed the importance of closely following structure and lithology in development work. Later a resident geologist (the author) was appointed and detailed geological mapping of all development workings, amalgamated with the regular sampling of ore in situ, became routine practice. Relevant data collected during that work have been incorporated in the present thesis.

Plate X

The ore outcrops near the tops of steep-sided hills, and access to the deposits is possible at a great many places. Fine opening in the highest part of the Forth Hills.

Plate XI

View to the north from the North Hills. The outcrop of the Sandstone Pavement can be traced round to the left from the opencast working in the foreground. The basement rocks are exposed in Wadi Fimeira, bottom right. The sandy tract with trees in the middle distance, right, is the Wadi Baba, with the Wadi Kharig joining it from the north. Faulted and tilted strata can be seen just in front of this confluence.

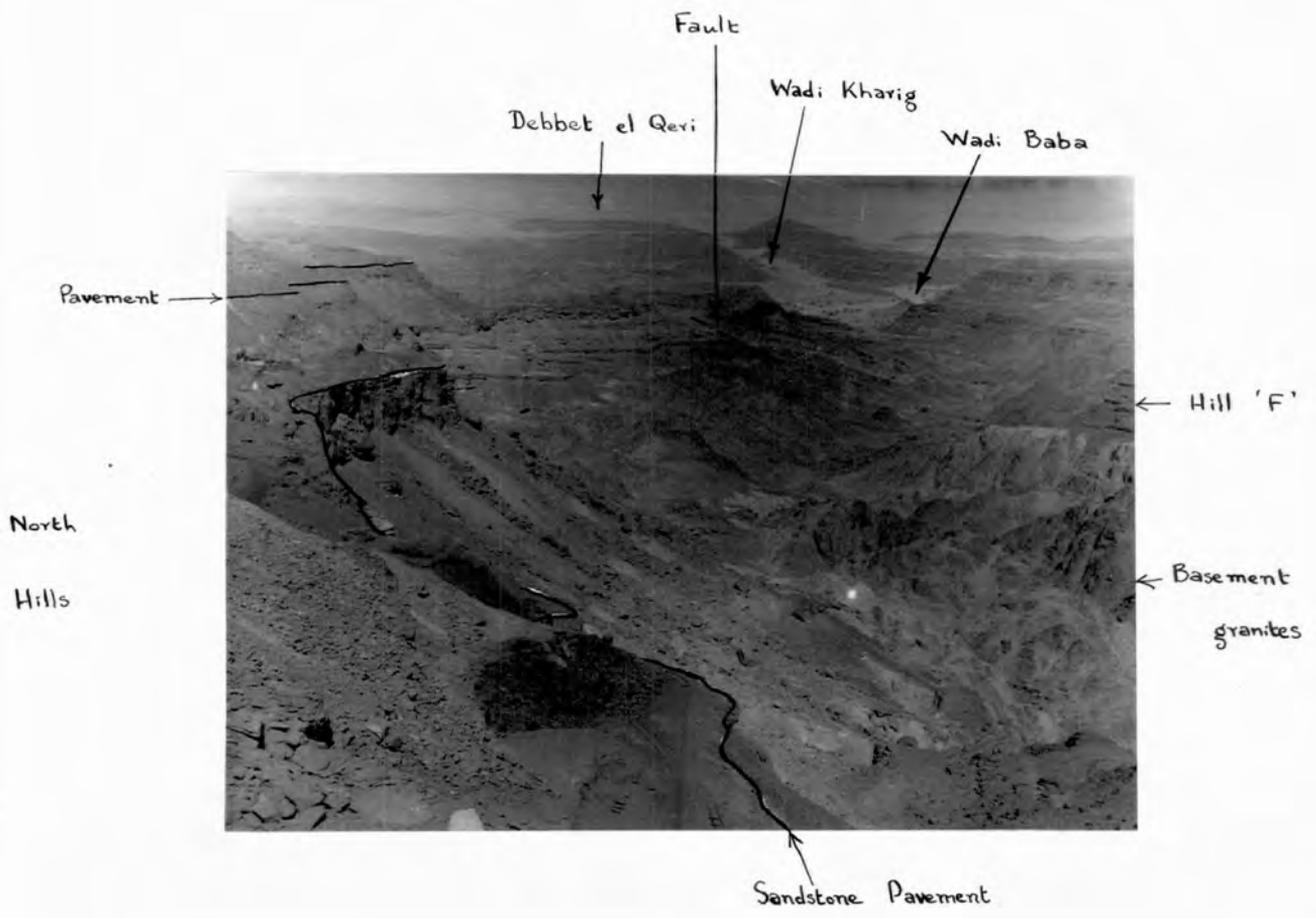
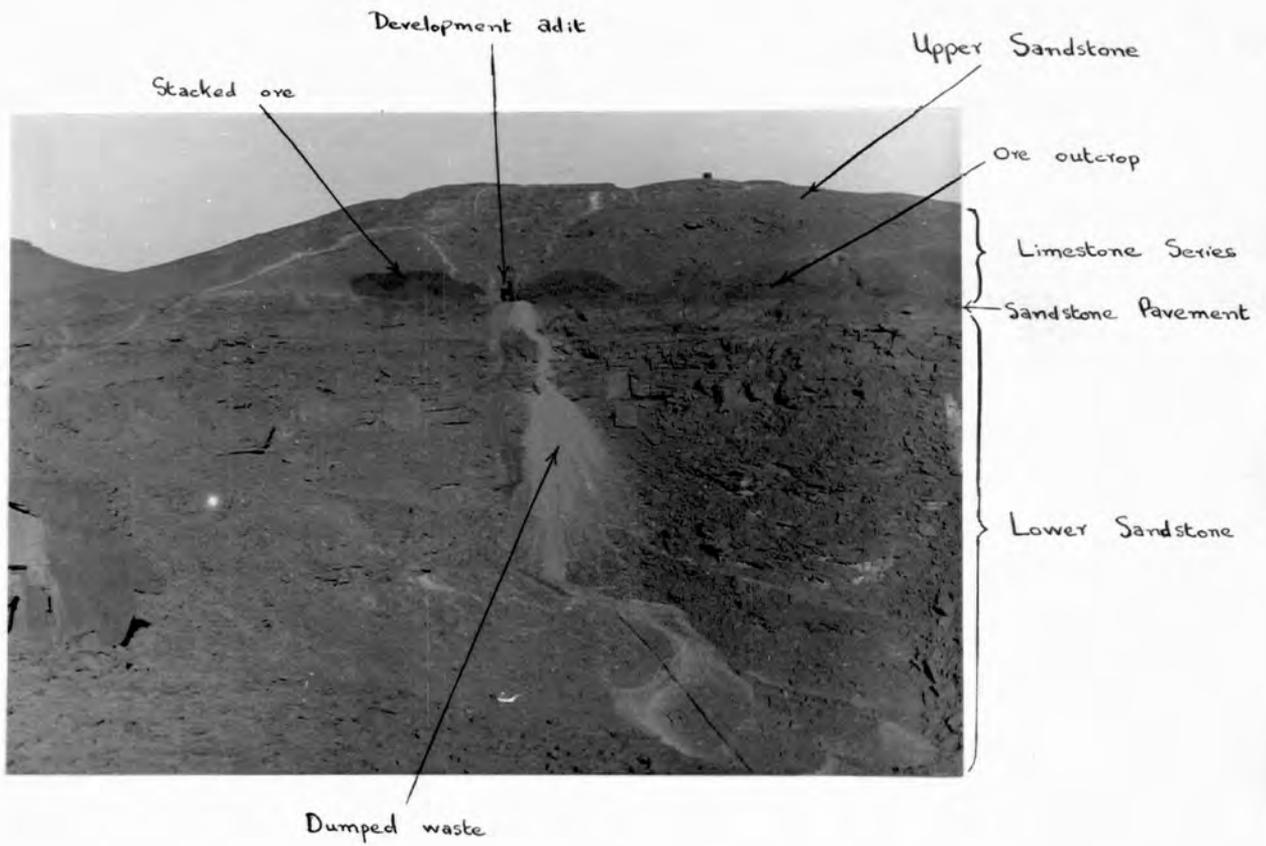




Plate XII

View to the north-west from the Central Hills. Light coloured granite of the basement can be seen in the foreground, with darker diorite beyond the Wadi Baba. The planed-down surface of the basement appears in the scarp facing the camera, overlain by Lower Sandstone capped by the Limestone Series which forms a plateau, seen here as a "false horizon". Beyond, the dark basement rocks reappear where they have been uplifted adjacent to the westerly bounding fault of the Suez Rift with sediments dipping away to the right (north-east). Beyond this again, and farther to the right the same sedimentary sequence is seen at a higher level.

Plate XIII

View to the south from North Hill. The largest of the East Hills is on the right, in shadow. The hard base of the Lower Sandstone forms a small scarp at the bottom of the picture (mainly in shadow) while the softer shaley sands of the middle of the formation make up the rounded features in the floor of the cirque. The Limestone Series outcrops above the steep cliff face. The Upper Dolomite, forming a small scarplet on the left of the picture, disappears when traced across to the right.

(2) STRATIGRAPHY

The main features of the regional stratigraphical geology are shown on Map I, and sections are given for W. Central Sinai with others for neighbouring areas for comparison.

(i) Crystalline Basement Rocks.

The sediments rest unconformably on a Pre-Cambrian platform of granites, gneisses, schists and porphyries, corresponding to the "Aqaba Granite Complex" described by Quennell (1951) in the area to the east of the peninsula. In the immediate vicinity of Om Bogma light grey and pink granites and gneisses occur. Towards their upper surface these rocks show marked decomposition, especially in shattered fault-zones, so that the top of the granitic rocks is often more easily weathered than the overlying sandstone; but in the deep wadis the granites appear quite fresh. The surface of unconformity has been planed with remarkable regularity; the junction between crystalline and sedimentary rocks shows up by colour difference when viewed from a distance of more than eight miles and can be seen to be quite flat except where it has been disturbed by later faulting. This feature can also be seen in the Aqaba region of Jordan where the sandstone is "lying like a cake on the igneous table" (Blake, 1939).

(ii) The Nubian Sandstone.(a) History of the name.

This term is applied to the north-easterly outcrops of the sandy rocks, principally of terrestrial origin, which occur in many parts of Africa north of the equator and in the past covered most of the northern part of the continent and Arabia. The beds are largely unfossiliferous and in many cases their age is uncertain even within very broad limits. There has been a good deal of confusion and controversy about this term, but it is a useful one and is being retained in modified form. Its earlier history has been admirably summed up by O.H. Little (1938) in the *Lexicon de Stratigraphie*, prepared and published as a result of the XVth International Geological Congress.

The term was first used by Russeger (1843) in re-naming his "Gat-aract Sandstone" of Upper Egypt and Nubia. He came to the conclusion that these sandstones are not younger than Lower Cretaceous. Lartet (1869) regarded them as being of Middle Cretaceous age. Bauermann (1868) collected some fossils from the sandstone of Sinai, but there was some doubt as to whether they should be referred to the Trias or to the Carboniferous. Von Zittel (1883) pointed out that for different localities of Egypt, Sinai and Palestine the Nubian Sandstone had been assigned to various periods, from Carboniferous to Middle Cretaceous, and he suggested that the term should be either reserved for the Upper Cretaceous sandstone or abolished. He placed the Nubian Sandstone in the Senonian. Lyons (1894) also believed it to be entirely of Cretaceous age.

Fourtau (1902) was of the opinion that Nubian Sandstone should only be used as a petrographical term with no stratigraphical significance, but members of the Geological Survey of Egypt, notably Hume, Barron and Ball, continued for many years to place this formation in the Cretaceous System, excluding only those sandstones known to be of Carboniferous age or older. In the key to his map of West Central Sinai, Ball (1916) referred the name Nubian Sandstone to the unfossiliferous beds lying between the Upper Carboniferous Sandstone and the base of the Cenomanian clays, and rather misleadingly includes them in the Cretaceous System, although he was aware of the difficulties of these age relations.

Douville (1916) also used this questionable method of dating by referring unfossiliferous beds to the next lower age-group to that of the overlying dated stratum in suggesting that the term Nubian should be reserved for the lowest sandstone forming the middle of the Moghara dome in northern Sinai. This is below Bajocian beds "and therefore of Triasso-Liassic age." Moon and Sadek (1921) reviewed the previous work on the Nubian Sandstone and proposed "to drop the term, wherever possible, and use instead Lower Cretaceous Sandstones to denote the sandstones below the Cenomanian rocks, and Triasso-Liassic Sandstones for those forming the centre of the Moghara dome."

A more realistic attitude was taken by Hume and Little (1928) of the Geological Survey of Egypt:

"Nubian Sandstone has been retained for the series of sandstones and clays beneath the lowest fossiliferous Cretaceous beds. In Bahariya Oasis the uppermost beds of the Nubian Sandstone are immediately overlain by Cenomanian beds, while in Kharga and Dakhla Oases they underlie the Campanian. Nubian Sandstone, over 500 metres thick, extends from Kharga and Dakhla Oases to Owenat Oasis and into the Sudan, and possibly contains beds of various ages between Lower Carboniferous and Upper Cretaceous. East of the Nile, the sandstones, 200 metres thick, between the Carboniferous and Cretaceous in Wadi Araba, are Nubian and this formation extends south along the flanks of the Red Sea mountains. South of latitude 25° 30' N. the Nubian Sandstone forms the western portion of the Eastern Desert. In Sinai, 500 metres of unfossiliferous sandstones between the base of the Cenomanian clays and the Upper Carboniferous Sandstone, are included in the Nubian."

In recent years the whole subject of African Stratigraphical names and correlations has been taken up by the Association of African Geological Services, and in particular by the Commission on the International Geological Map of Africa.

Sandford (1948) has described some modifications of the term to give it a broad stratigraphical value. He has been able to link up "the old part of the Nubian Sandstone" with the "Continental intercalaire" respectively of French Equatorial Africa, the Sahara and Fezzan by following the succession from Egypt to the Chad Basin and Tibesti. The Nubian Series, which includes the continental beds above and separated from the Carboniferous beds of north-east Africa, are analagous in position to the Karroo System of the south. The Nubian Series thins to the south, with younger beds progressively overstepping as the equator is approached; the Karroo System behaves in the same manner towards the north. There are no glacial deposits below the Nubian however, and its coals are very restricted compared with the Karroo System; also vulcanism in its upper part was less than that which marked the end of the Karroo Period. Sandford divides the Nubian Series into three parts:

- (3) Buff ssts, with fossil wood, locally Senonian. Breccia.
- (2) Variegated beds.
- (1) Basal conglomerates.

The usage of the International Map can be tabulated as follows:

Continental	Oligocene			
terminal	to Pliocene			
Continental	U.Carb. to	Nubian Sst. (S.S.)	Nubian	Nubian
intercalaire	Mid. Cret.	or New Nubian Sandstone		
Continental	Dev. to	Old Nubian Sst.	}	
Post-Tass.	M.Carb.			
Continental	Silurian	Old Nubian Sst.		(s.latis-
Tassilien	Cambrian			simo

(b) Local development.

At the Om Bogma mines two thick sandstone series occur, separated by the marine Carboniferous Limestone formation which contains the workable ore deposits. These three formations are locally known, from below upwards, as the "Lower Sandstone", the "Limestone Series" and the "Upper Sandstone" respectively. The lower formation is 130 metres thick and rests on a flat surface of generally decomposed friable basement rocks. It consists of coarse angular and round-grained arkoses and quartz grits (i.e. with grain-size 2 - 4 mm., corresponding to the "granule conglomerate" of Wentworth) at the base overlain by red and green sandy shales, with a massive coarse-grained current-bedded sandstone at the top containing some thin and impersistent layers of quartz pebbles up to 1.5 cms. in diameter. This is the "Desert Sandstone" of Hull (1885) and it was referred to by Ball as the "Lower Carboniferous Sandstone" because it underlies a formation with fossils of Lower Carboniferous age, although no recognisable fossils have been recorded from this sandstone. Probably the best descriptive term for this formation is "Old Nubian Sandstone" (i.e. "Groupe ancien des grès de Nubie" of the International Geological Map of Africa).

The higher sandstone formation has been intruded at 150 metres and 200 metres respectively above its base by two thick massive sills of dolerite (described in a later section). These sills, with a few roof pendants, are the highest members of the rock sequence in the immediate

area of the mines and they have been taken by Ball as marking the top of the higher sandstone series. The sandstone is fine to medium even-grained, grey to white in fresh exposures, weathering light brown. It contains clay (principally kaolinite) in the matrix and locally concentrated as a workable clay-band. Carbonaceous matter, with associated pyrite, is present in the grey variety; at one horizon a 20 cm. seam of soft highly pyritous coal has been encountered. Ripple-marks and current bedding are common in this formation. It has also yielded rare plant remains, including a specimen of *Lepidodendron* found by Ball, and another found by the author which compares well with Ball's illustration. On this basis the formation has been called "the Upper Carboniferous Sandstone"; on the International Map it is included as "couches à *Lepidodendron*" in the Continental Post-Tassilien (Devonian and Lower and Middle Carboniferous).

(c) Surrounding areas.

To the north of Om Bogma some 500 metres of unfossiliferous sands and shales outcrop, forming a flat sandy area and the lower part of the scarp face of Gebel el Tih, where they are overlain by marine Cretaceous rocks. This is the "Nubian Sandstone" of Ball, but in the accompanying section I have included the whole of the arenaceous beds from the peneplaned top of the crystalline basement rocks up to the transgressive marine Cretaceous strata (about 800 metres in West Sinai) in the "Nubian Sandstone (sensu latissimo)." Part of these are roughly correlated with the "Upper Palaeozoic Sandstones" of the Sudan, where Carboniferous plant remains have also been found (Reed). Hume (1901 - Geological Magazine P. 200) states that in Eastern Sinai the "Nubian Sandstone rests directly on the basement rocks, the Carboniferous Sandstone of Western Sinai being apparently absent here." With Barron (1901) he also states that no Carboniferous remains have been found in the Eastern Desert of Egypt (i.e. south of the Wadi Araba outcrop). Reed notes that in the Sudan the "Nubian Sandstone proper" locally rests directly on the basement.

In the southern Negev the 350 metres of sandstone recorded from the Wadi Menaiye area, described as Lower Cretaceous by Blake and as Upper or Main Nubian by Picard (1952), correspond to the Nubian of Ball in Western Sinai. At Zerka Main in the Dead Sea area 700 metres of

sandstones and shales occupy this stratigraphical position, but the age range here is less uncertain as a 60 metre thickness of fossiliferous sandstones and shales of Lower Triassic age has been recorded in the lower part of the Series.

It is interesting to note that in Central Lebanon the marine Cretaceous beds (represented by the Aptian and succeeding stages) are underlain by 300 metres of sands and shales with some fossil wood and lignite but no recognisable flora or fauna, a typical Nubian facies. Marine calcareous Jurassic rocks are present in the area up to Kimmeridgian, so it is quite logical to put the sandstones in the Lower Cretaceous; it is indefensible however to extrapolate from this and put the rocks of similar facies to the south within the same system. In a recent paper Sturm (1953) quotes a "terminology of stratigraphic units established by Dr. Bentor", but as he does not say how it was established and is himself sufficiently uncertain to place a query after each term it is not considered worth while quoting them here. The most recent tabulation of these successions has been made by Quennell (1948), and it is reproduced for comparison at the end of this section.

(d) Summary.

The basement rocks where they are exposed in Sinai and generally to the south and west, are overlain by massive sandstones and shales, collectively known as the Nubian Sandstone (*sensu latissimo*). They can be divided into a lower member, the Palaeozoic Nubian now called "the old part of the Nubian Sandstone", and the upper or main Nubian called the "Nubian Sandstone (*sensu stricto*)". The former is relatively thin and is not always present, though whether this is due to non-deposition or subsequent erosion is not certain at any one place. In the Sudan it is apparently better developed and has been sub-divided into a Lower and Upper Palaeozoic Sandstone (Reed) separated by a thick mass of rhyolite, but it must be understood that "Lower Palaeozoic" in this context does not necessarily imply an Old Palaeozoic age. "Lower" and "Upper Old Nubian Sandstone" would avoid this confusion. On the International Map the terms "Continental Tassilien" (Camb. and Sil.) and "Continental Post Tassilien" (Dev., L. and M. Carb.) respectively are used. The

Nubian Sandstone (s.s.) (Continental intercalaire) attains a thickness of several hundreds of metres and ranges in age from Upper Carboniferous to Middle Cretaceous. The Nubian Sandstone (s.l.) appears to have covered most of North Africa at one time or another extending as far north as the Lebanon, where it probably reached its maximum extent in Lower Cretaceous times. Only rarely is it sufficiently fossiliferous to be dated, but occasionally there have been incursions of marine limestones in and around Sinai itself as at Om Bogma and in the Negev and Dead Sea areas.

(iii) Marine facies of pre-Cretaceous age.

To the south and south-west of Sinai marine rocks are not met with between the crystalline basement and the Upper Cretaceous, and few fossiliferous beds are found between these limits, until the Karroo formations are reached in Central Africa.

(a) Cambrian.

At the base of the Zerka Main section near the Dead Sea, a black limestone has yielded Hyolithes, trilobites and Tentaculites (Blake), and other fossils have been recorded from this formation, also indicating a Cambrian age (King). Blake (1936) claimed to have found specimens of the brachiopods Siphonatreta and Obolus in black coarse-grained limestones in Wadi Menaiye, showing these beds to be Cambrian too, but Picard (1952) claims a Silurian age for them. Blake described the beds immediately overlying these limestones as Carboniferous on the basis of the similarity of their manganese ores with those of Om Bogma, although he accepted an epigenetic origin for the manganese ores in both cases - a doubtful correlation to say the least! Quennell (1951) suggests that both this formation and another manganese-bearing dolomite in Wadi Dana, Jordan, are equivalent to the Burj Limestone of Lower Cambrian age.

(b) Carboniferous.

The Limestone Series of Om Bogma consists variously of massive dolomites, bedded dolomitic limestones, shales and siltstones resting with slight disconformity on the Lower Sandstone. To the north-west of Om Bogma, the Limestone Series thickens to about 41 metres in Gebel

Mukhul (Ball) indicating that the Carboniferous Sea was deeper and marine conditions remained for a longer period in that direction. At Gebel Mukhul and generally in the area north of the Wadi Baba the lower part (up to 15 metres thick) of the Series was laid down as a massive limestone, which has been dolomitised, in places resting directly on the underlying sandstone so that the boundary can be determined in the field only by very close inspection. The higher beds are similar to those at Om Bogma: thin beds of dolomite and earthy limestone separated by shales and sandy bands, with one persistent bed, 2 to 5 metres thick, of massive crystalline dolomite near the top of the Series. To the south-east of Om Bogma the Limestone Series thins and disappears altogether. The facies changes are dealt with more fully in a later section.

The palaeontology of this Carboniferous Limestone of Western Sinai has been described in some detail by Ball. No attempt has been made in the present research to investigate the palaeontology of these beds, although several fossiliferous localities were observed about the manganese mines. Ball's description is here quoted in full, as there may now be difficulty in obtaining copies of his work.

The Carboniferous rocks also outcrop in Wadi Arabah, an eroded anticline on the west side of the Suez Gulf, to the north-west of Om Bogma. The limestone is poorly developed and thins to the west, but the fauna is generally similar to that in Sinai.

(c) Mesozoic.

No Triassic rocks have been recognised in Sinai, but marine fossiliferous beds, including a thin limestone, of this system have been reported from a terrace north-east of the Dead Sea.

Jurassic beds (Bajocian - Bathonian in age) have been reported from an inlier (the Moghara Dome) in northern Sinai, but do not occur in the south. In Jordan south-east of the Dead Sea the system is represented by 200 metres of beds between grey limestone with shale and gypsum below, probably Triassic in age, and sandstone above. Farther north, in the Lebanon and Hermon, the Jurassic rocks are over 1,000 metres thick.

Quennell (1951)) includes the marine Triassic and Jurassic rocks of the Dead Sea region in the Zerqa Group, which he regards as being equivalent in age to the Um Sahm Series of terrestrial or estuarine sandstones which interdigitate with them.

(iv) Cretaceous.

The Nubian Sandstone is succeeded in West Sinai, apparently conformably, by marls and clays of Cenomanian age, with limestones above, and these are succeeded in turn by clays, limestones and chalk of the higher stages of the Cretaceous System, giving a total thickness for the marine Cretaceous in the escarpment of El Tih of 750 metres (Ball, 1916).

(v) Tertiary.

The Eocene is represented to the west of Om Bogma by 300 - 400 metres of limestones, marls and clays. The Miocene contains conglomerates and sandstones besides limestone and clay. The maximum thickness of the Miocene in the area west of Om Bogma is 300 metres (Ball, 1916). Ball (Chap. VI) described the entire sedimentary sequence as being without visible unconformity, but he found no deposits of Oligocene age, and on his map (Plate I) he shows Miocene rocks resting in some places on Cretaceous strata. There is therefore at least one distinct hiatus in the Lower Tertiary succession, if not angular unconformity. Busk (1929) shows an unconformity above the Eocene, but not below it; neither Busk nor Ball listed any Danian sediments, so there is probably another hiatus at the base of the Eocene System.

A great deal is known, unfortunately much of it unpublished about the Cretaceous and early Tertiary rocks of this and other parts of the middle East, more particularly from the exploration for oil, but a more detailed discussion is not considered relevant to this work.

(vi) Pleistocene and Recent.

Post-Miocene deposits in Sinai consist mainly of alluvial and aeolian deposits. Ball refers to raised beaches of Pliocene age in the neighbourhood of Suez; there are also numerous terraces of gravel or hard cemented conglomerate in the wadis cutting the basement rocks of the peninsula. Hume (1901) described high gravel terraces in the principal valleys, often over 20 metres high, composed of fragments of local origin, of all shapes and sizes, in a matrix of the same derivation. He deduced from their flat upper surfaces that they were laid down in lakes or marine fjords. They contain no fossils, but on the coast of the gulf of Aqaba they were found to overlie coral reefs with Pleistocene or Recent forms.

Barron and Hume also describe gravels and conglomerates from the Red Sea coast plain (western shore) with igneous pebbles similar to the rocks of the Red Sea Hills. They are found both underlying and overlying Pleistocene limestones, and resting unconformably on the Pliocene. Raised beaches are present, and there are five series of coral reefs, the youngest being below sea-level and the third youngest up to 170 metres above sea-level and four to seven kilometres inland. The older reefs are disturbed and dip 20° to the east.

GEOLOGICAL HISTORY OF JORDAN & SINAI

PERIOD	NORTHERN SINAI	NORTHERN JORDAN	CENTRAL JORDAN	SOUTHERN JORDAN	SOUTHERN NEGEV	WESTERN SINAI	IGNEOUS ACTIVITY	TECTONICS
QUATERNARY								
NEOGENE		Jordan Valley (fresh water)				Suez Gulf margin	Basalt lavas in Jordan Dolerite dykes & sills in Sinai	Differential movements with Rift faulting
PALAEOGENE								Mainly positive movements
CRETACEOUS		Cenomanian Transgression						
JURASSIC								
TRIAS								
PERMIAN								
CARBONIFEROUS								
DEVONIAN								
SILURIAN								
ORDOVICIAN								
CAMBRIAN								

Submerged conditions: hatched

Continental conditions: stippled

Mainly negative gentle orogenic movements only

Stratigraphical Geology - The Carboniferous Limestone.

(quoted from "The Geography and Geology of West Central Sinai" by John Ball, 1916).

"Fossils are on the whole rather scarce in the Carboniferous Limestone series, but they are fairly frequently met with in certain localities, especially round the eastern flanks of Gebel Nukhul and in the upper part of Wadi Khaboba. The fossils are all marine, and mostly indicative of fairly deep water conditions.

"Of corals, the simple form *Zaphrentis* is by far the most frequent, hundreds of specimens having been collected from the earthy middle beds. The tabular *Syringopora* occurs more sparingly in the upper beds, while *Favosites* is still rarer.

"Crinoid stems are in some places extremely abundant, being often well seen on weathered surfaces of the hard upper beds. Bryozoa are not infrequently met with in the earthy layers, the commonest forms being *Fenestella* and *Monticullipora*.

"Here as in other parts of the world it is the brachiopod fauna which is the most characteristic feature of the organic remains of the Carboniferous. By far the most common form is *Spirifer striatus*. The more elongated and strongly ribbed *Spirifer* cf. *moosakhailensis* is much less frequent, but is very characteristic. The small delicately sculptured *Orthis Michelini* is fairly abundant, and has been found not only in the middle earthy beds, but also sparingly in a silicified condition in the upper crystalline dolomite. Of the *Productidae* the most frequent form is the small *P. longispinus*; *P. semi-reticulatus* and *P. scabriculus* are not very rare, though mostly found in a fragmentary condition. Of the genus *Athyris*, the species *A. lamellosa*, *A. Roysii*, and *A. Planosulcata*, are all fairly frequent. Of Brachiopods more rarely met with, *Orthotetes* (*Streptorhynchus*) *crenistria*, *Syringothyris cuspidata*, *Chonetes hardrensis*, *Rhynchonella pleurodon*, and *Dielasma* (*Terebratula*) *hastata*, are the most striking forms; the last two are quite rare.

"Lamellibranchiata are poorly represented. The only form which is at all common is a new species of *Hinnites*. This oyster-like fossil is fairly abundant in the earthy middle beds of the series, and is easily

seen when present owing to its black colour; but the shells are so friable and flaky that long search is usually necessary to get entire specimens. Of the genus *Edmondia*, only one or two casts were picked up, and these in situations where their exact horizon was not very certain; the casts were of sandstone, and possibly came from the lowest beds of the Upper Carboniferous sandstone rather than from the limestone series.

"Gastropods are extremely scarce. A specimen of the characteristic *Bellerophon tenuifascia* and one or two other forms resembling *Murchisonia* and *Euomphalus* were picked up at Gebel Nukhul.

"The vertebrates are represented only by the palatal teeth of selachian fishes, which are occasionally met with in the hard crystalline dolomites. They are conspicuous in the rocks by their very high polish and sometimes opalescent appearance; with a lens, the surfaces are seen to be minutely pitted. The specimens collected have been referred by Mr. Bullen Newton to *Psephodus* and *Psammodus*.

"LIST OF CARBONIFEROUS FOSSILS.

"Collected by the author from the limestone of Sinai.

CORALS:-

Zaphrentis sp., Wadi Budra, Um Bogma, Gebel Nukhul, Wadi Khaboba.
Favosites Michelini Edw. et Haime, Gebel Nukhul.
Syringopora ramulosa Goldfuss, Gebel Hazbar, Um Bogma, Gebel Nukhul.

CRINOIDS:-

Stem-ossicles, various.

BRYOZOA:-

Coscinium sp., Wadi Khaboba, Gebel Nukhul.
Fenestella sp., Gebel Nukhul.
Monticulipora sp., Um Bogma, Gebel Nukhul.
Heterotrypa ramosa Edw. et Haime, Gebel Nukhul.

BRACHIOPODA (provisional determinations by Mr. Bullen Newton):-

- Rhynchonella pleurodon Phillips, Wadi Nasib, Gebel Nukhul.
 Athyris planosulcata Phillips, Gebel Nukhul.
 Athyris Roysii L'Eveille, Gebel Nukhul.
 Athyris lamellosa L'Eveille, Gebel Nukhul.
 Productus longispinus Sowerby, Wadi Khaboba, Gebel Nukhul.
 Productus scabriculus Martin, Gebel Nukhul.
 Productus semireticulatus Martin, Gebel Nukhul.
 Spirifer cf. moosakhailensis, Gebel Nukhul, Wadi Khaboba.
 Spirifer cf. striatus Martin, Gebel Nukhul, Um Bogma, Wadi Khaboba.
 Spirifer integricostatus Phillips, Gebel Nukhul.
 Spiriferina laminosa M'Coy, Gebel Nukhul.
 Orthotetes crenistria Phillips, Gebel Nukhul.
 Dielasma hastata Sowerby, Gebel Nukhul, Wadi Khaboba.
 Syringothyris cuspidata Martin, Gebel Nukhul.
 Chonetes hardrensis Phillips, Gebel Nukhul, Wadi Khaboba.
 Orthis Michelini L'Eveille, Gebel Nukhul, Wadi Khaboba.

LAMELLIBRANCHIATA:-

- Edmondia sp., Gebel Musaba Salama, Gebel Nukhul.
 Hinnites sp. nov., Gebel Nukhul, Wadi Khaboba.

GASTROPODA:-

- Bellerophon tenuifascia, Um Bogma.

PISCES:-

- Psephodus sp., Wadi Bud'a.
 Psammodus sp., Um Bogma."

Plate XIV

The correlation between the thickness of the Limestone Series and the undulations in the Sandstone Pavement can be seen in the field. View to the north from Ain Abu Hamata. The Limestone Series outcrops above the steep cliff face with large windows. At the left edge of the picture the Series is poorly developed; it thickens to the right, but pinches out altogether above the scree, a little right of centre. Towards the extreme right it thickens once again.

Plate XV

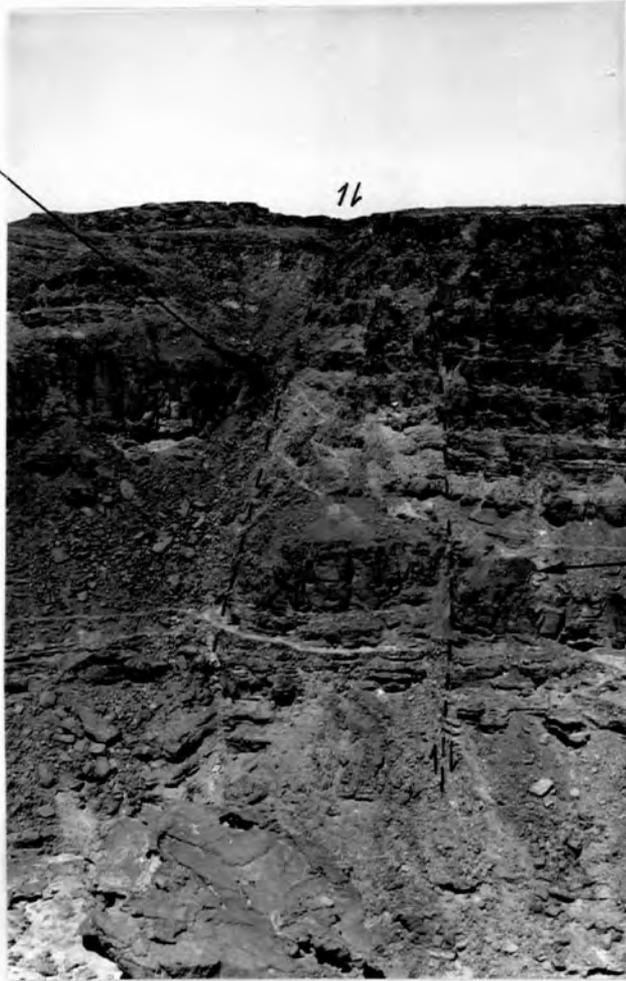
Efflorescent silky fibres of epsomite grow in profusion on exposures of the dark carbonaceous rocks.

Roof (dark grey dolomite) of Devt. 2 main, no. 11 branch to fault.



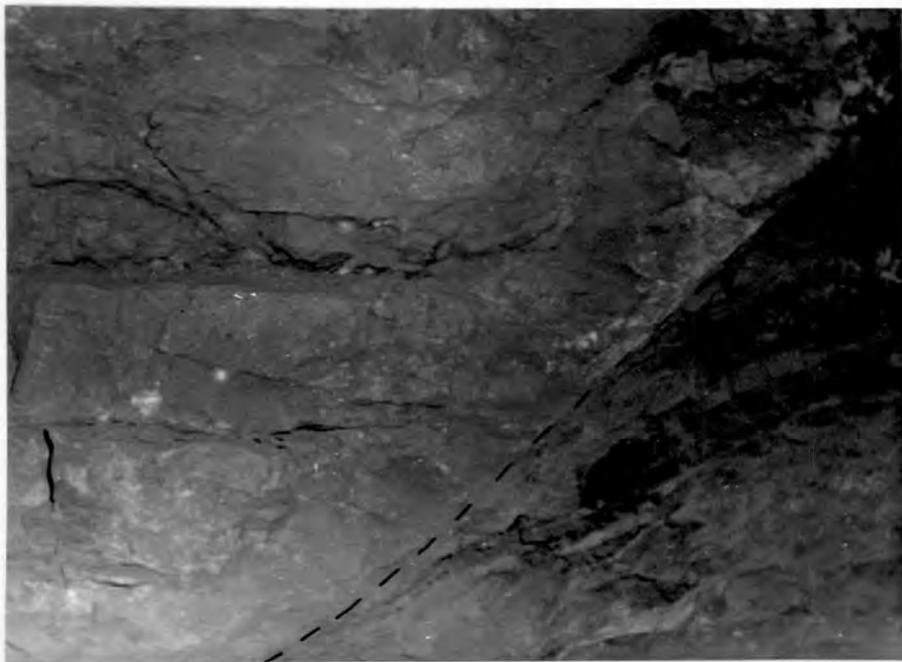
Ore

16



Ore

Grey dolomitic
Limestone



Black silty shale

Plate XVI

Faulted strata in the south face of Hill 'F'. Ore occurs in association with both of these faults, which are thrown respectively 40 m. and 9 m.

Plate XVII

Faults exposed underground sometimes have a low dip, tending to merge into bedding plane slip.

Small fault exposed in Mourad cross-cut, beneath the northern edge of Gebel Farsh el Azraq.

This displacement coincides with a change in facies, with beds of dolomitic limestone on the left giving way to shales.

(3) STRUCTURAL GEOLOGY.(i) Central Sinai.

The central part of the peninsula of Sinai is an elevated block strongly and closely faulted and deeply dissected by erosion. The structure of the basement rocks is complex but we are concerned here primarily with the tectonics which have also affected the overlying sediments. These latter show virtually no folding apart from very local fault-drag with tilting of faulted blocks. The uplift of this area has been strongest along its south-east and south-west margins; the rocks dip away from the gulfs of Suez and Aqaba towards a point to the north of the centre of the peninsula at an average angle of 1° - 2° . The faults increase both in frequency and magnitude towards the south; the inclination of the intervening rocks also increases; in the neighbourhood of Om Bogma dips of 10° - 15° are the rule, but they are all in the same general direction - i.e. to the north and east.

The fractures of the Central Sinai block can be conveniently described under three headings, viz: the major faults, the cross-faults and the joints.

(a) Major faults.

In the Om Bogma area these are somewhat sinusoidal in strike, varying between N.-S. and N.W.-S.E., but their general trend is N.N.W. to S.S.E., i.e. parallel to the long axis of the neighbouring Gulf of Suez. The throw of the individual faults varies up to about 300 metres or more and they are downthrown either to the east or west, so that the area is divided into a series of "graben and horst" structures. The Nahman Areas, east of Om Bogma, forms one such graben.

These faults are all normal faults, with dips varying between 60° and 80° . Some of them have a tendency to split and "feather", occasionally giving rise to a zone perhaps 100 metres or even 200 metres wide of fractured ground. Fault drag, where it is found, may take the form of a flexure of the beds adjacent to a fault plane, but most commonly a series of small (or occasionally fairly large) step faults occur on one or both sides of a large fault. Fault drag is by no means the rule; there are

examples of a clean break with no sign of flexure or sympathetic faulting on the one hand, and pronounced fault-drag on the other, occurring at different points along the same major fault and in the same type of ground.

Structure lines with this same trend, in particular numberless dykes which do not penetrate the sediments, can be seen in the basement rocks. Excellent examples occur half-way along the Wadi Raba, and in the lower part of the Wadi Samra. The north to south fault at the junction of Wadi Zobeir and Wadi el Sih exactly coincides with the strike of the schists forming the basement on the upthrow side, while a little to the south the strike of the major fault along Wadi Lahian and Wadi Zobeir is parallel with that of numerous closely-spaced dykes in the basement.

This agrees with the observations (vide Dixey (1946), Quennell (1948) and Shackleton (1950)) that "rift" faulting follows a pre-existing "grain" of the basement rocks. The rule is not of universal application however, as a few kilometres to the south and south-east of Om Bogma the dykes, which are so closely spaced in the basement rocks that they make up almost half the total volume of this complex, nearly all have a north-easterly strike while the rift faults and most of the erosion pattern of steep ridges and valleys are at right angles to them.

Hume (1901) described a series of straight valleys in eastern Sinai, parallel to the Gulf of Aqaba, showing vertical displacements of the rocks of 200 to 600 metres. He observed that to the west of a line nearly corresponding with longitude 34° East there is a series of north-west to south-east "rifts" (which he calls the "Suez type"), "including the Gulf of Suez, Wadi Qena and possibly part of the Nile valley". To the east of this line are the Aqaba series of rifts. Hume (1921) did not reach any conclusion as to whether these faulted valleys had been formed as a result of compression or of tension.

(b) Cross-faults.

At Om Bogma the cross-faults have a general north-easterly trend. Their throw is comparatively small, usually being of the order of 5 metres. Most of these faults appear to be normal faults with variable dip; one example in the Nahman Areas which is nearly vertical at the surface was found to be so nearly horizontal at a depth of 65 metres that its dis-

placement was almost taken up by bedding-plane slip. Some of the cross-faults however show unmistakable compression phenomena where they cut the less competent limestones and shales in that the beds on both sides of the fault planes are turned upwards, and may show crush-breccia. The cross-faults sometimes terminate against major faults, or sympathetic faults with parallel trend, elsewhere they die out laterally. From the air some of these fractures can be traced across several of the major N.N.W. fault-blocks, either continuously or intermittently, for distances up to 20 kilometres.

To the south of Om Bogma there ~~is~~^{are} a number of cross-faults with considerable throw, possibly up to 400 metres in one case; some of these strike north-east to south-west and others strike nearly east to west. Ball (1916) has shown some of these cutting straight across the major faulting.

Hume (1901) also suggested "a transverse type of dislocation" from the regularity and parallelism of the valleys in Central Sinai.

(c) Joints.

Joint patterns show up very prominently in the granites and diorites, etc. of the basement, where they form most of the principal lines of weakness and hence control the pattern of erosion. This is also true, but to a lesser degree, of the dolerite capping of Gebel Farsh el Azraq and several other hills. In the Lower Sandstone and Limestone Series jointing (contrasted with faulting) has had far less effect in guiding erosion than have the differences in hardness and resistance of the sedimentary beds themselves, but in the Sandstones the joints often do show up plainly on the surface as a result of weathering, because they are the loci of dark iron and manganese staining or because other minerals, (most commonly calcite), have been deposited from solutions passing through them to form an indurating cement in and close beside the joint planes.

The pattern of the joints is similar to that of the faults: over most of the area of the mines there are three principal sets of joints, striking north-east, east and north to north-north-west respectively, i.e. the two former sets intersect at an angle of approximately 50° , while the third (parallel to the "rift" faults) sometimes bisects the obtuse angle between them.

A study of aerial photographs shows these joint directions to be the most widespread, but there are variations from place to place; one set may be less developed, one or more sets, or even the whole system may be slewed round, or additional sets may appear locally. The individual joints are often very strong and persistent, especially those striking north-east which sometimes form a continuation of a fault-line.

(ii) The Clysmic Area.

This term (derived from Clysma, the Roman name for Suez) was used by Hume (1921) to describe the area between the uplifted ancient granite masses of the northern Red Sea Hills on the west and the corresponding hills of Sinai to the east. The area includes the Gulf of Suez and the coastal strips principally of younger rocks on either side of it.

(a) Boundary faults.

There are striking faults at the boundaries of this area, (See Map I), with throws of the order of several thousands of metres; the vertical displacement of the fault systems as a whole increases to the south-east, that is to say towards the Red Sea proper. At the latitude of Om Bogma the boundary faults are 80 kilometres apart and the throw of the western one is about 2 kilometres, and possibly more. The faults appear to be normal as they are nearly vertical or dip towards the downthrow side. Ball (1916) described a case at the western end of the scarp of Gebel el Tih, where the beds on the downthrow side of a fault dip strongly towards the fault in a manner reminiscent of large-scale land-slipping. Faults at the northern end of the gulf on the western shore were also described by Ball (1910) as large land-slips. Towards the south, however, where the displacement is greater, the younger beds on the downthrow side of the boundary fault-system are very highly disturbed; there is some attenuation of the beds and folding which suggests that there may have been some lateral compression during or after the fault movements.

(b) Structure within the area.

Within the Clysmic area there is a broad anticlinal structure, with the strata in general dipping away from the Gulf of Suez. Owing to irregularities in the coast-line the axis passes close to the shores of the gulf at Abu Durba, in Sinai, and Gebel Zeit, on the western side near the Red

Sea, and at these two places the ancient basement rocks are exposed. There is a number of faults, more or less parallel with the margins of the area, and generally downthrown towards the central axis, which cause repetitions of the stratigraphical succession in a series of inclined steps as one proceeds towards the margins from the centre of this area.

Moon and Sadek (1925) in describing the Gebel Khoshera area, some 60 kilometres south-east of Suez, conclude that the series of parallel faults in that region (the eastern foreshore of the gulf) was formed in order from east to west. There were two (at least) periods of movements on the most westerly fault exposed here with some erosion and the deposition of Upper Miocene sediments in the interim.

Continued or repeated movement of the faults in the Clysmic area in Tertiary times, and in particular during the Miocene Period, has had a marked effect on sedimentation. There has been erosion and the building of coral reefs on the upthrown ridges, while in the troughs great thicknesses of sediments have developed, including thousands of metres of evaporites (Hume, 1916). In places anticlines in younger sediments have been shown to be the result of renewed movement on a pre-existing fault in the underlying beds. These facts make the estimation of the total movement on these faults difficult or impossible, and the same argument applies to the boundary faults, where great banks of gravel (fanglomerate of Quennell) have been heaped against the uplifted mass of the Central Sinai block, from whence they were derived.

Hume (1921) remarked that the rocks of this area are "folded and faulted to a remarkable extent", but Busk (1929) described it as a region of normal faulting with subsidiary warping and folding. Busk noted two main types of fault, which he names crescentic and hinge faults, the former "depending for its form on the fact that the upthrust block dips away from the fault face." His figure (fig. 85) shows such a fault convex on the upthrow side, while another figure (fig. 89), "showing the rift faults of the Gulf of Suez margin", depicts a number of faults, nearly all crescentic, with the upthrow side to the north-east and convex in plan.

This configuration suggests that there has been a positive uplift on the upthrow side rather than a collapse due to gravity of the rocks on the downthrow side, vide Brock (1953) who states:

"A ramp fault, by definition, must have a convex curve on the upthrow block and the same must hold in plan,..... ; the converse holds for a genuine normal fault."

Although this dogmatic statement will not be found to apply to all cases in practice, the inference may be drawn here, that there has been a definite upthrust, possibly by rotation, of wedges of the granitic substratum giving rise to apparent normal faulting in the overlying younger sediments.

(iii) Neighbouring Rift Formations.

Quennell (1951) has interpreted the structure of Jordan in the following manner:

Minor folds in the Belqa Cherts (highest marine formation, U.Cretaceous in age), affecting the older but not the younger members of the series, are the first effects of stress directed W.N.W. - E.S.E. Later the stress direction changed to N.W. - S.E. (or N.N.W. - S.S.E.) and failure by shear took place along planes of weakness predetermined in Pre-Cambrian times, with sinistral oblique slip on the major Rift Valley faults. At a later stage complementary shears developed as E. - W. thrust-faults, while N.W. - S.E. normal faults and grabens developed as tension fractures.

Quennell suggests that the Arabia, Sinai and Palestine block moved to the east in late Tertiary times, then Arabia swung to the north with an anti-clockwise rotation; the Gulf of Suez and Red Sea being formed by tension and the Dead Sea by compression with horizontal shearing. Accumulating evidence strongly supports the theory of Continental Drift which requires a tearing asunder of the continents in this region. The coast lines of the Red Sea and Gulf of Aden are as suggestive in this connection as are those of the South Atlantic, the narrowing of the Straits of Bab el Mandeb being accounted for by the extrusion of Tertiary volcanic rocks and some sediments of Jurassic and later age. There seems to be a good case for the sinistral rotation of Arabia; it is difficult to account for the wide and deep troughs of the Red Sea and Gulf of Aden by compressional Rift formation. But on the other hand it is equally difficult to explain their upthrust margins purely by tension.

McConnell (1948) has suggested that the eastern side of the East African Rift System has shifted southwards in ancient times in relation to the western side; taken with Quennell's evidence concerning the Arabian

block there seems to be a case for tension at some stage in the formation of these abnormally wide rifts. It may be significant that only positive gravity anomalies have been reported in the region of southern Egypt and the Red Sea (Gutenberg & Richter).

(4) IGNEOUS ACTIVITY.(i) Sills in the Upper Sandstone.

The biggest intrusions in the area of the mines are the sills of olivine dolerite capping Gebel Farsh el Azraq (Blue Carpet Mountain) to the east of Om Bogma. Two of these "sills", in fact more nearly laccoliths, have been partly preserved here on a sunken fault block, but the former limits of only the lower one can now be traced. At the lower horizon there are two parts of what may have been a continuous intrusive mass but which is now divided by two deep ravines, the whole measuring about one and a half kilometres from north to south, about five kilometres from east to west and about 80 metres in thickness. At its northern boundary the lower "sill" terminates abruptly at a small fault in the country rock, the fault-plane forming (more or less) the northern lateral limit of the intrusion. Part of the roof of the sill is preserved, giving no doubt of the original limit of the dolerite. To the south the dolerite thins to 30 or 40 metres beneath the northern remnants of the second intrusion, which is about 50 metres higher in the sedimentary succession. Near the eastern end of this belt of "overlap" there is a peculiar conical hill of sandstone (local name - Deleidim) whose apex is composed of dolerite and has the appearance of an "outlier" of the higher sill. At the base of this hill on its northern side erosion has cut down to the lower sill. I regard this hill as the site of a feeder to the sills, the peculiar conical shape being due to the resistance to erosion of recrystallized sandstone surrounding a magma pipe or neck. Elsewhere the sandstone surrounding the dolerite, including that above it, has been partially re-crystallized for a thickness of a metre or more. Locally there is also marked staining of this sandstone by iron and manganese oxides.

Concordant intrusions at about the same stratigraphical horizon are preserved on the tops of hills and faulted outliers to the south-west of Om Bogma between Wadi Abu Natash and Wadi Shellal and close to the largest of the Rift faults along Wadi Budra, extending to the south as far as Wadi Sidri, about 20 kilometres distant from Om Bogma, and they also occur to the east for a similar distance. To the north, where the full succession of the Upper Sandstone remains over a wide area, only a relatively thin

sill is known at this horizon, outcropping to the west of Gebel Hazbar.

(ii) Discordant Intrusions.

These take the form of dykes of doleritic rock, one of which, known at the mines as the Om Bogma or Barren Dyke, strikes nearly due north-east and outcrops almost continuously for more than 25 kilometres with a fairly constant width of 5 metres. This strike is parallel to one set of prominent structure-lines. This dyke is nearly vertical and cuts through a number of faults without lateral displacement, showing that it post-dates the major faulting of the region. Locally there has been vertical displacement, rarely more than 5 metres, between the sediments on either side of the dyke, but the throw is not always in the same direction. The position of this dyke is of some importance to the main subject under discussion as it bisects the ore-field along its long axis.

Another dyke, exactly similar to the above, but striking roughly east and west, outcrops to the north-east of Gebel Um Rinna on the projected line of the Om Bogma Dyke. It appears to join up with a much wider dyke (up to 50 metres in width) which Ball described as extending to the north-west up into the Cretaceous rocks of Gebel El Tih, where "..... it has altered the limestone into a black crystalline form which strongly resembles the basalt itself in appearance." No suggestion is made as to the nature of this dark colouration, but it is not an unique occurrence - similar black stains associated with another dyke farther east along the crest of El Tih show up very plainly on aerial photographs. A study of these photographs shows the presence of a number of dykes in the wide sandy area to the north and east of Gebel Um Rinna, striking either N.E. - S.W., E. - S. or N.W. - S.E., some having a slightly zig-zag outcrop.

(iii) Other Igneous Activity.

Sills of dolerite occur in the Cretaceous rocks in the scarp of El Tih and in rocks up to Miocene age in the down-faulted area bordering the Gulf of Suez. At the mouth of Wadi Teyiba, a few kilometres north of Abou Zenima, there is a band of dolerite in rocks of Miocene age which according to Ball "has the appearance of an interbedded lava", but he did not use this as evidence for dating the igneous activity as a whole. In this case the dolerite is underlain by a bed of purple shale, whose colour

appears to be due to heavy staining by iron, and possibly also by manganese oxides. A number of dykes have also been reported in the younger sediments nearer to the Gulf, where they sometimes appear to be associated with the introduction of hydrocarbons into the exposed parts of the rocks, (Hume, Madgwick, Moon & Sadek).

(iv) Mutual Relations of the Igneous Rocks.

Ball concluded from his field observations and macroscopic examination (but not petrographic or chemical analyses, which had not been made when his work on this area was published) that all the dolerite and basalt intrusions in the sediments of this region are of the same age and were derived from one magma. Some of the intrusions are found in Miocene rocks and some have been involved in the faulting which Ball has dated as late Miocene, so he assumed that the tectonic and igneous phenomena are connected, the magma finding an outlet by means of some of the first formed fractures.

Dr. J. W. Evans, in a private communication to the Sinai Mining Company listed the following sequence:

- (1) intrusion of sills of dolerite in the Upper Sandstone,
- (2) formation of normal faults striking E.N.W. - S.S.E.,
- (3) intrusion of the basic dykes.

He noted that the sills on Gebel Farsh el Azraq were similar to some of the dykes in the basement rocks, with which they might be genetically connected, but he had "seen no dykes of similar composition in the sediments."

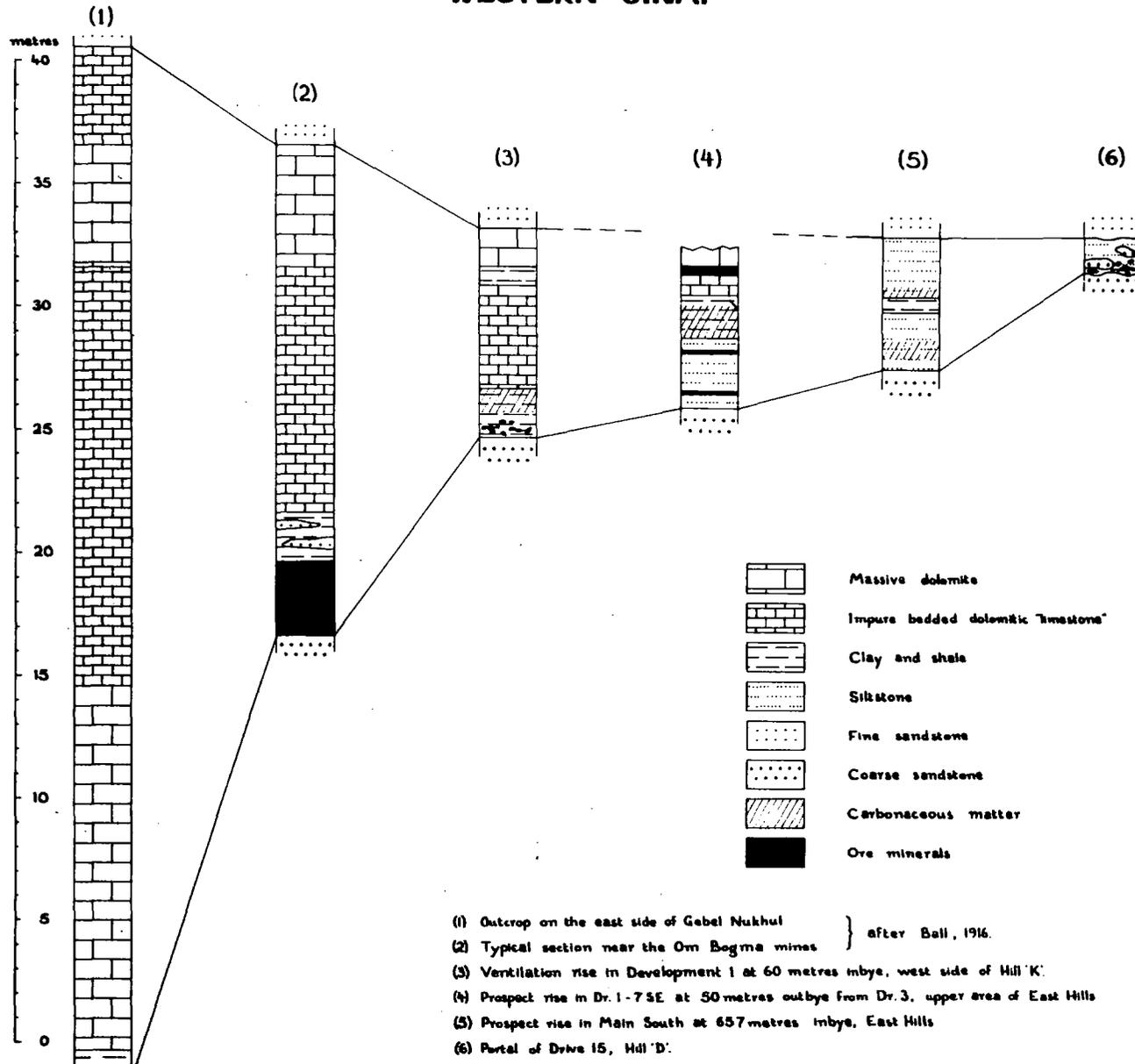
The Om Bogma Dyke does not closely resemble the rock of the Farsh el Azraq sills in appearance in the field as it is much more easily weathered and decomposed than the latter; even in underground exposures at a depth of 50 metres below the outcrop it is difficult to find a reasonably fresh specimen of the dyke-rock while at the surface the dolerite is completely altered to a soft greenish-yellow friable rock. The dolerite of the sills on the other hand is being broken up and eroded by mechanical means rather than chemical weathering. This striking difference may be partly due to the fact that the Om Bogma Dyke is an important aquifer (two wells sunk into it, Bir Rais and Bir Nasib, give a perennial supply); the salts

dissolved in the percolating water perhaps assisting in the early stages of the decomposition of the rock.

In thin section the rocks are of a similar nature with the exception that in the sills fresh olivine is present, but in the dyke olivine can be identified by crystal outline only.

The Om Bogma Dyke cuts cleanly through nearly all the faults which cross it, and thus post-dates them, but in the case of the sills only a few of the smaller faults definitely ante-date the intrusion. There is no physical connection between the Farsh el Azraq sills and any of the dykes so their mutual genetic and age relations must remain in some doubt, but it seems almost certain that their origins are closely bound up with the tectonic disturbances which have affected this part of the globe in Tertiary times, particularly in the Miocene Period.

SECTIONS OF THE CARBONIFEROUS LIMESTONE SERIES OF WESTERN SINAI



(5) FACIES VARIATION IN THE LIMESTONE SERIES.

The ore deposits are entirely confined to the Carboniferous Limestone Series and the top of the underlying Lower Sandstone, so the lithology of these formations will be considered in more detail. There is a considerable variation in both the thickness of the Limestone Series and its lithology from place to place, and there is a definite relationship between the facies and the character of the ore deposits. In this chapter the various rock types will be described, their distribution in relation to the development of the Series as a whole and to the configuration of the "Sandstone Pavement" (i.e. the top of the Lower Sandstone) will be discussed and finally an attempt will be made to reconstruct the conditions which prevailed during and immediately after sedimentation.

The alteration of the rocks associated with the deposition of the oxides of iron and manganese will be dealt with in a later chapter.

(i) Rock-types.

The types of country-rock exposed in the outcrops and encountered in the underground mining operations vary from almost pure dolomite through sandy or muddy dolomitic limestone, clays and shales to siltstone and coarse sandstone.

(a) Dolomite.

In weathered outcrops the dolomite appears typically as a massive light brown or grey rock. It is very hard and resistant to weathering and forms vertical cliff faces, sometimes overhanging softer underlying rocks. As a result of this resistance to erosion of the dolomite the Carboniferous Limestone Series is frequently found capping flat-topped hills, or "mesas", and forming plateau surfaces.

In fresh exposures on the surface the dolomite is seen to be white or yellow in colour, composed of a mass of individual crystals adhering strongly together so that the rock gives a characteristic "ring" under the hammer and breaks through the crystals rather than between them, but at the same time there are intergranular pore-spaces, more particularly in the coarser-grained varieties.

The dolomite frequently contains fossil remains of a more or less fragmentary nature; locally these make up the bulk of the rock. Corals, brachiopods, crinoids and bryozoa are most commonly found. The palaeontology of the Series has been described by Ball and has been quoted in Chapter 2; it need not be further discussed here, but it is significant to note that most, if not all, of the dolomite was originally a biogenetic limestone.

In underground workings below the oxidised zone of weathering, which in the dolomite penetrates to a depth of about twenty metres, this rock is generally grey. When it is powdered and heated the colour changes to a pale red or pink, which suggests that the colour of the original rock is due to the presence of carbonaceous matter. The change from grey to pale yellow at the limit of surface oxidation is a gradual one; the alteration extends farthest along joints and fracture cracks and penetrates only gradually to the centre of unbroken blocks of dolomite.

In thin section the rock is seen to be made up of an interlocked mass of hypautomorphic carbonate crystals, generally of uniform size in any one specimen. There is, however, a considerable variation in grain size in this dolomite from place to place, up to a maximum of about 1 mm. The refractive index of the ordinary ray, n_0 , of the carbonate grains is in the range 1.679 to 1.685, the grains often having narrow outer zones of slightly different refringence from that of the cores. These measurements indicate a small ferrodolomite or mangan-ferrodolomite content in the dolomite, up to 5% on the data of Smythe & Dunham, 1947. Chemical analyses of unaltered (unoxidised) rocks show up to 0.3% MnO and 0.3% equivalent Fe_2O_3 (other than pyrite, which makes up about 5% of the rock), but part of this may occur in detrital minerals which are often present in small amounts. The yellow varieties of dolomite contain a small amount of interstitial limonitic clay, and are usually finer grained than the white dolomite.

(b) Impure dolomitic "limestones".

The rock described as limestone at the Om Bogma mines is distinguished from the dolomite by its softer and more friable nature and by the fact that it is generally well bedded, often with thin interbanded sandy shale. In outcrops the colour varies from pale cream to bright yellow.

This rock contains more or less quartz silt or sand and clay, its hardness varying roughly with the ratio of carbonate to interstitial matter. The carbonate of the softer varieties can be separated by washing and is seen to be composed of single automorphic rhombs and little aggregates of intergrown crystals. The refringence of the carbonate rhombs shows them to be of a similar composition to those of the hard dolomites, but calcite is present in some rock-specimens either in xenomorphic grains or in the clay fraction. Quartz and other detrital minerals are present, both within and between the carbonate rhombs, as rounded and angular grains, most commonly of silt grade. The clay is predominately illite showing an admixture of iron oxide in D.T.A. The yellow colouring matter is almost certainly limonite, and it is fairly evenly distributed among material of all size fractions, even permeating some of the carbonate rhombs and rendering them semi-opaque. In at least one locality the rock has an oolitic texture and is strongly limonitic, but this is an exceptional case.

In exposures below the zone of surface oxidation the colour of the "limestone" is grey to black, and is shown by a combustion test to be principally due to the presence of carbonaceous matter. In thin sections this is seen in discontinuous belts and streaks parallel to the bedding, and also along grain boundaries and as inclusions in the carbonate rhombs. There are also numerous opaque specks disseminated within and between the crystals; these can be recognised in polished section as pyrite. Chemical analysis indicates between four and five per cent of pyrite in this type of rock.

When some fragments of the rock were shaken for six hours in slightly ammoniated tap water the solution after settling gave positive reactions to potassium ferrocyanide and barium chloride, indicating slight oxidation of pyrite to ferric and sulphate ions. Blank tests on tap water gave no immediate reactions, and only weakly positive ones on standing for several minutes. The oxidation of the carbonaceous matter was almost completed in the clay fraction in two weeks at about 35° C. by the gradual addition of 100 volume hydrogen peroxide. Presumably in natural conditions of oxidation by percolating meteoric waters the iron is re-precipitated as "limonite" while the sulphate radical is carried away in solution; analyses of local well water show that while dissolved iron is virtually absent the

concentration of sulphates in solution is of the order of 500 to 1,000 parts per million.

When the dark impure dolomites have been exposed in underground workings for several weeks long silky fibres of epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) develop in profusion, eventually forming a crust up to 5 cms. thick.

(c) Clays and shales.

These rocks are not generally well exposed in the outcrops as they are most easily eroded and tend to be hidden under scree or other detritus from the harder beds. Close to the surface they are in the oxidised state and appear mottled in a variety of colours including reds, yellows and pale greens, or bleached almost white. Surface oxidation, however, does not normally penetrate more than a few metres into this type of rocks.

The unoxidised clays and shales are invariably black, and are usually soft and soapy to the touch. Bedding is usually not well developed. These argillaceous rocks are typically much disturbed, with numerous curved and slickensided partings; they readily break up into lumps from about 10 to 20 cms. across. Small-scale folds and "rucks" can also be seen. These features are regarded as being due to adjustment during consolidation under load, probably accentuated by shocks during later earth movements.

The clay in these rocks is essentially a mixture of illite and kaolin. More or less quartz silt is present in angular grains. Mica is often present, locally in abundance, both dark and white mica being found.

Besides carbon and small quantities of fine-grained pyrite the clays and shales contain traces of copper, often sufficient to give an emerald green colouration to a carbide flame. This is confirmed by the growth of efflorescent fibres of chalcantite ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) on underground exposures here and there.

(d) Siltstone.

The siltstone is hard and compact, becoming almost splintery when dry, and generally shows well-developed bedding. It does not form prominent scarps in the outcrops, however, as the processes of weathering (essentially the removal of carbon and alteration of pyrite) render it

somewhat friable and rather more easily eroded than much of the overlying Upper Sandstone. In the oxidised zone it appears, like the clays, bleached or mottled in a variety of colours. Again surface oxidation does not usually extend very far below the outcrops.

In underground exposures the siltstone varies from almost pure white to dark grey or black, according to the amount of carbonaceous matter present. Generally this black material and pyrite can be seen in the hand specimen as ramifying and discontinuous streaks and strings along the bedding. Occasionally larger pieces of pyrite are found, up to a centimetre or more across. In polished section minute pyrite crystals can be seen disseminated throughout the rock in sizes down to the limit of visibility. Locally small aggregates of these grains suggest by their form replacement of fossil fragments.

The rock is predominately made up of quartz silt in angular grains, with larger quartz grains where the rock grades into a fine sandstone. The matrix contains either illite or kaolin, or both of these. Locally mica is present in considerable proportions, but its occurrence is not typical.

The clay fraction of a micaceous specimen of siltstone gave a D.T.A. curve similar in some respects to those of a specimen of bituminous coal. The resulting furnace brick after heating to 1050° C. was pale red in colour. The carbonaceous matter and iron sulphide of another portion of this clay were oxidised by the gradual addition of 100 volume hydrogen peroxide at about 35° C. for a period of four weeks. At the end of this time the clay, which had originally appeared dark grey, was a very pale yellowish grey, and it became bright orange on heating to 1050° C.

(e) Sandstone.

The rock type described under the previous heading is sometimes coarse enough to be classed as fine-grained sandstone, especially higher in the Series, where it closely resembles and merges into the Upper Sandstone, but there is a distinct type of coarse sandstone which is similar to the Lower Sandstone. This is composed of well rounded grains of quartz in the 0.2 - 2.0 mm. size range, with smaller angular grains down to 0.05 mm. Patches of clay minerals mixed with silt occur between the quartz grains,

more or less impregnated with red iron oxides.

In underground exposures the condition of this rock is exactly the same as in the natural outcrops: no carbonaceous matter or sulphides have been found in it.

The following are objective descriptions of representative unmineralised specimens of the various rock-types found in the Carboniferous Limestone Series at Om Bogma:

Dolomite.

Sp. No. OB/9.	Grey crystalline dolomite.
Collected from:	Main South, Lease 9, at north side of collar of 2E., 2 m. above the Sandstone Pavement. (c. 100 m. below surface).

A dark grey mass of interlocking carbonate crystals, some of which appear to be fragmentary fossils, forming the bulk of the lower part of the Limestone Series. In this area the dolomite is somewhat lenticular, and is associated with shales, which are more or less calcareous and / or arenaceous.

Under the microscope the rock consists of an interlocked mass of hypautomorphic carbonate crystals, even grained, averaging 0.15 mm. or a little more, with many crystals reaching 0.2 or 0.25 mm. There are also some larger plates which represent dolomitised crinoid ossicles, showing traces of trabecular tissue. Much of the carbonate has nO 1.685, indicating a ferrodolomite or manganiferrodolomite -content of up to 5% in the dolomite. Clear, but narrow outer zones can be seen on fragments in powder. Some detrital quartz, in sharply angular grains up to 0.1 mm. across, is scattered through the rock. No calcite or other carbonate has been found. There is a slight tendency towards spherulitic arrangement in the dolomite.

The dark colour is due to opaque material along crystal boundaries and in cleavages. Opaque material (but possibly not the same) also occurs as tiny disseminated granules within the carbonate.

Limestone.

Sp. No. OB/19. Yellow sandy limestone.
 Collected from: east side of Drive 17 cutting, Lease 179,
 4.5 m. outbye from the portal, 2 m. above
 the Sandstone Pavement.

The specimen was collected from a series of bedded limestones and sandy shales with bands of intermediate composition, one of which is represented by this specimen. The limestone bands are from 5 to 15 cms. thick, the shale bands are thinner, the whole being pale yellow in colour. The shales are soft and crumbly, with a high proportion of sand grains.

The formation makes up the middle part of the Limestone Series, the whole Series being of the order of 15 m. thick at this place. The bedded rocks are resting on a massive pink crystalline dolomite, the junction being a sharp transgressive solution boundary, with a 2 cm. thickness of red sandy shale material separating the two formations. The beds have been slightly tilted, but very little broken, by the effects of the solution.

The limestones are overlain conformably by a dolomite similar to that below them.

In thin section the specimen is seen to be a sandy bedded partially dolomitized limestone. Quartz is scattered through the rock in angular grains, mainly of silt grade. Cloudy xenomorphic carbonate, at least in part calcite, is the most abundant constituent of the rock, but rims and areas of clear hypautomorphic dolomite with n_D near 1.681 are also present. The calcite contains yellow pigment (possibly limonite), but it shows no fossil remains.

Shale.

Sp. No. OB/4. Contorted black shale.
 Collected from: Drive 31 - 11 S.E., Lease 179, south-east
 of the 5 m. fault. (c. 40 m. below surface).

This specimen was taken from the middle part of the Limestone Series in an area where the calcareous beds are poorly represented, the full

thickness of the Series here being about 8 m. The rock shows no recognisable bedding-planes, but is divided up by numerous irregular slip-surfaces with well-marked slickensiding. In fresh specimens it is soft and soapy to the touch. The colour is black.

In thin section angular quartz grains can be seen dispersed in a matrix containing:

- (i) cryptophyllite birefringent clay, probably illite;
- (ii) abundant opaque material.

The appearance in section suggests that some of the latter is original carbonaceous matter, but as the black colour is not dispelled by heating to redness it cannot be wholly due to this cause. Probably some fine grained pyrite is present;

- (iii) tiny mica flakes, visible at high power;
- (iv) little angular pockets of fibrous and vermicular kaolinite, seldom over 0.1 mm. long.

Siltstone.

Sp. No. OB/2.	Hard black pyritous siltstone.
Collected from:	east side of Drive C South at 20 m. north from 11 S.E., Lease 170, 1.5 m. above the Sandstone Pavement. (c. 150 m. below surface).

The specimen was collected from an area where the Limestone Series is very poorly represented, and entirely non-calcareous; a locality corresponding with a "high" area with respect to Sandstone Pavement contours. The siltstone passes upwards imperceptibly into the Upper Sandstone, so that the true thickness of the Limestone Series is uncertain here.

Bedding is visible, emphasised by thin streaks of pyrite. This specimen shows two parallel joint planes, at about 45° to the bedding. Tiny quartz-grains are visible on a bedding surface. The rock is hard, breaking to a sharp edge, and is not affected by exposure to the air. The colour is dark grey.

In thin section the rock is seen to be composed predominately of quartz varying up to 0.1 mm. grain size, but mostly of silt grade, in sharply angular grains. The only other non-opaque mineral is fibrous

or vermicular kaolin having n_Z 1.568, elongation positive. The kaolin also occurs as finely divided material between the quartz grains. The matrix is black or dull brown material which fails to take any polish in polished section, and which is thus probably carbonaceous in nature; with abundant pyrite in ramifying streaks, having groups of little crystals with them.

As seen in polished section, minute pyrite crystals are disseminated throughout the specimen with sizes down to the limit of visibility at high power (x 400). Locally small aggregates of these grains are seen, the form of the aggregates suggesting replacement of small fossils. Larger shell fragments have been replaced by pyrite crystals of about 0.5 mm. size and annular areas of pyrite indicate replacement of crinoid ossicles. A few equant grains of pyrite up to 0.5 mm. are seen.

(ii) Relation of facies to the Sandstone Pavement.

(a) Facies and thickness of the Limestone Series.

In its thickest and most complete developments the Limestone Series can be divided into four lithological units: (i) the Basal Dolomite; (ii) shaley bedded "limestone"; (iii) the Upper Dolomite; (iv) bedded "limestone". There is often a layer of sandy shale or clay (the "Pavement Shale") between the Sandstone Pavement proper and the Basal Dolomite; it rarely exceeds a metre in thickness and is usually much less than this.

The Basal Dolomite is made up entirely of massive crystalline dolomite, reaching a maximum thickness of 15 metres in Gebel Nukhul, where the entire Limestone Series exceeds 40 metres. Where the Series as a whole is less than 15 metres thick, as in some parts of the Om Bogma mines, the Basal Dolomite is absent altogether or present only as isolated lenses of small extent, sometimes only two or three metres across and a metre thick, in a matrix of clay or shale.

The bedded limestone is composed of layers of impure earthy dolomitic limestone, sometimes with thin bands of crystalline dolomite, separated by shales or sandy layers. The maximum thickness (Gebel Nukhul) is 17 metres for the middle part of the Series and 4 metres for the uppermost

part. Beyond the limits of the Basal Dolomite the bedded limestone persists with reduced thickness until, with the continued thinning of the Limestone Series as a whole, it grades through calcareous shale to clay or siltstone or until the individual beds pinch out (see Map III and Sections). Typically these beds of limestone or dolomite do not thin gradually but terminate rather abruptly within a metre or two, the beds disappearing in turn from the lowest upwards.

The Upper Dolomite is the most widespread of the calcareous formations. It is more uniform in thickness than the other divisions of the Series, being generally of the order of 5 metres thick and rather less where the non-calcareous facies assumes importance.

Siltstone is characteristic of the poorest developments of the Limestone Series, which may consist entirely of a few metres of this rock. As the siltstone often closely resembles the lowest part of the Upper Sandstone, or merges imperceptibly into it, it is sometimes difficult to determine the exact thickness of the Limestone Series.

Coarse sandstone is only found within the Series where the calcareous rocks are virtually absent, or at most very restricted. It takes the form of irregular lenses separated from the Pavement and surrounded by shale or siltstone. In extreme cases a lens of this "Floating Sandstone", as it is called at the mines, may extend for a hundred metres or more, but generally these lenses are only a few metres in extent. In areas where the Floating Sandstone occurs the Sandstone Pavement is itself often very irregular, with steep ridges and hummocks projecting 2 metres or more up into the shales and siltstone of the Limestone Series.

(b) Distribution; the facies map.

In addition to the thinning of the Limestone Series from north-west towards the south-east, and its complete disappearance some 6 kms. beyond Om Bogma, there are numerous variations in thickness, with related changes in facies, from place to place in the mining areas. The broad differences in thickness and facies are known from the outcrops round the edges of the hills, while the lithological character of the base of the Series has been plotted in detail by careful profile-drawing of most of the mine development headings, which follow the Sandstone Pavement as closely as is practicable. It has thus been possible to construct a map of the mining

areas showing the distribution of facies in the Limestone Series (Map III).

Irregular areas devoid of calcareous rocks and varying in extent from about a hundred square metres to something approaching a square kilometre occur in all parts of the region mapped. No significant trends can be seen either in the shape, orientation or distribution of these areas. There is, however, an increase in their size and numbers towards the south-east as would be expected from the general thinning of the series in this direction.

(c) Configuration of the Sandstone Pavement.

The practice of taking the Sandstone Pavement as the floor of the mine workings has revealed that this horizon is not an evenly dipping surface but locally steepens, flattens or dips in an unexpected direction, even where there is no recognisable warping or folding of the beds above or beneath it. The "rolling" of the Pavement has caused some inconvenience to the engineers, particularly in driving primary development headings that later have to be used as main tramming roads. Close supervision has been necessary throughout such work to ensure that the Pavement is not lost beneath the sole^o of the level during the advance.

The measurement and recording of accurate reduced levels on the Sandstone Pavement has been a part of the routine survey operations from the earliest stages of development in the mines, and latterly this formed part of the geologists' work. From these records it has been possible to compile a stratum contour map for the Sandstone Pavement covering most of the principal mining areas (Map III).

From this map it can be seen that there is a regional dip to the north-east with local modifications close to faults, and that the minor irregularities of the Pavement are superimposed upon this gently dipping plane. An attempt has been made to apply a correction for this dip in the lower and western areas of the northern hill or "Lease 8 Group", a relatively unfaulted part of the mines, in order to bring these irregularities into perspective (Maps V & VI). The result shows a number of low elevations and shallow depressions with a difference in levels of the order of 10 - 12 metres.

(d) Relation of facies to the corrected Pavement contours.

A comparison of the facies distribution with these corrected Pavement contours shows a very close agreement between the patterns and can leave no doubt of a direct connection between the thickness of the Limestone Series and the rise and fall of the Pavement. The deepest parts of the hollows coincide with the thickest and most complete developments of the series, while on the rising slopes the basal dolomite disappears and the highest elevations are characterised by sandy and shaley facies.

An examination of the Pavement contour and facies maps for the central, or Lease 9, hill leads to the same conclusion, and although information for the east, or Lease 10, hill is less detailed and probably less accurate the rule can be seen to apply there also. Even in the outcrops in the steep sides of some of the wadis it is possible to see the rise and fall of the Sandstone Pavement and the accompanying variations in thickness and facies.

(iii) Conditions of Sedimentation.

(a) Variations in thickness.

It is apparent both from the foregoing observations and from the appearance of the formation in the field that the variations in thickness of the Limestone Series are the direct result of differences in deposition from place to place rather than of subsequent erosion. Ball (1916) and others have suggested that differences in thickness and more particularly the local absence of the lower part of the series are primarily due to later solution by hydrothermal activity from below. While there can be no doubt that such solution has taken place it is clear from field investigations that it has not been sufficient for this purpose, nor are its visible effects as marked where the Limestone is now seen to be thinnest as they are in some of the thicker parts of the formation. These effects will be more fully described and discussed in a later chapter.

(b) Formation of the Pavement.

There are virtually no flexures in the planed surface of the basement rocks, or in the overlying Lower Sandstone. There is therefore no reason to suppose that the "rolling" in the Sandstone Pavement is the result of folding, upward doming or subsidence of strata. The coarse and false-

bedded nature of much of the Lower Sandstone indicate rapid, but not necessarily continuous, deposition in a littoral, deltaic or terrestrial environment. The material of the lower part certainly, and probably the whole, of this formation was derived from the basement rocks during the process of planation.

With the beginning of the deposition of the Limestone Series there was a definite change, both in the material deposited and in the conditions of sedimentation. Apart from the Floating Sandstone, which is small in amount and never far removed from the Lower Sandstone, the rocks above the Pavement are all finer grained than those immediately below it. In the Upper Sandstone, where current bedding is common and some thin bands of coarse sandstone occur, no detrital grains exceeding one or at the most two millimetres in diameter have been seen, while the bulk of the particles are much finer than this, contrasting with the quartz pebbles larger than a centimetre which are frequently found below the Pavement. This in itself suggests that the higher sediments may have been derived from a pre-existing sedimentary rock, rather than directly from the crystalline basement, in any case there would appear to have been a change of conditions in the provenance of the detritus at the Pavement horizon suggestive of a time interval.

The local irregularities in the Pavement, in the form of sharp ridges and hummocks, indicate erosion of a previously consolidated rock. There is thus a strong probability of a hiatus in the succession at this horizon: as there is no direct fossil evidence of the age of the Lower Sandstone it is possible that this formation is much older than has been supposed, and it may have been much thicker before being peneplaned to form a platform for the later deposition of the fossiliferous strata of known Carboniferous age.

(c) Lower Carboniferous palaeogeography and sedimentation.

Marine deposits of Carboniferous, or of any other Palaeozoic age, are unknown to the south of central Sinai; the area represents the ultimate limit (excluding the possibility of other marine sediments having been removed by erosion) of the encroachment of the Palaeozoic sea on to the northern edge of this part of Gondwanaland. The change of facies with the varying level of the floor of deposition, as represented in the

earliest stages by the Sandstone Pavement, can be used in conjunction with the characteristics of the rocks themselves in deducing the conditions of sedimentation.

There are no physical barriers between the areas of calcareous and non-calcareous facies; hence in a normal marine environment there would be open circulation with uniform physico-chemical conditions. The change in facies cannot be directly related only to the proximity of a source of detrital material, as some of the siltstone areas appear as "islands" entirely surrounded by limestone deposits. The variations within these non-calcareous areas, i.e. the increase in the proportion of the coarser component with a rise in the floor of deposition, indicate that sorting of an evenly distributed sediment rather than a locally concentrated supply was the primary factor in facies control, with finer material being washed out from the elevations to be deposited in the deeper water. The tops of the higher elevations were therefore subjected to an agency which had no significant effect in the deeper parts of the sea; wave action is implied here.

With the exception of fringing reefs, which are not found in the Carboniferous rocks of Sinai, organic limestones generally increase in importance in deeper water away from a littoral environment. The distribution of limestone can thus be directly related to the variations in the depth of water if the sea as a whole is assumed to have been fairly shallow; that is to say the difference in depth of the order of ten metres (indicated by the corrected Pavement contours) must have been a sufficient proportion of the total depth to change the environment.

This line of reasoning leads to the conclusion that the depth of the sea did not exceed 20 metres anywhere in the Om Bogma hills or the Nahman Areas. The hypothesis is supported by the presence of a fauna characteristic of shallow and marginal seas, principally composed of brachiopods, crinoids and corals.

From the remarkably complete planation of the crystalline basement rocks coupled with the great stability of the whole area throughout Palaeozoic times, and probably for a greater period, we must deduce that the neighbouring land was low lying and as a consequence erosion and transport was slight. This is confirmed by the paucity of coarse detrital

material in the marine sediments, and the regularity of the lower beds of the Upper Sandstone when traced beyond these marine deposits to the south-east.

During the earlier part of this marine phase the deeper water was evidently quite clear, with an abundant fauna whose hard parts gradually accumulated uniformly on the sea bed. Probably as the sea advanced some of these calcareous remains were swept into the inlets and shallow basins closer inshore, becoming more or less broken in the process. Thus a relatively pure limestone was deposited. The shallow water along the shore and surrounding numerous off-shore islands was more muddy, giving rise to the clays and shales which are now found surrounding the dolomite masses and lenses.

At a later stage transport of detritus from the neighbouring land increased so that considerably more detrital material was deposited with the limestone. At the same time the area of deposition increased, suggesting an overall rise in the relative level of the sea. This period must have been characterised by a series of slight oscillations to account for the alternations of muddy or sandy limestone and sandy shale. There are signs of slight erosion here and there in these bedded rocks, and occasionally beds are seen to bifurcate or coalesce, but the differential movements which would appear to have caused this must have been very slight, affecting individual beds only.

The siltstone areas must at this time have been sandbanks or barely submerged shoals of silt. The carbonaceous matter suggests a plentiful flora, some of whose remains apparently became deposited with the muddy limestones. The "floating sandstone" (small irregular patches of coarse sandstone within the Limestone Series) would appear to be material of the Lower Sandstone derived from the erosion of rocky islands.

Towards the end of the marine phase clear water conditions again became almost universal as the rate of deposition decreased once more, and nearly pure limestone was again being deposited. By this time the deeper hollows in the Pavement had been filled up and the islands were reduced in size or submerged, allowing uniform deposition over a wider area than hitherto. Finally there was a return to muddy water conditions for a shorter period before fine sand (i.e. the Upper Sandstone) spread over the entire

area supporting a good deal of vegetation, some of which has been preserved as coal.

Throughout this period of marine deposition the shore-line in this neighbourhood extended from north-east to south-west, curving a little towards the south. On the western side of the Gulf of Suez the coast apparently swung towards the north, as thin marine Lower Carboniferous deposits of Wadi Arabah appear to indicate the proximity of a shore-line at a slightly more northerly latitude than Om Bogma. This difference in latitude could also be explained, as Ball (1916) suggested, by a lateral shift on the rift faults.

(d) Conditions for the deposition of iron and manganese.

Krumbein and Garrels (1952) have classified chemical sediments in terms of the pH and Eh of their environments. On their data conditions in the normal marine open-circulation environment, which is indicated for the Limestone Series in western Sinai, would be (assuming uniformity) slightly alkaline (pH in the range 7.5 - 8.4) and mildly oxidising (Eh in the range 0 - 0.4), with salinity at about 3.5%. Dissolved iron would vary between 0.02 and 0.002 parts per million and manganese between 0.01 and 0.001 parts per million, both being involved in organic processes and therefore strongly affected by biological activity. With a nearby land-mass there is the possibility of rather higher concentrations of these ions, and even colloidal matter, being brought into the sea. In these conditions both iron and manganese could precipitate as the oxides together with calcite.

(iv) Diagenesis.

(a) Preservation of carbonaceous matter and pyrite.

From the foregoing interpretation it appears that the sediments of the Lower Carboniferous marine phase were deposited in an epineritic environment in conditions of open circulation, which implies that deposits consisting principally of calcite and aragonite organic remains, and including also the soft parts of animals and plants, were being laid down in oxidising conditions. A number of diagenetic changes must consequently be invoked to account for the present state of the country rocks beyond the zones of subsequent oxidation.

Rubey (1930) concluded that the most favourable conditions for the formation and preservation of calcium carbonate, organic matter and pyrite together were probably rather shallow water and a rapid accumulation and burial of organic matter. Under these conditions much organic matter and carbonate would be preserved by burial and iron sulphide would form in the ooze - chiefly below its upper surface. This is supported by observations on estuarine muds, where anaerobic conditions often obtain beneath shallow oxidising waters (Hatch, Rastall & Black, 1950).

(b) Redox potential.

The most striking change in conditions as sediments pass from the settling medium into the diagenetic environment below the surface of the sea floor is in the oxidation-reduction potential (Eh), as described by Krumbein and Sloss (1951) and Pettijohn (1957). ZoBell (1946) concluded that sediments containing organic matter become reducing through the activity of anaerobic bacteria. Once created the reducing conditions are maintained by ferrous iron, divalent manganese, hydrogen sulphide, etc. As a general rule both Eh and the reducing capacity decrease with depth, pH increasing slightly. Finer sediments, he found, are more strongly reducing than coarse deposits.

(c) Iron and manganese.

Reactions involving these metals are of particular interest in consideration of the suggested sedimentary origin of the ore-deposits.

Goldschmidt, (1954), described two processes affecting manganese in the transport, and after settling, of silts, muds and oozes:

1. solution of manganese as the divalent ion in non-oxidising conditions in carbonated waters, forming the bicarbonate ($\text{Mn}(\text{HCO}_3)_2$).
2. precipitation of insoluble manganese dioxide (MnO_2) in oxidising conditions.

In the presence of decaying organic matter oxidation is limited to surface layers of oceanic sediments, hence manganese accumulates in a thin surface layer in contact with oxidising waters. Selective solution in reducing conditions also affects iron, which is dissolved as the ferrous bicarbonate ($\text{Fe}(\text{HCO}_3)_2$), but manganese is preferentially dissolved because manganous

hydroxide ($\text{Mn}(\text{OH})_2$) is a stronger base than ferrous hydroxide ($\text{Fe}(\text{OH})_2$) as a result of the larger size of the divalent manganese ion.

The average manganese content of the igneous rocks is of the order of 0.09%, while the ratio of manganese to iron is about 0.017. Smaller values than this in sediments indicate leaching, while larger values show concentration, of manganese. Goldschmidt concludes (ibid):

"Green, blue or black muds (indicating presence of ferrous iron, sulphides or humic substances) will suggest leaching of manganese. Red clays (indicating oxidation to ferric iron) will be indicative of fixation and reprecipitation of manganese also."

Mason (1951) gives the ionic potentials as follows:

Mn^{2+}	Fe^{2+}	Fe^{3+}	Mn^{4+}
2.2	2.4	4.5	7.7

Ions with a smaller potential tend to go into solution more readily and stay in solution longer than those with larger potential.

Krumbein & Garrels (ibid) note the complexities introduced by diagenesis. Sediments deposited in oxidising conditions may be radically changed in the diagenetic environment. Reducing conditions ($\text{Eh} < 0$) would prevent the complete oxidation of carbon and thus black carbonaceous matter, if preserved by rapid burial, would remain in the rock. Sulphate ions from organic matter would be reduced to yield H_2S which could react with iron at an Eh of less than -0.25 at pH 8 and eventually form authigenic pyrite (FeS_2). In similar conditions manganese would be expected to form alabandite (MnS), but probably an even lower Eh is required.

In less strongly reducing conditions (Eh -0.1 to Eh -0.25 at pH 8) siderite and rhodochrosite would occur, while between Eh 0 and Eh -0.1 the oxides would be stable in the presence of organic matter.

Thus at Om Bogma, where the unaltered sediments contain pyrite and carbonaceous matter, manganese would be expected to occur in the form of rhodochrosite or alabandite. In fact neither of these minerals has been found in western Sinai. These rocks are generally very poor in manganese, as shown by the assays:-

	% Mn
Grey dolomite (OB/69)	0.03
Dark grey shale (OB/22)	0.013
Black micaceous siltstone (OB/106)	0.02

In general the carbonaceous country rocks at Om Bogma contain quite small amounts of manganese in spite of their proximity to large ore deposits: one specimen of grey dolomite assayed 0.03% Mn and its ratio of Mn : Fe was 0.012.

(d) Dolomitization.

The conditions for penecontemporaneous dolomitization are described by Hatch, Rastall & Black (1950) and seem to have been fulfilled during the deposition of the Carboniferous Limestone of Sinai. These are:

1. shallow water near the shore, between 0 and 50 m. depth.
2. the presence of carbon dioxide, causing partial solution of the limestone; this would be present in the sea-water enclosed in the newly deposited sediment, the coarse nature of the shell fragments allowing some circulation and where circulation was restricted by interstitial mud and carbonaceous matter the bacterial oxidation of part of the carbon with oxygen derived from sulphate-reduction would provide some carbon-dioxide. (This might lead to the deposition of small amounts of iron and manganese as carbonate, but would certainly not cause a concentration of these metals).
3. porosity of the limestones, allowing the percolation of sea-water; here again finer sediments contain a higher proportion of connate water although circulation is restricted.
4. sufficiently slow subsidence to render the change complete; the muddy "limestone", whose burial would have been more rapid, are less completely dolomitized than the purer dolomite-rock.

A significant point concerning the availability of magnesium during diagenesis is the presence of this element in the shales and siltstones as revealed by the formation of epsomite on the underground exposures. As this mineral forms more readily on muddy "limestones" and non-calcareous rocks than on the dolomites it is unlikely that the magnesium is derived from the solution of dolomite crystals. It is most probable that this element was adsorbed by the clay minerals, or was attached to them by base exchange from the connate water soon after deposition. Magnesium is the second most abundant cation in sea-water at present, exceeding the concentration of calcium ions threefold (Krumbein & Sloss, 1951).

Hatch, Rastall & Black (ibid) describe how aragonitic shells "such as those of gastropods and cephalopods" are altered before calcitic fossils "such as crinoids, stout brachiopod shells or rugose corals." At Funafuti, the site of the classical work on modern diagenetic dolomitisation, all the aragonite was found to have been dissolved before metasomatic replacement by dolomite of the calcite began, the first-formed crystals apparently having grown from solution. This sequence of events also agrees with observations in the Om Bogma area: the bulk of the dolomite is composed of automorphic crystals and the majority of the fossils consist of corals, crinoids and brachiopods, while lamellibranchs are poorly represented and gastropods and cephalopods are scarce or absent.

The virtual completion of dolomitisation in the area of Lower Carboniferous outcrops, even in country-rocks otherwise unaltered by mineralising activity, suggests that the dolomite is of diagenetic origin. The formation of automorphic rhombs with carbonaceous and pyrite inclusions in the calcareous black shales, and the appearance in thin section of shale laminae bending round these rhombs lend support to the view that dolomitisation took place in the early stages of compaction.

(e) Compaction.

The effects of compaction in reducing the overall volume of the sediments have been stronger in areas of shale and siltstone facies than in the "limestones" and dolomites, serving to emphasise the differences in thickness of the Limestone Series. In spite of this, however, the top of the Series is more regular than the Sandstone Pavement.

(i) General features of the ore deposits.(a) Size and shape.

The larger ore-bodies are tabular in shape, with an average thickness of about five metres, going up to a maximum of eight metres. Laterally they extend continuously for more than half a kilometre, sometimes linking up with smaller bodies of ore. The floor of these deposits conforms, more or less, to the Sandstone Pavement; there may be up to a metre of "Pavement Shale" between them or, at the other extreme, up to two metres or so of the Lower Sandstone may have been almost entirely replaced by ore, leaving only corroded remnants of the original rock. The roof is always a red, or occasionally brown, shale, sometimes even and regular but more commonly undulating. The lateral terminations are abrupt, but the outlines in plan are generally irregular with many indentations and apophyses. Because of their dimensions these large deposits are often referred to as "beds", but the term can be misleading as they are not true beds in the stratigraphical sense.

The smaller deposits range in size down to small pockets and, in the extreme, to nodules. The small ore-bodies are often lenticular in shape, most commonly with a nearly level floor and a domed roof. Irregular and more disperse deposits are also known, with the ore minerals occurring intermixed with material of the country-rocks.

The original size of the largest single ore-bodies, those of the Om Bogma hills, is unknown as they had been dissected and truncated by erosion during the formation of the present topography, but each was well in excess of a million tons before mining began. It is probable that the total original deposits in the central area, within a radius of 2 kms. of the trigonometrical survey station at Om Bogma, amounted to between ten and fifteen million tons before they were greatly reduced by erosion. The amount of the original deposits of the entire exposed ore-field is of course even more conjectural, but it was possibly of the order of twenty million tons containing between four and five million tons of manganese metal, the average tenor being between 20% and 25% Mn. These estimates include rock which would not all necessarily be classed as "ore" in the technical sense at any given time, although composed almost entirely of iron and manganese

oxides, as this status depends on so many outside factors.

(b) Composition.

An analysis (Gill & Ford, 1956) of ore as shipped, that is to say a sample of a cargo of ore from many parts of the mine, gave the following composition:

MnO ₂	32.76	Mn	21.46
MnO	0.97		
Fe ₂ O ₃	51.47	Fe	<u>36.03</u>
FeO	nil	"Joint metals"	57.49
SiO ₂	5.80		
Al ₂ O ₃	2.38		
CaO	0.78		
MgO	0.10		
BaO	0.40 other than contained in BaSO ₄	
K ₂ O	0.30		
Na ₂ O	0.10		
BaSO ₄	0.90		
P ₂ O ₅	0.24		
SO ₃	0.25 other than contained in BaSO ₄	
CuO	0.05		
PbO	0.07		
ZnO, NiO, CoO	traces		
As	0.01		
CO ₂	0.12		
Combined Water	3.25		
	<u>99.95</u>		

The high state of oxidation of the principal metals, indicated by the above analysis, is a feature of all the deposits. No compounds of iron other than the ferric oxides have been recognised within the ore deposits, and the only lower oxide of manganese (hausmannite, Mn₃O₄) is of very minor importance. The "joint metal" content is also constant within narrow limits throughout the bulk of the deposits.

(c) Variation in the ores.

The ores show a very wide variation in the ratio of manganese to iron over quite short distances both horizontally and vertically. Under these

conditions mining to produce a constant grade of shipping ore (priced on the units of manganese contained) called for constant sampling and a detailed knowledge of the ore-bodies. With practice it was found possible to estimate the tenor in manganese of ore in situ within arbitrary limits by comparison with parts previously sampled and assayed. By this means detailed plots were produced showing the variation in the ratio of the two metals, but no recognisable pattern was ever discovered and it was never found possible either to deduce a controlling factor or to predict changes in the grade of the ore in undeveloped parts of an ore-body.

There are also variations in the texture and mineralogy of the ore, but these are not so sudden as with the metals ratio. These features are described more fully below.

(d) Gangue minerals.

About 85% of a typical dried sample of ore is composed of the oxides of iron and manganese. With these should be included some combined water, baria, potash and lead, which are respectively essential components of some of the ore minerals. The bulk of the remainder, including silica and alumina, appears as traces of the country-rock which have become inter-mixed with the ore. Thus the true gangue minerals form only some two or three per cent of the total.

Barite is the most obvious gangue mineral, of wide distribution and generally present as radiating groups of coarse tabular crystals, often lining small vugs. These crystals are colourless or (occasionally) pale yellow, with many faces developed, particularly for several values of (hCl) and (Ok1). Sometimes this mineral occurs white and massive in pieces up to 10 cms. across, or intimately mixed with the ore minerals and visible only under the microscope. The barite usually appears to have crystallised later than the ore minerals, but quite often coarse needles of pyrolusite can be seen terminating against a well formed crystal of barites.

Calcite occurs in the ore on a much more restricted scale. It has been seen in veinlets associated with pyrolusite, and appears to be a late stage mineral.

Dolomite also appears to have crystallised at a late stage within the ore. It occurs most commonly as a matrix in stalactitic masses of goethite, sometimes cementing brecciated fragments of this mineral.

Rarely it is found in well developed pyramids in vugs within the ore.

Aragonite has been recognised under the microscope in some sections.

(ii) Texture of the ores.

The following ore types were recognised in the mining areas:

- | | | |
|----|------------------|---|
| 1. | Mixed ores | Banded ore
Nodular ore
"Run of mine" ore. |
| 2. | Segregated ores | Rich ore (dioxide)
Massive iron ore (goethite)
Ochre and redde
Red iron ore (haematite). |
| 3. | "Hard blue" ores | Psilomelane type
Hausmannite type. |
| 4. | Eluvial deposits | "Float". |

(a) Banded ore.

Large areas of the bigger deposits are composed of ore arranged in alternating iron rich and manganese rich horizontal bands. The bands are about 1 cm. wide and often show up very clearly in old mine workings as the manganese rich layers tend to become encrusted with efflorescent rock-salt helictites and flowers (cf. Huff, 1940). Under the microscope the manganese layers are seen to be composed of more or less spherical structures of microcrystalline to finely crystalline pyrolusite with concentric shrinkage cracks, suggesting crystallisation from a colloidal precipitate. The matrix is formed of more coarsely crystalline pyrolusite with some associated botryoidal goethite.

The iron rich layers contain earthy haematite, often with associated fine quartz grains, giving the impression of the remains of shale or siltstone. Specimen no. OB/31 is typical of this type of ore.

(b) Modular ore.

This is the most common type of ore in the larger deposits. Manganese rich nodules of various sizes from one to five or more centimetres

across, are embedded in a matrix of earthy iron ore. The nodules may be discrete or grouped together in bunches; where they are very numerous they coalesce to form a very coarse spongy texture, with the interstices filled by the friable iron oxide.

The nodules themselves are either an intergrown mixture of very finely granular pyrolusite and haematite enclosing rather coarser crystalline pyrolusite or radiating coarse needles of pyrolusite. Remnant grains of quartz are often found in the former type of nodule (as in OB/34), indicating replacement of a siliceous host-rock.

The widespread nodular and banded habits of the ore have been made use of in the past in beneficiation by screening. It was found that by separating the fine material from broken ore a product (the lumps and rubble) could be obtained which was several per cent richer in manganese than the original ore as mined.

(c) "Run of mine" ore.

This type of ore is so-called from its lack of any readily identifiable features, such as are seen in the other types described here. It is essentially an intimate mixture of goethite and pyrolusite in varying proportions, these minerals being distinguishable in the hand specimen. It is found in ore-bodies of all sizes, and generally in places where the field relations suggest replacement of a dolomite or dolomitic "limestone".

A specimen of this ore (OB/33) under the microscope shows irregular areas of powdery and finely crystalline pyrolusite with occasional poorly developed concentric structure. These areas are surrounded by cryptocrystalline goethite with associated coarsely crystalline pyrolusite.

(d) Rich ore (dioxide).

Locally in the large deposits there occur lenticular and irregular pockets of an ore very rich in manganese and correspondingly poor in iron. Where these were of sufficient size and purity they were worked separately for chemical grade ore, or "dioxide". This type of ore also occurs in persistent and intermittent layers extending for a hundred metres or more in some of the deposits where there has been a good deal of segregation of the metals, as in the Central and East Hills.

This ore consists almost entirely of pyrolusite, ranging from a soft powdery grey material, very finely crystalline, to a mass of coarse, hard

metallic grey crystal needles in intergrown radiating aggregates. In extreme cases the individual needles attain a length of several centimetres.

In polished section (Sp. no. OB/32) the finer varieties are seen to be composed of interfering irregular concentric structures with centres of soft powdery pyrolusite surrounded by radiating needles made up of tiny grains with parallel extinction. (There is a tendency for α MnO_2 to occur in needle-like bundles of micro-crystals with their c-axes parallel to the length of the needles, but with the other axes at random, Butler & Thirsk, 1952). These core areas are crossed by fine veinlets of pyrolusite suggestive of filled shrinkage cracks. Away from the centres the crystals increase in size, their free ends either protruding into small vugs or embedded in a matrix of gangue mineral, usually a carbonate.

(e) Massive iron ore (goethite).

Segregations of iron within the thick ore "beds" are generally larger than those of rich manganese ore. In one form the iron occurs as large masses of goethite in closely packed stalactitic forms, or in concentric layers of radiating fibres. Gangue minerals are typically present in this type of ore, as veins and filling interstices.

A section of the stalactitic goethite (OB/14) showed perfect examples of colloform radiating structures rimmed by microgranular pyrolusite and locally brecciated. In the brecciated areas were acicular crystals of aragonite and plates of barite, the whole being set in a matrix of dolomite which extended as veins across the unbroken part of the specimen.

Another section (OB/35) showed an irregular spheroidal structure with many shrinkage cracks. The core areas were usually goethite surrounded by finely crystalline and amorphous material.

In the mine spheroids up to 60 cms. in diameter have been seen. In one example alternating concentric layers of fine-grained massive and radially banded manganese oxide (probably pyrolusite) were surrounded by a thick layer of massive goethite with ill-defined radial banding at its outer edge terminating in a smooth spheroidal surface.

(f) Ochre and Reddle.

These earthy iron ores are very widespread, forming the matrix of the nodular ore, and in some localities making up virtually the full thickness of the ore "bed" for areas of up to a hundred square metres.

In section a specimen of yellow ochre (OB/30) showed very thin veinlets of gangue bordered by bands of goethite cutting across a mass of softer cryptocrystalline material, identified as goethite by x-ray powder photography.

(g) Red iron ore, (haematite).

Very fine grained bright red iron ore is typical of the deposits in a siltstone or sandy facies of the host. This ore occurs in fairly thin layers, occasionally reaching a thickness of three metres or more but usually of the order of one metre or less. Usually several of these layers occur one above the other or a larger body of ore may contain bands and pockets of included country rock. This iron ore is typically friable, crumbling into small more or less rectangular fragments a few millimetres in size. Manganese may be present but many of the mine samples assayed up to 66% iron (Fe) with often less than one per cent manganese (Mn).

A polished section (OB/13) of this ore showed very fine grained material which was shown by an x-ray powder photograph to be haematite. A small amount of goethite and wad was found in veinlets, possibly fractures or joints.

(h) "Hard Blue" ore (Psilomelane type).

There are two varieties of "Hard blue" ore; both are very hard, not easily taking a scratch from a steel knife blade, and are grey with a slight metallic blue tinge.

The Psilomelane type of ore is homogeneous in appearance, although it contains both iron and manganese in varying proportions. Over the range from nearly pure manganese oxide down to a manganese to iron ratio of 1 : 3 there is no detectable difference in the hand specimen, but with decreasing manganese content the lustre becomes dull, the ore becomes more brittle and shows a red streak, grading into massive haematite. This ore may be jointed, tending to break into rectangular fragments. Under the microscope botryoidal texture and colloform or diffusion banding can be seen, and while some anisotropic granular material can be detected under high magnification much of the material appears to be amorphous.

This variety of ore occurs adjacent to the doleritic Om Bogma Dyke, (OB/11), and also occasionally in association with a non-calcareous host (OB/12).

(i) Hausmannite type.

By contrast this other variety of Hard Blue ore is granular and crystalline. It is typically of high tenor in manganese, often exceeding the theoretical maximum of 63% for pure pyrolusite, but it is low in MnO_2 . This Hard Blue ore strikes fire under the hammer and breaks off in thin flakes with an uneven surface and a very sharp edge. It is never jointed, occurring in irregular slabs and fairly extensive "beds" up to a maximum thickness of about a metre. It is never found in the larger ore deposits, but occurs away from the main centres of mineralisation, either alone or associated with, (but not mixed with), haematitic iron ore, and often in a non-calcareous host. It appears to predominate over all other types of ore in the outcrops, probably because it is extremely resistant to weathering and stands out prominently while other ores are eroded or buried beneath scree, but there is a suggestion that the ore becomes hardened by weathering processes as outcrops of Hard Blue often lead to softer ore under the surface.

In section (OB/15) there is no sign of colloform banding in this type of ore: the predominate mineral is hausmannite. In one underground exposure (Sp. no. OB/16) hausmannite was found in angular pieces up to about a centimetre across, altered marginally to psilomelane and set in a matrix of calcite associated with pyrolusite. These latter minerals were apparently introduced after the formation of the hausmannite.

(j) "Float".

This is a prospector's term for loose material derived from a solid ore body, and it is used here for recent eluvial deposits which are useful as a guide to ore in situ rather than for their own value as ore. In western Sinai manganese float, being of high specific gravity, becomes concentrated near the source in a thin surface layer of hard black pebbles as the lighter minerals and rock fragments are washed away. The ore fragments vary in size from about 1 cm. in diameter upwards to nearly 3 metres across in extreme cases. These latter blocks sometimes become detached on steep hillsides as a result of undercutting as the softer rocks are removed in the normal course of erosion. Dark patches of the smaller fragments show up very prominently against the general light sandy background, and by their aid the presence of ore (or of a previously existing ore-body) can often be detected from a distance of several miles.

(iii) Significance of the mineralogy.(a) The ore minerals.

The ore minerals never show automorphic crystals; they have been identified in a limited number of specimens by means of their optical properties, confirmed by x-rays. In other specimens and in the field they have been recognised by analogy with those specimens more fully investigated, comparing in particular habit and colour, and form and hardness of aggregates where these appear to be distinctive. That the specimens examined, which were carefully selected in the field as being typical of the various types of ore making up the deposits, do give a fair mineralogical representation of the whole of the deposits is supported by the assays and in particular by the analysis quoted (q.v.).

The ore minerals recognised are as follows:

(1) Forming the bulk of the deposit:

Goethite	$\alpha \text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$	
Haematite	$\alpha \text{Fe}_2\text{O}_3$	
Pyrolusite	βMnO_2	
Hollandite	αMnO_2 with Ba	} recognised as a group
Cryptomelane	αMnO_2 with K	
Coronadite	αMnO_2 with Pb	
Psilomelane	MnO_2 with H_2O and Ba	

(2) of minor importance only:

Hausmannite Mn_3O_4

(3) also suspected in very small quantity, but not proved:

Crednerite CuMn_2O_4 .

(b) Colloform textures.

Much of the ore displays textures which are generally associated with precipitation from colloidal solutions. This is particularly true of the goethite, which typically occurs in stalactitic habit with smooth rounded surfaces, and of the α manganese dioxides. It is probable that the bulk of the ore minerals were formed in this manner, crystallisation from colloidal gel being more advanced in some parts of the ore-bodies than in others.

(c) Conditions of deposition.

The minerals of this suite and their modes of occurrence give some indication of the conditions of deposition. The presence of hausmannite appears to suggest a higher temperature as it is the stable oxide of manganese at higher temperatures and can be formed by heating pyrolusite to 1000° in air. Hausmannite occurs, however, as veinlets in dolomite (to be described in Chapter 7) which shows no other thermal effect. It seems likely therefore that the hausmannite was formed at a lower temperature, and that the manganese owes its lower state of oxidation to another cause, such as a reduced oxygen pressure in the environment of formation. The hausmannite is, in any case, of minor importance in the ores and only of significance in indicating purely local conditions at the time of formation.

The most important factor determining whether the oxides of iron and manganese shall be formed, and the valency state of these metals, is the oxidation-reduction potential during their formation. Oxygen, of course, is an essential constituent: the presence of vast amounts of the higher oxides of iron and manganese in itself indicates that there was an abundance of available oxygen at the time of deposition. The actual minimum value of Eh required for the precipitation of these oxides will vary with pH. At higher values of pH precipitation of these oxides can take place at a lower Eh. The presence of dolomite and calcite in the gangue implies alkaline conditions, at least in the later stage of mineralisation when much of the gangue appears to have been introduced. These conditions can be assessed more accurately by reference to the effects of mineralisation on the host rocks; this will be discussed in the next chapter.

The colloidal origin indicated by the mineral textures implies precipitation from, and transport in, an aqueous medium at low temperature. Whether the metals were actually transported in the colloidal state can only be determined after a study of the wider environment of the deposits.

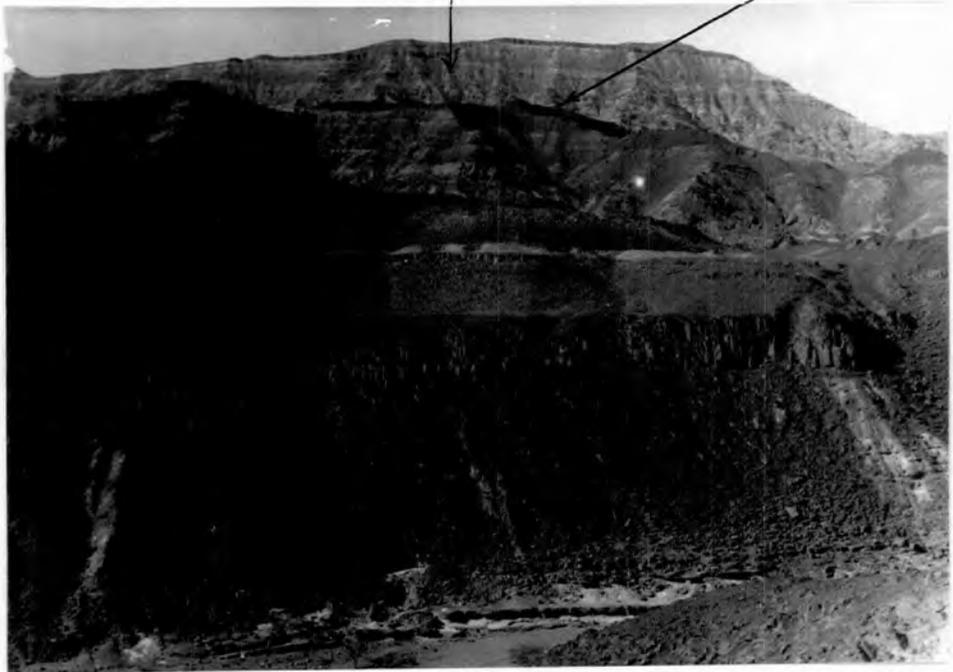
Plate XVIII

Thin sills of dolerite intruded into the Upper Sandstone;
Wadi Abu Natash, 5 kms. south-west of Om Bogma.

The high ridge in the background (to the south-west) is
composed of Cretaceous marls and limestones, beyond the
main eastern boundary fault of the Suez Rift.

Cretaceous rocks

Dolerite



Upper Sandstone

(Carboniferous)

Dolerite

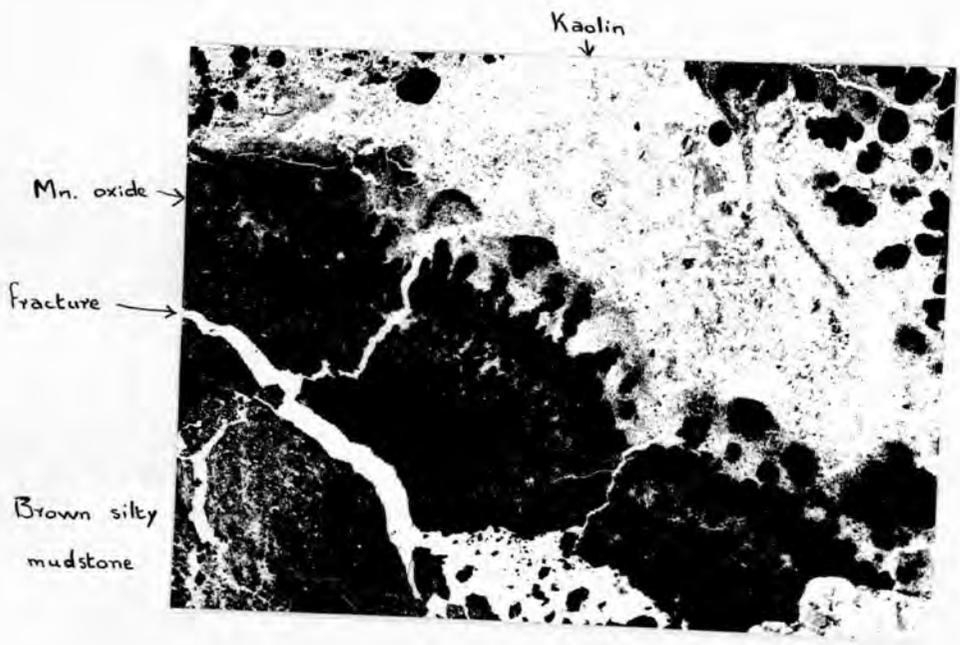


Plate XIX

Marginal alteration of shale with impregnation by manganese oxides.
Sp. OB/24 from face of Devt. 2 - 1 rt. at 43 m. inbye, 2 m. above the Sandstone Pavement and about 40 m. below the surface.
Thin section in ordinary light, x 6.
Bottom left: heavily stained brown silty mudstone.
Black growths: manganese oxide.
White ground: kaolin.
(irregular white lines are fractures in the section).

Plate XX

Siltstone impregnated by red iron oxides.
Sp. OB/26 from C North, E. wall at 4 m. inbye, 1 m. above the Sandstone Pavement and 160 m. below surface.
Thin section in ordinary light, x 6.
The opaque material is principally iron oxides.

Plate XXI

Margin of the oxidation halo in muddy dolomite.

Sp. OB/21 from E. side of Drive 19A at 51 m. inbye, 2m. above the Sandstone Pavement and about 20 m. below the surface.

Thin section in ordinary light, x 30.

Top right: pale greenish zone, dolomite rhombs in a clay matrix.

Bottom left: dolomite in a matrix of red iron oxide.

(There are numerous holes in the section).

Plate XXII

Manganese vein in dolomite.

Sp. OB/20, location as above.

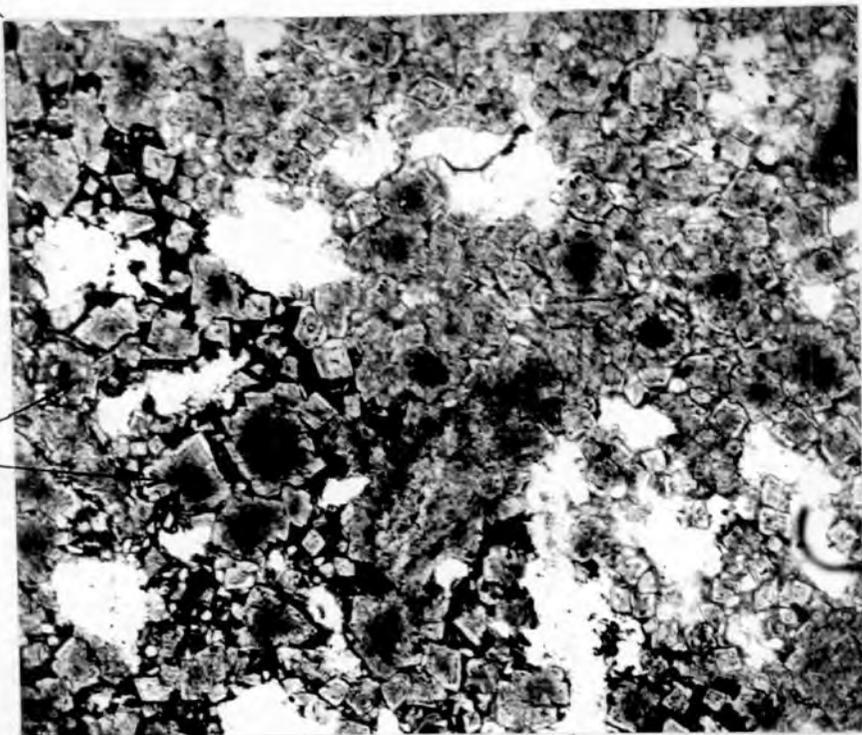
Thin section in ordinary light, x 15.

Narrow veinlet of dense manganese oxide cutting iron impregnated dolomite. Corrosion and absorption of the carbonate crystals can be seen. Penetration was assisted by solution and replacement.

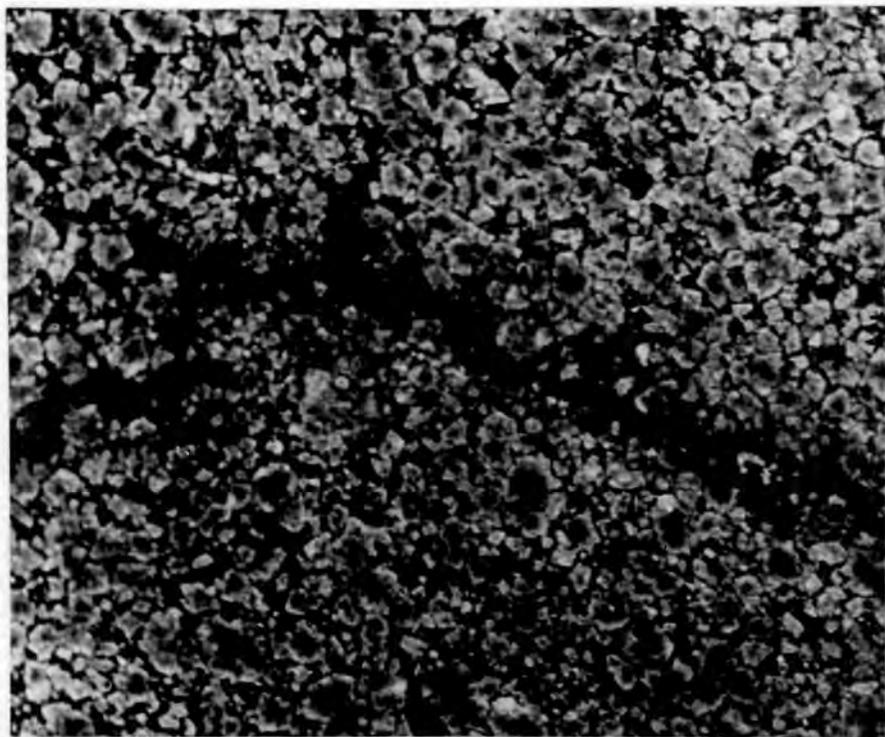
Pale greenish zone

Red zone

Dolomite



Holes in slide



Automorphic
dolomite

Corroded
dolomite

Reticulate pattern
made by ore mineral
replacing dolomite



"Atoll" of
manganese oxide

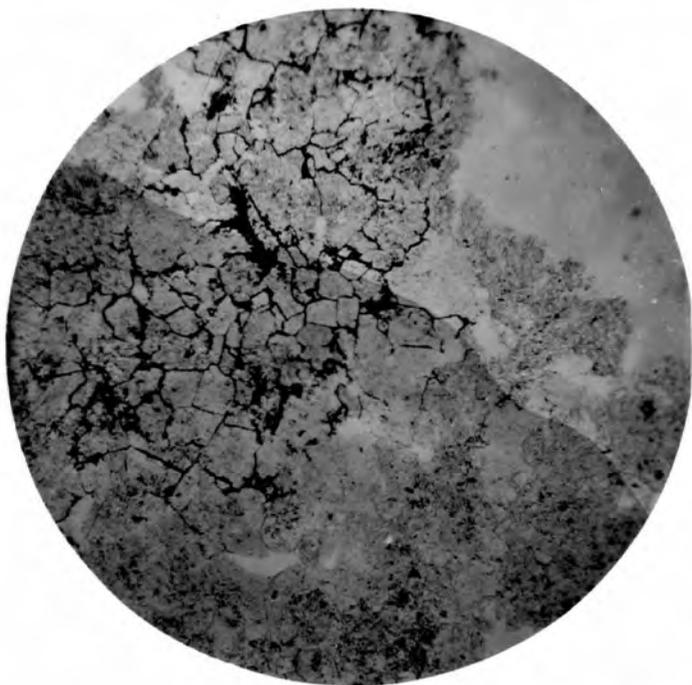


Plate XXIII

Metasomatism of dolomite.

Sp. OB/1 from N. side of Main South - 2 E., 1m. above the Sandstone Pavement and about 160 m. below the surface.

Thin section in plane polarised light, x 30.

"Ghosts" of fossil remains, replaced metasomatically by ankeritic dolomite, and showing incipient replacement by manganese oxides.

Note the reticulate pattern produced at the centres of the organic remains, and the development into an "atoll" (right) with residual rim and core.

Plate XXIV

Impregnation of purer dolomite.

Sp. OB/68, exact location in Om Bogma unknown.

Thin section in plane polarised light, x 30.

The primary invasion of the dolomite by manganese oxides takes place along the crystal boundaries, and in cleavages. Penetration was more rapid than replacement.

Plate XXV

Sp. OB/18 from E. side of Drive 17 cutting, 4 m. outbye from the portal 2.5 m. above the Sandstone Pavement and 2 m. below the surface.

Thin section in ordinary light, x 6.

Tiny ramifying veinlets of manganese oxide (right) and spots of hydrous iron oxides (left) in a nearly pure ankeritic dolomite.

Plate XXVI

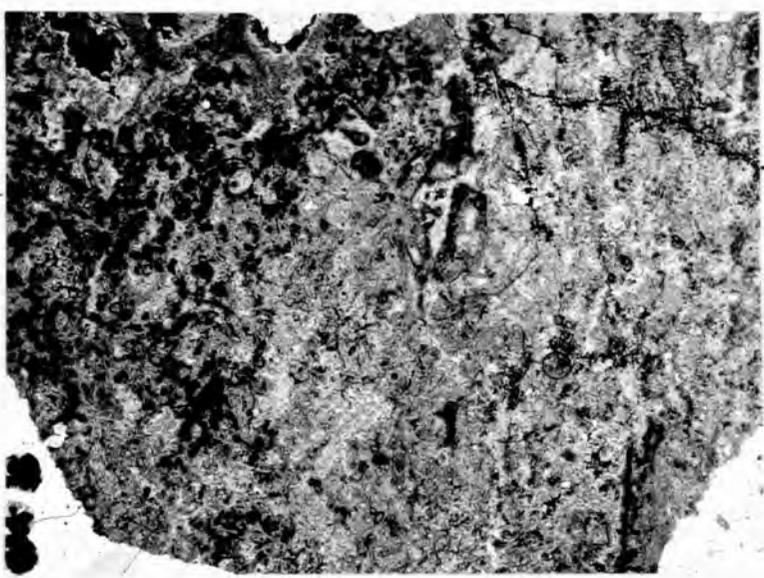
Sp. OB/51 from the surface about 75 m. south of the ventilation shaft on Hill 8 (Lease 180).

Upper Dolomite in the neighbourhood of a prominent fracture.

Thin section in ordinary light, x 6.

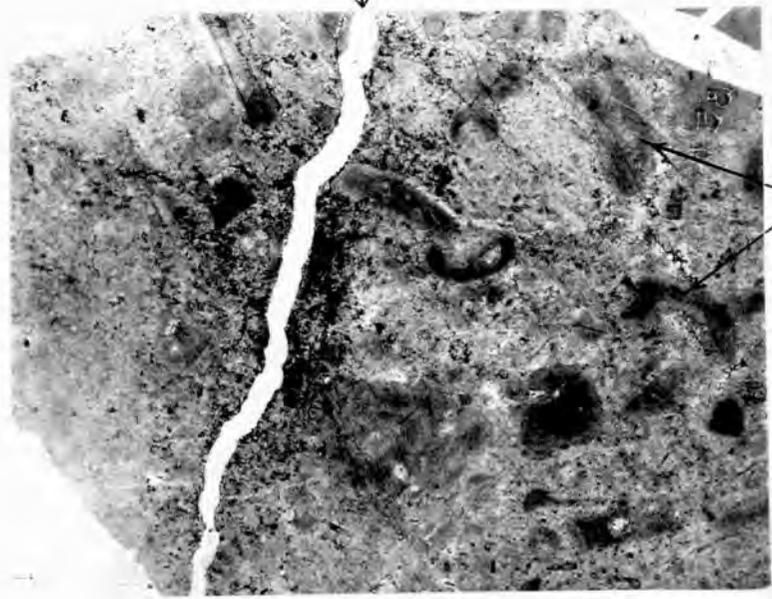
Fossiliferous dolomite with manganese oxides spreading outwards from a small fracture.

Spots of iron
oxide →



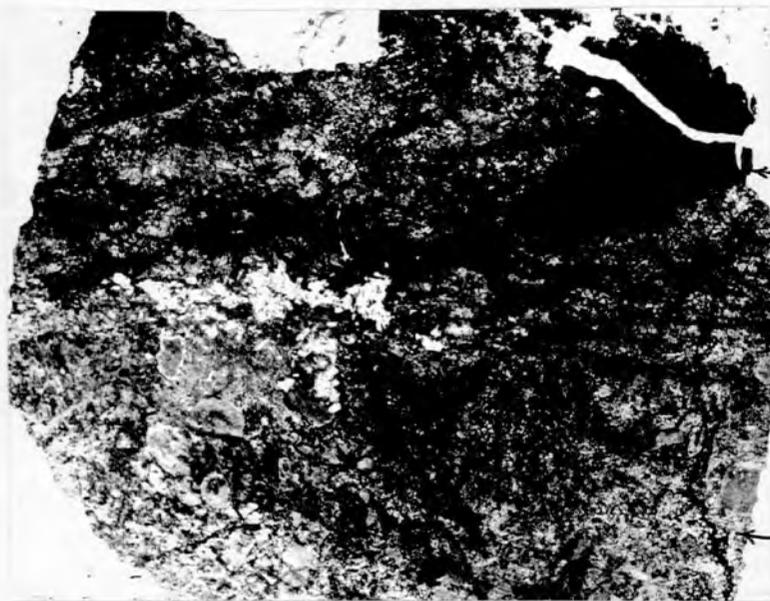
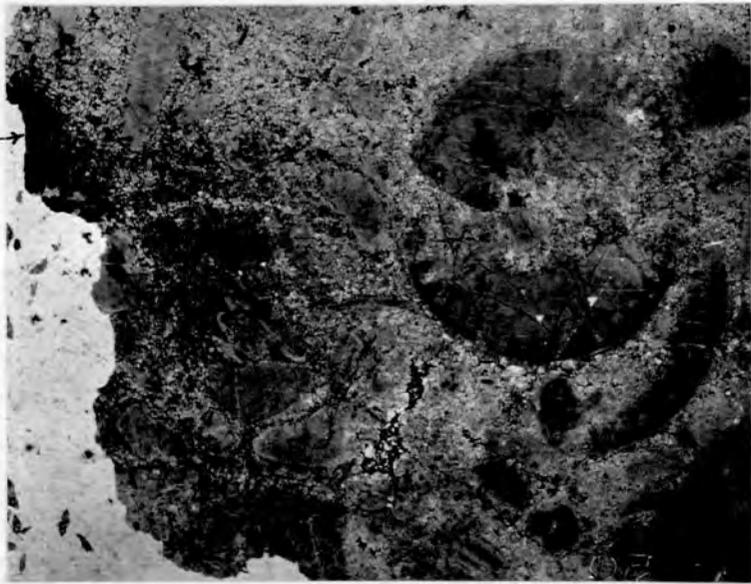
← manganese veinlet

Fracture
↓



Traces of Fossils

One side of an
irregular fracture →



← Ore minerals

← Dolomite

Plate XXVII

Sp OB/50, location as for OB/51, but nearer to the large fracture.

Thin section in ordinary light, x 6.

Impregnation of the rock proceeding along crystal boundaries, with complete replacement close to a fracture.

Plate XXVIII

Sp. OB/49, location as for OB/51, adjacent to the main fracture.

Thin section in ordinary light, x 6.

Replacement well advanced.

Plate XXIX

Lower Sandstone impregnated with manganese.

Sp. OB/78 from a road cutting between the East and North hills, about 100 m. below the Sandstone Pavement.

Thin section in ordinary light, x 15.

Ill sorted sandstone partially impregnated with manganese oxides. The boundary of the impregnated area is regular and fairly well defined.

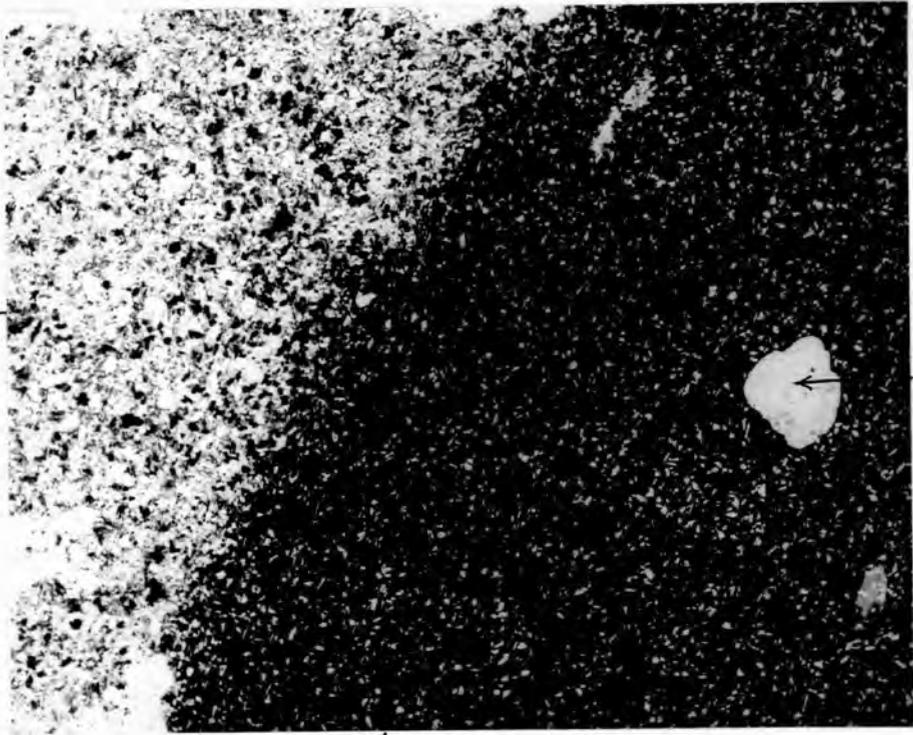
Plate XXX

Sp. OB/77, exact location in Om Bogma unknown.

Thin section in ordinary light, x 20.

Very ill sorted sandstone (Lower Sandstone) rather patchily impregnated and replaced by iron and manganese oxides.

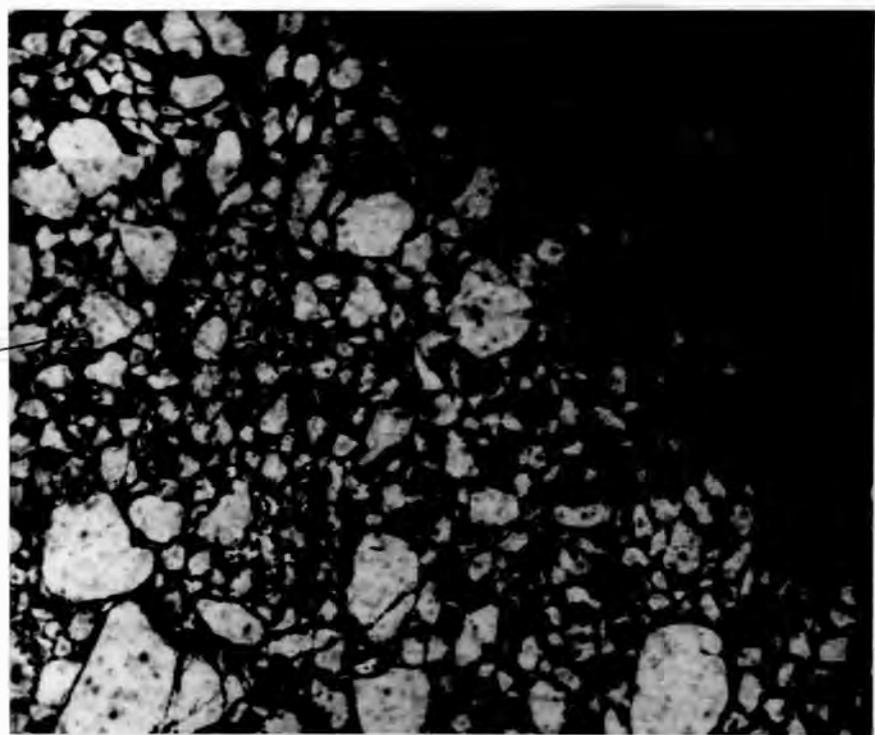
ill. sorted
sandstone

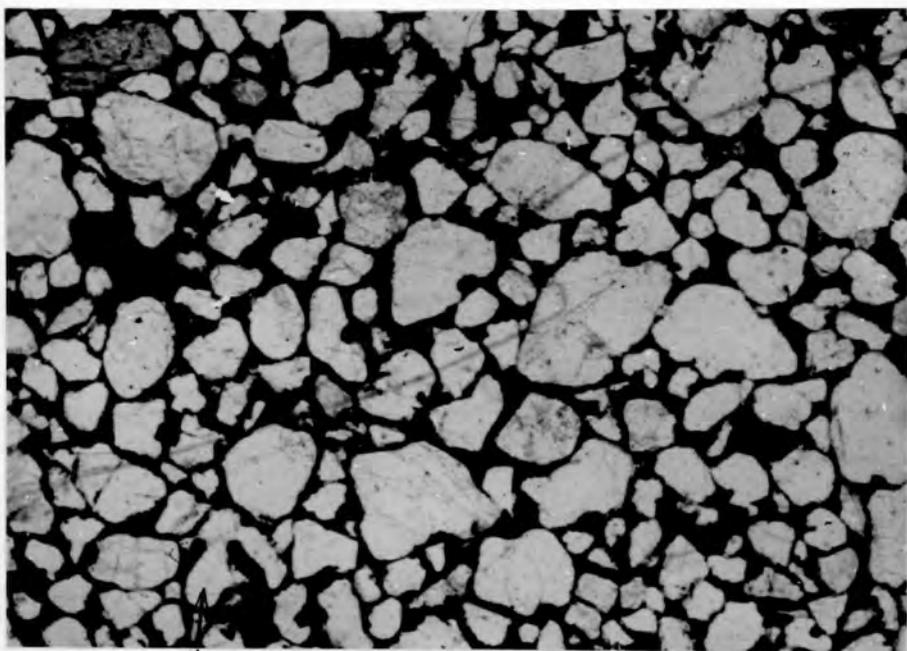


Large quartz-
grain

Matrix of ore mineral with corroded sand & silt grains.

Corroded sand
grain





Partially replaced quartz grain

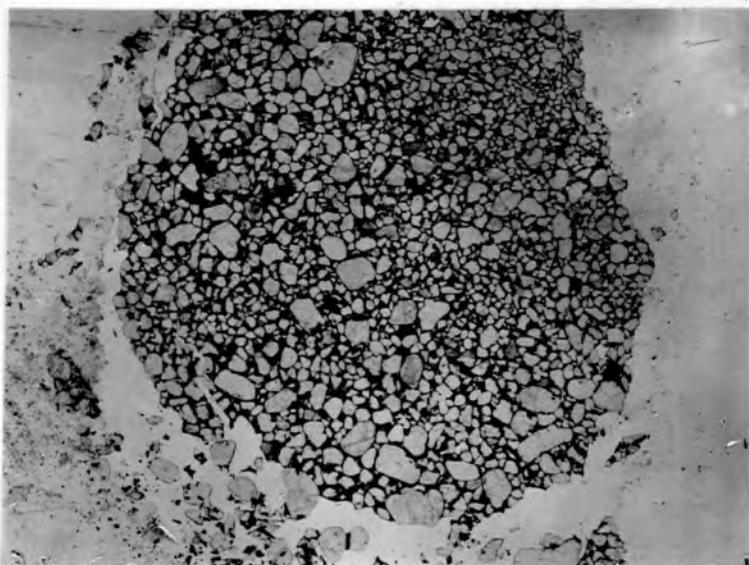


Plate XXXI

Lower Sandstone with incipient manganese replacement.

Sp. OB/76 Lower Sandstone from the southern slope
of Hill 8 (Lease 180).

Thin section in ordinary light , x 6.

Ill sorted sandstone cemented by manganese oxides.

Plate XXXII

Same as above, x 30.

Numerous embayments in the sand grains show
incipient replacement of quartz by the
manganese oxides.

Plate XXXIII

Halo oxidation in siltstone.

Roof of Devt. 2 main at no. 15 branch to the fault, about 150 m. below the surface.

Top and bottom of picture: unaltered grey to black carbonaceous siltstone.

Centre: very irregular patches, alternating bands of bleached and heavily iron-stained siltstone.

Plate XXXIV

Carbonaceous clay preserved in a fault plane.

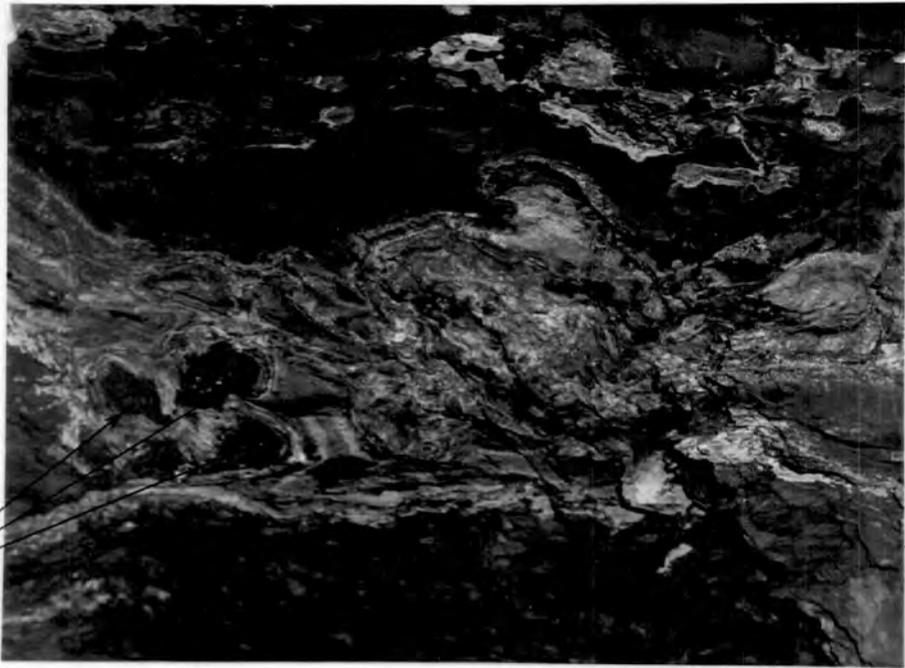
The Tony Fault exposed in Devt. 2 main, no. 12 branch to fault. 1 - 2 m. above the Sandstone Pavement on the upthrow side, 350 m. from the outcrop at Pavement level (above Ain Abu Hamata) and about 170 m. below the surface.

Right: light yellowish brown Upper Sandstone.

Left: red iron-stained siltstone of the non-calcareous facies of the Limestone Series.

Centre: the black material is carbonaceous clay dragged into the fault plane. The white line is a bleached zone.

Dark grey (unoxidised) siltstone is seen at the bottom of the picture.

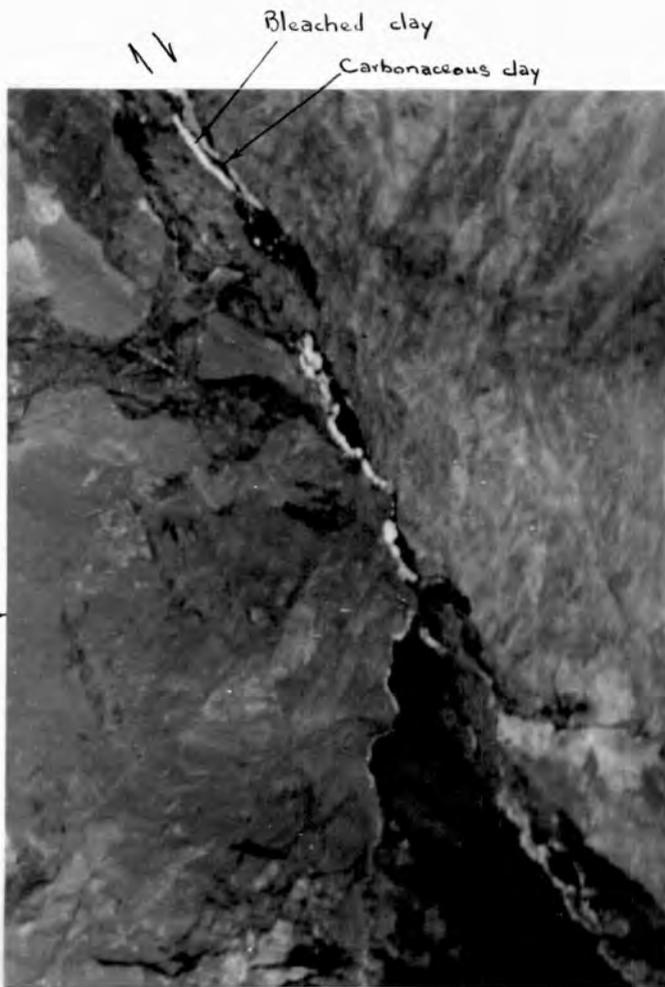


Narrow bleached zone

Red siltstone

Dark grey siltstone

Red iron oxide nodules



Bleached clay

Carbonaceous clay

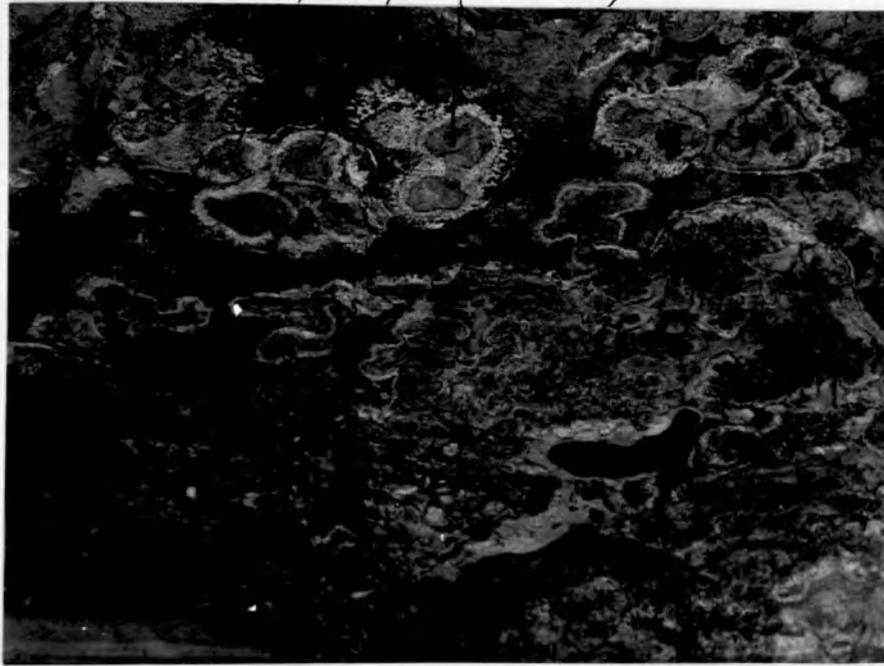
Upper Sandstone

Red iron
siltstone

Carbonaceous
siltstone

Brown iron patches

Grey siltstone



Mottled siltstone

Dark grey siltstone

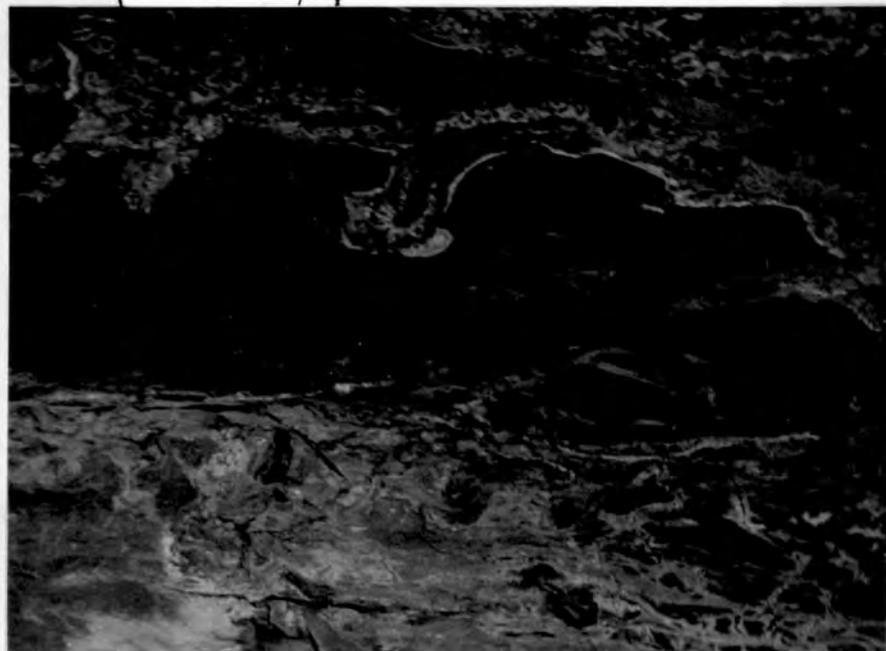


Plate XXXV

Roof of Devt. 2 main, about 150 m. below surface.
Patches of brown iron-stained siltstone surrounded
by bleached boundary zones in unaltered carbonaceous
siltstone.

Plate XXXVI

Well defined, but extremely irregular, boundary
of the oxidised halo.
Mourad cross-cut, about 70 m. below the surface.
cf. Plate XIX.

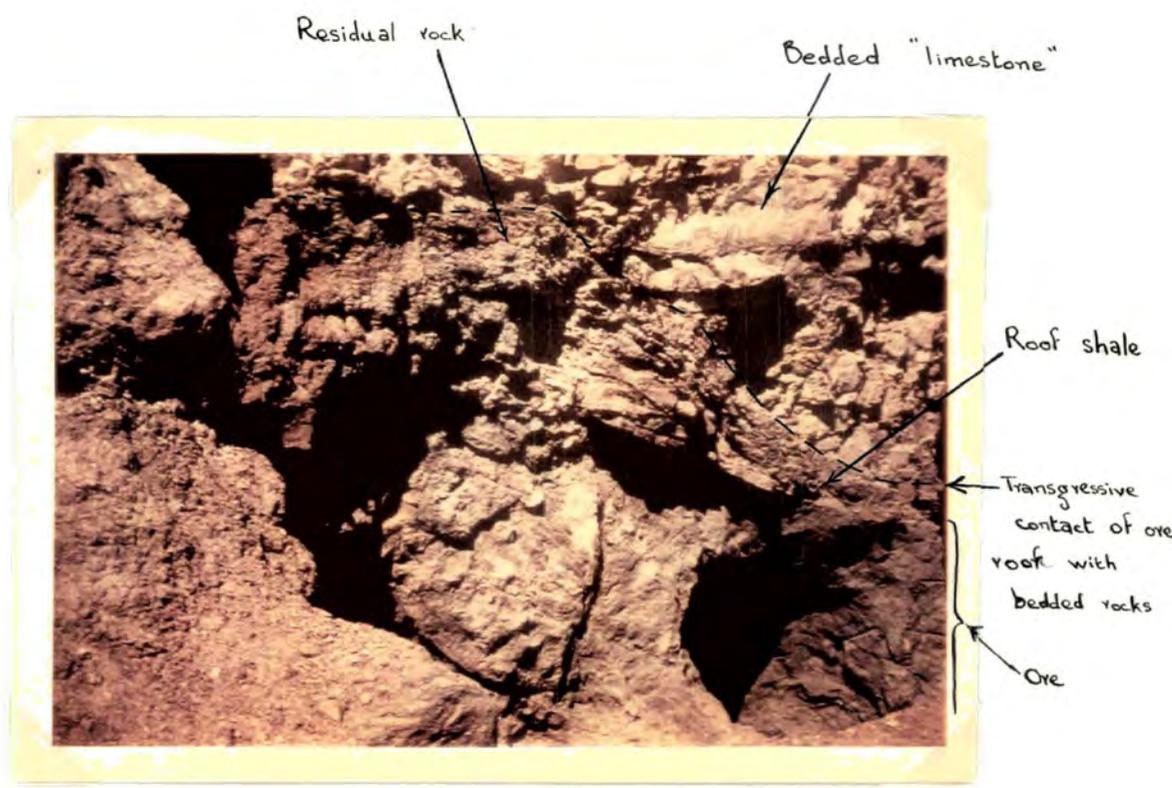
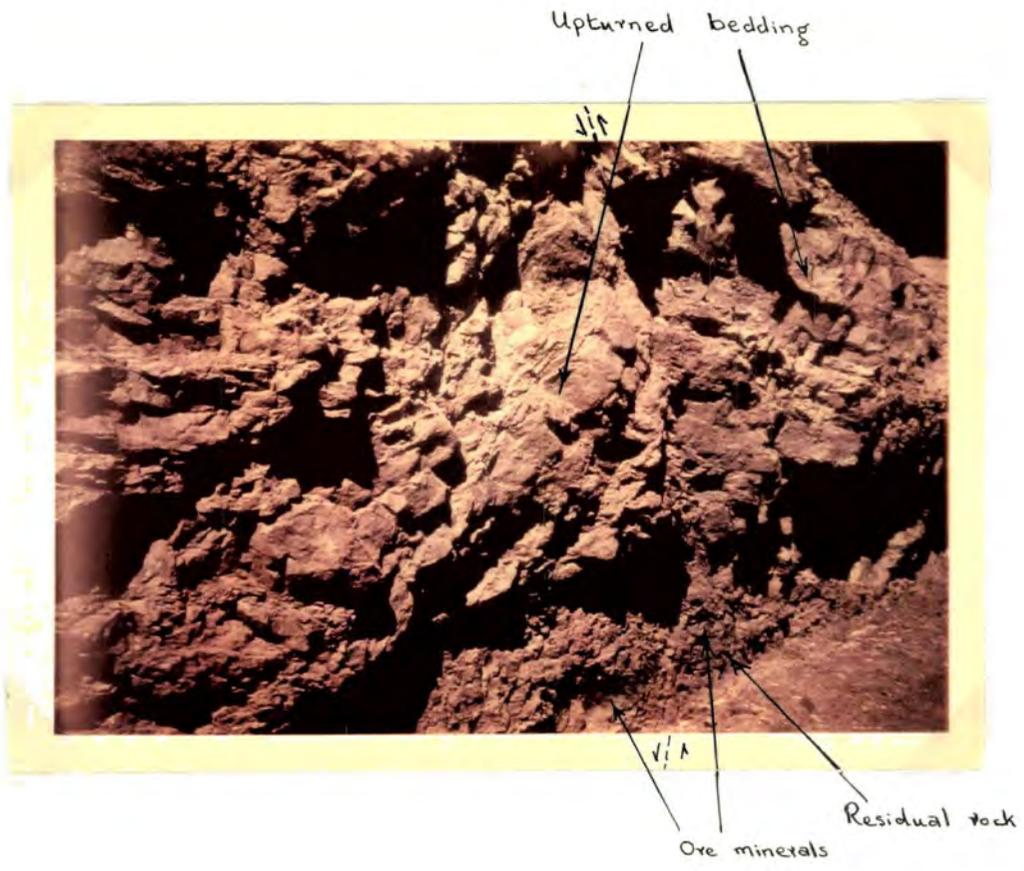
Plate XXXVII

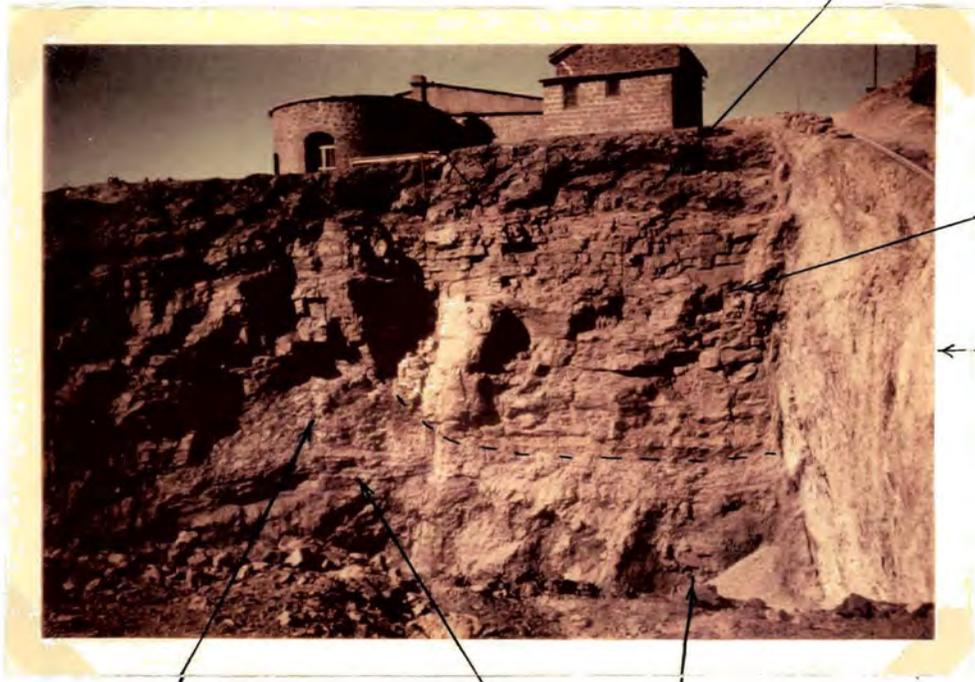
Upturned bedding on both sides of a small fault.
Opencut face on the east side of the Central Hills,
showing dolomite and shale beds of the Limestone
Series.

A little ore and residual rock are associated with
the fault, shown at the bottom of the picture.

Plate XXXVIII

Part of an ore lens, showing roof shale and the
transgressive relations with the overlying beds.
Opencast face on the east side of the Central
Hills.





Upper Dolomite

Bedded "limestone"

← Om Bogma Dyke

Dome of residual rock

Roof shale

Ore

Plate XXXIX

Opencast face in the Central Hills.

A typical thick "bed" of ore is partly seen near the bottom of the picture, with its base obscured by detritus. It is in the position normally occupied by the massive basal dolomite in barren areas. The ore is overlain by a shale roof, separating it from the bedded dolomitic "limestone", which is unmineralised. A dome of residual rock (with secondary dolomite rhombs) can be seen, a little left of centre, extending upwards from the roof shale into the bedded rocks. The dark layer at the top of the face is the Upper Dolomite, stained purple and partially replaced by manganese oxides.

The Om Bogna Dyke can be seen on the extreme right of the picture.

(7) MARGINAL ALTERATION OF THE COUNTRY-ROCKS.

From the genetic point of view the ground immediately surrounding ore bodies is often of more interest and significance than the ore itself. This is so at Om Bogma where the nature and configuration of the alterations to the country-rock adjacent to the ore give the strongest clues to the probable origin of the ore, and their study leads on to the subject of ore controls, which is to be discussed in the two following chapters.

(i) The "oxidised halo".

The unaltered country-rocks of the Limestone Series at Om Bogma and their respective weathered states have been described in Chapter 5. The rocks immediately surrounding the ore-bodies and associated with less concentrated mineral deposition present a striking contrast in that they are typically bright red, pink or brown in colour, and only occasionally yellow, although they are fundamentally the same rock strata. The association of this predominately red colouration of the host-rocks with the ore is such that the term "halo" can be used to describe the zone where they occur.

"Marginal mineralisation" would be a misnomer here as generally speaking the boundaries of the larger ore-bodies in the mining areas are sharp, with no gradation into barren ground. "Marginal ore" and "sub-ore" in the commercial sense at Om Bogma have been rock with a comparatively low manganese to iron ratio, rather than rock with a low total metal content, and they will not be discussed in this section. Partially mineralised ground, with about 30% - 50% iron plus manganese, was not found in sufficient quantity to warrant the establishment of more than the most primitive beneficiation procedures. The oxidised halo is, however, slightly mineralised, and it has been closely studied in the search for "leaders" to hidden ore.

(a) Dolomite.

Very commonly, and virtually always in the mining areas, the massive beds of almost pure ankeritic dolomite are pink or pale purple in colour. Analysis showed the manganese content of a pink specimen of this rock to be 0.3% (Mn.), which is considerably higher than the average for sedimentary carbonate rocks in general and ten times the concentration of manganese found in a specimen of carbonaceous dolomite. A series of six analyses

quoted by Ball (1916) of specimens of the dolomite from widely separated localities in West Central Sinai indicated, as is suggested by the colour of the rock, that these relatively high manganese values are the rule rather than the exception in the massive nearly pure dolomites.

It is a moot point whether the whole mass of the basal dolomite was originally carbonaceous in character, probably it was not as the only grey carbonaceous dolomites to be found now contain about 20% at least of silica, alumina and other impurities. Nevertheless by analogy with the other rock types at Om Bogma and in contrast with the almost pure white basal dolomite of areas remote from the ore deposits (e.g. the upper part of Wadi Baba and Wadi Ikhfi), the pink manganiferous dolomites are assumed to form part of the "halo" of altered host rocks.

The pink dolomite is typically massive, very hard and coarse-grained, with hypautomorphic crystals and open intergranular cavities often clearly visible to the naked eye. On the whole recognisable fossils are infrequent, but locally they are abundant, standing out well on weathered surfaces.

In many places, particularly close to fractured ground, this type of rock is traversed by numerous ramifying veinlets of opaque oxide minerals, most commonly pyrolusite (MnO_2), with some hausmannite (Mn_3O_4). In thin section smaller and more widespread veinlets and strings of these oxide minerals can often be seen extending between the dolomite rhombs and along cleavages and fractures within the individual crystals.

Replacement of the dolomite by the metal oxides is generally more restricted in distribution than the impregnation described above. This solution and replacement has occurred in two ways at Om Bogma, viz. concurrently, (metasomatism); and consecutively, partial replacement by deposition of colloidal oxides after the virtually complete removal by solution of a part of the dolomite. The latter method appears to have operated to produce the largest ore bodies, giving rise to some of the structures to be described in a later section of this chapter.

Examination of thin sections shows that metasomatic replacement did not begin in the dolomite until impregnation was well advanced. Usually fossil remains, originally calcite or aragonite, have been replaced by larger and often clearer crystals of dolomite than those which make up the bulk of the rock, and these have been more susceptible to attack during

the introduction of iron and manganese. In such a case replacement began on a roughly reticulate pattern within the crystal, tending to continue most rapidly at the centre so that in the next stage the grains may show an "atoll" of carbonate surrounding an opaque "lagoon" of oxide mineral. Elsewhere in the rock the ramifications of the invading veinlets have cut off "islands" of residual carbonate, surrounded by opaque material. Locally very fine needles, 0.02 to 0.1 mm. in length, probably of pyrolusite, radiate from a centre situated on an intergranular boundary into the surrounding crystals. Shorter and more stumpy reddish translucent crystals, up to 0.01 mm. in length, probably of goethite, can be seen more rarely radiating in a similar manner. (These latter can also be seen where iron oxide has been replacing secondary quartz).

(b) Impure dolomitic limestones.

Within the oxidised halo these rocks are generally bright red, but sometimes, away from strong mineralisation, as to the south-west of Hill 'D' (Map II), some beds are locally yellow. The red colouration is due to iron oxide disposed between the carbonate crystals and also along intercrystal faces and cleavages. This oxide appears to have replaced the original intergranular material, mainly clay. At the limits of the oxidised halo there is typically a narrow pale green band where the interstitial clay has no staining matter associated with it. This boundary is generally, but not always, irregular, the alteration having advanced with more facility in some places (e.g. along fractures) than in others, but it is not so erratic in its disposition as in the non-calcareous rocks. In shallow underground workings the rock beyond this narrow bounding zone is often bright yellow and only slightly ferruginous, presumably having been oxidised by deep weathering at a later date than the oxidation associated with the iron and manganese mineralisation. In deeper exposures the pale green zone is invariably sandwiched between dark grey to black rock on the one hand and red to yellow rock on the other. Where individual beds are traced across the boundary they can usually be seen to be harder and, in the case of the more shaley rocks, even less calcareous than the normal country rock.

The impure limestones often contain veinlets of black manganese oxides, which are thicker and less diffuse than in the purer dolomites. These manganese oxides corrode and replace the carbonate grains. Apparently the interstitial matter has obstructed somewhat the easy passage of the mangan-

ese oxides, but has been no serious barrier to the iron oxides. The association of the halo with ore mineralisation can best be seen where an apophysis of the oxidised zone has a vein of black manganese oxide at its centre enclosed by a broad irony red area, which in turn is surrounded by a narrower pale green band.

(c) Clays and shales.

The clays are typically bright red within the halo, but they sometimes appear bright yellow and occasionally with alternate red and yellow bands resembling Liesegang diffusion rings. Impregnation with red and yellow iron oxides is indicated, but the soft plastic clays rarely contain deposits of manganese oxides. Their other physical properties, notably plasticity, soapy feel and irregularly orientated slickensided partings remained unaltered during the colour change.

The boundary of the oxidised halo in the clays and more argillaceous and micaceous shales is generally marked by a narrow band, ranging from a few millimetres to a maximum of five centimetres in width, with very sharp edges. This band is very pale green. (as in the case of the shaley dolomites), and while it rarely contains a few crystals of pyrite, it has no trace of either the carbonaceous matter of the unaltered country rock or the iron oxide which characterises the oxidised halo.

The coarser, rather silty shales show a whole range of colour in this oxidised zone from dark red through brown to dull orange and yellow. They show varying proportions of iron oxide, which when present in excess occurs as nodules or thin irregular layers. Manganese oxides also occur in this latter manner; usually the nodules are composed of a mixture of the oxides of both metals. The nodules range in size from 1 to 10 cms., and the laminae vary from a millimetre or two up to over a metre, when the rock, according to circumstances, may become considered as ore.

Very rarely manganese oxides have been found within the original black shale, but never at a distance of more than a centimetre or two from the altered red shale. More typically a number of iron/manganese nodules, or patches of irony red shale, appear scattered in the black shale, each within its own small halo of bleached and red rock, (see Plates ~~XXXIII~~ and ~~XXXIV~~).

Such patches and nodules would appear to be interconnected and also joined to the oxidised zone proper - usually along fractures - but the connection is not always visible in the section exposed.

The shales are often indurated by their iron content, particularly when it is fairly high. The original bedding is preserved, but where there are nodules of iron and manganese minerals the laminations are commonly disturbed, indicating that many of these nodules have grown in situ displacing the surrounding shales in the process. In other cases, notably where there is more quartz silt present in the shale, the oxide nodules have apparently replaced the shale metasomatically.

Sturm (1953) in his description of the deposits in Wadi Menayeh noted the occurrence of nodular concretions of pyrolusite in clay and shale which is distorted in such a way as to indicate that the concretions had pushed it outward and away during growth. He illustrates the point with an excellent photograph, which shows conditions very similar to those in some of the shales at Om Bogma.

(d) Siltstone.

The siltstone of the oxidised halo also appears brown and occasionally yellow, but usually it is either red or almost pure white, often in irregular alternating bands and patches. A typical association is for red, white and black siltstone respectively to occur in ascending order immediately overlying the Sandstone Pavement or above an ore body. These colour differences are a symptom of the more erratic distribution of iron in the siltstones; the white rock consists of quartz silt in a matrix of illite or kaolin, while the red rock is composed of quartz silt in a red iron oxide (haematite) matrix. The iron content varies considerably; often there are bands of haematite with a little goethite and wad in veinlets (possibly infilled shrinkage cracks) and irregular patches, assaying over 65% Fe. The boundaries of the oxidised halo in the siltstone are similar to those in the closely related shales, with projections along joints and bedding planes leading to nodules and patches of irony siltstone surrounded by the unaltered carbonaceous rock.

Manganese oxides occur in two ways in the siltstones. In the bleached and red association, where there is generally an abundance of iron, manganese is found in pockets of "hard Blue" ore, composed of

psilomelane (s.l.) often with a coarse spongy texture enclosing wad in the cavities. In the brown siltstone, on the other hand, especially in the general vicinity of large ore bodies, soft, grey powdery pyrolusite is sometimes found in nodular concretions and veinlets which are typically associated with disturbed bedding in the enclosing shale. Concentric and radiating textures are common in these nodular oxides, and the appearance in section, as exposed in the sides of a development heading, strongly suggest an upward and outward growth in situ, pushing away the enclosing rock. Examples of this type of occurrence were recorded in the East and North Hills; in the former case these deposits stretched for over a hundred metres and locally formed a discontinuous "bed" which was worked for manganese dioxide ore.

Descriptions and analyses of representative specimens follow to show the differences between the unmineralised rocks and those within the oxidised halo.

Dolomite.

Sp. No. OB/18

Pink dolomite.

Collected from:

East side of Drive 17 cutting, 4 m. out-
bye from the portal, Lease 179; about
2.5 m. above the Sandstone Pavement, and
2 m. below the surface.

The specimen is part of the basal dolomite, collected within 5 m. of a small lens of ore. It is pink in colour, with individual carbonate crystals visible to the naked eye. On one side of the specimen a fragment of a fossil coral can be seen. Tiny black oxide veinlets are visible on a cut surface.

In thin section an even grained interlocking mass of hypautomorphic carbonate crystals in the size range 0.05 mm. to 0.25 mm. can be seen. Refractive index (n_0) varies up to 1.683, indicating a slightly ankeritic dolomite. The veinlets of opaque oxides run between and around the dolomite crystals, and are clearly post-dolomite.

Chemical analyses of this specimen and of a specimen (No. OB/69) of unaltered grey dolomite from Incline 1 C, south-west of Hill K. are given for comparison:

	<u>OB/18</u>	<u>OB/69</u>
SiO ₂	1.5	11.7
Al ₂ O ₃	0.5	2.6
CaO	28.9	24.2
MgO	22.2	17.2
K ₂ O	0.4	1.1
Na ₂ O	trace	trace
MnO	0.4	0.04
Fe ₂ O ₃	0.9	0.3 (other than con- tained in pyrite)
FeS ₂	-	4.7
CO ₂	45.9	35.8
H ₂ O	0.7	1.5
	<hr/>	<hr/>
	101.4	99.14
	<hr/>	<hr/>
Ratio Mn/Fe	0.5	0.012

The greater part of these analyses was carried out by the rapid methods of Schapiro & Brannock.

Shale.

Sp. No. OB/22 Mottled shale.
 Collected from: Roof of Drive 31 at 66 m. inbye, Lease 179;
 2.5 m. above the Sandstone Pavement and about
 40 m. below the surface.

This specimen was collected within a few metres of a medium-sized ore body, at the edge of the oxidised halo. The unaltered country rock is dark grey shale similar to Sp. No. OB/4 (collected 50 m. away). Black manganese oxide can be seen infiltrating along a joint plane, surrounded by a comparatively broad (about 1 cm.) purple zone and a narrower bleached zone. The latter shows broad apophyses and (apparently) detached areas

containing purple specks.

The grey unaltered part of the specimen became orange yellow on heating to redness, showing the dark colour to be due to carbonaceous matter. Chemical analysis showed it to contain 0.013% Mn.

In section the shale can be seen to consist of birefringent cryptophyllite "illite" with a little quartz silt of about 0.05 mm. grain size. Black manganese oxide occurs as tiny disseminated granules within the clay and as more solid masses which appear to have pushed aside the clay.

Siltstone.

Spp. Nos.	OB/106	Black micaceous siltstone.
	OB/107	Pale green silty clay.
	OB/108	Red irony siltstone.
Collected from:		Roof of Development 2 Main at 430 m. inbye, about 5 m. above the Sandstone Pavement and 200 m. below the surface.

These three specimens were taken from an area of rather patchy mineralisation in a thin development of the Limestone Series. They were all collected within a few centimetres of one another, at the edge of the oxidised halo. The black siltstone represents the unaltered country rock; the pale green specimen is from the narrow boundary zone, here about 5 cms. wide, and the bright red rock is from the halo proper. From their relations the two latter rocks are clearly alteration products of the former.

Sp. No. OB/106 was disintegrated by agitating in water for 8 hours, and separated into the following (approximate) proportions:

<u>Size</u>	<u>Proportion</u>	<u>Remarks</u>
+ 200 mesh	10%	Almost entirely opaque plates, probably mica flakes coated with carbonaceous matter. Some flakes of white mica and dark brown mica can be seen.
- 200 mesh	50%	Rounded and sub-angular quartz grains, and some flakes of mica. Abundant opaque (carbonaceous?) material, both free and coating crystals of other minerals.

<u>Size</u>	<u>Proportion</u>	<u>Remarks</u>
clay	40%	Settling velocity less than 2 cms./hr. Predominately illite and carbonaceous matter.

Sp. No. OB/107 shows no sign of either carbonaceous matter or opaque oxide minerals. Sp. No. OB/108 is heavily stained with red iron oxide.

Differential Thermal Analysis. The material was prepared by the Macaulay process, as follows:

The specimens were broken into small lumps and placed in quart milk bottles two thirds full of tap water. .880 ammonium hydroxide solution was added as a dispersing agent and the bottles agitated until the water remained turbid on standing for several hours. OB/107 and OB/108 required 2 mls. of dispersing agent and six hours agitation for this, but OB/106 (black siltstone) contained more free electrolyte (principally sulphates) and required a change of water, 5 - 10 mls. of dispersing agent and eight hours agitation. After standing for 15 hours the clay suspension was siphoned into a wide glass dish, and the bottles were re-filled and shaken to yield a further clay suspension.

The ammoniacal solutions were neutralised (to litmus) with acetic acid, and magnesium chloride was added to precipitate the clay. The OB/107 (pale green silty clay) suspension did not flocculate on the gradual addition with stirring of much magnesium chloride, followed by gentle heating, so it was finally separated by centrifuge.

A portion of the OB/106 clay fraction was further treated separately to eliminate carbonaceous matter. The suspension was gently warmed (by placing on a radiator) and 20% (100 volume) hydrogen peroxide was gradually added with periodic stirring. The reaction was very slow, bubbles being evolved slowly for 28 days, during which time the colour of the clay changed from dark grey to very pale yellow. The water turned green, giving positive reactions for iron and the sulphate radical - indicating oxidation of pyrite. The water containing the other clay suspensions showed no dissolved iron.

The clay fractions were washed in alcohol (methylated spirit) and separated by centrifuge four or five times and finally dried in a small

beaker in a dish of water over a water bath. Before being placed in the D.T.A. furnace they were crushed to pass a 100 mesh sieve and kept in a controlled moisture desiccator.

The following colour changes took place on heating these clays to 1050°:

		Before	After
OB/106	unoxidised	dark grey	pale red
	oxidised	very pale yellow- ish grey	orange
OB/107		white	pinkish yellow
OB/108		dark red	bright red

Differential Thermal Analysis showed no apparent difference in the clay minerals (illite and a little kaolin) of these respective specimens, (see D.T.A. curves). Chemical determination of the manganese content (% Mn.) also showed little change across the halo boundary, viz:

OB/106	OB/107	OB/108
0.022	0.014	0.012

The significant changes in this country rock during the halo oxidation were thus:

- (1) Complete removal of carbonaceous matter.
- (2) Impregnation with red oxide of iron.

Argillaceous dolomite.

Spp. Nos. OB/20
OB/21

Yellow and red dolomite.

Collected from: East wall of Drive 19A at 51 m. inbye, Lease 178, 2m. above the Sandstone Pavement and about 20 m. below the surface.

A rather coarsely crystalline carbonate rock, partly yellow and partly red with a narrow, very pale greenish zone about 1 cm. wide separating these parts. The red colouration of the rock is usually associated with

veinlets of black manganese oxide.

The rock is made up of automorphic zoned dolomite crystals up to 0.4 mm. across with refractive index n_D in the range 1.673 to 1.682. Fossil crinoid and shell fragments up to 3 mm. in diameter are present. In the yellow part of the rock there are pockets of yellowish brown birefringent material, probably limonite-stained clay, between the carbonate crystals. There is also a little quartz of silt grade and some opaque brown limonite. The pale greenish zone contains a clay mineral with little or no staining matter and some quartz silt. In the red portion of the rock the interstitial clay, and to a lesser extent the carbonate crystals themselves, have been impregnated by red iron oxides. A veinlet of manganese oxide has altered and corroded the carbonate.

Differential Thermal Analysis. Analyses were made of pieces of each of the three coloured parts of these specimens, ground to pass a 100 mesh sieve, and of their respective clay fractions, separated and prepared by the same technique as was used with the siltstones (q.v.). The clay suspensions were decarbonated by adding a few drops of 1 : 1 hydrochloric acid and allowing to stand till effervescence ceased and did not recommence on the addition of more acid - a period of one or two days.

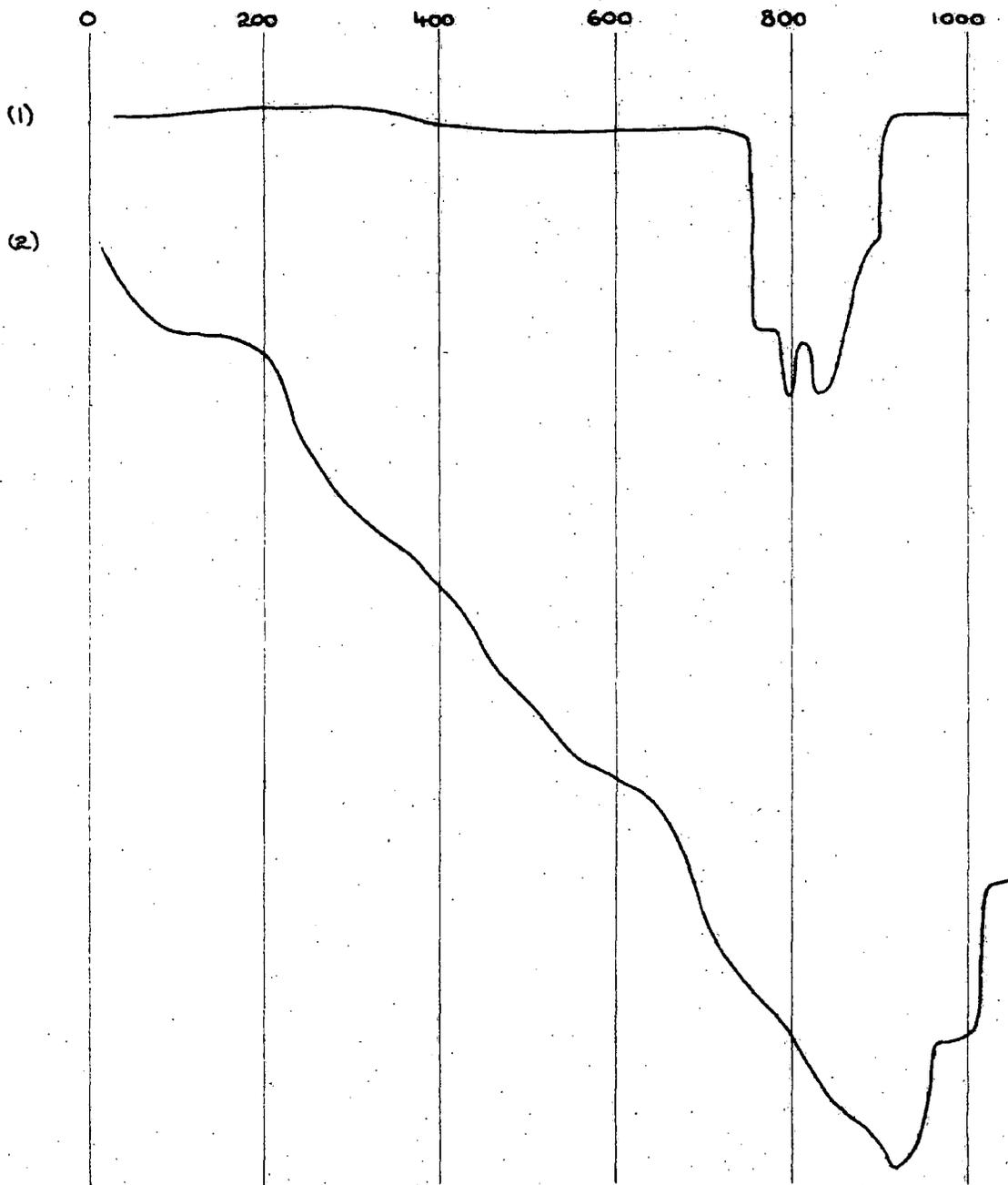
For comparison the clay fraction of a specimen of grey carbonaceous dolomite (OB/69) was also separated and analysed by this method. As with the carbonaceous siltstone, this clay did not disperse until a certain amount of electrolyte (including sulphate ions) had been removed by changing the water. Oxidation of the carbonaceous matter of this sample took 17 days.

The colour changes on heating the clays to 1050° were as follows:

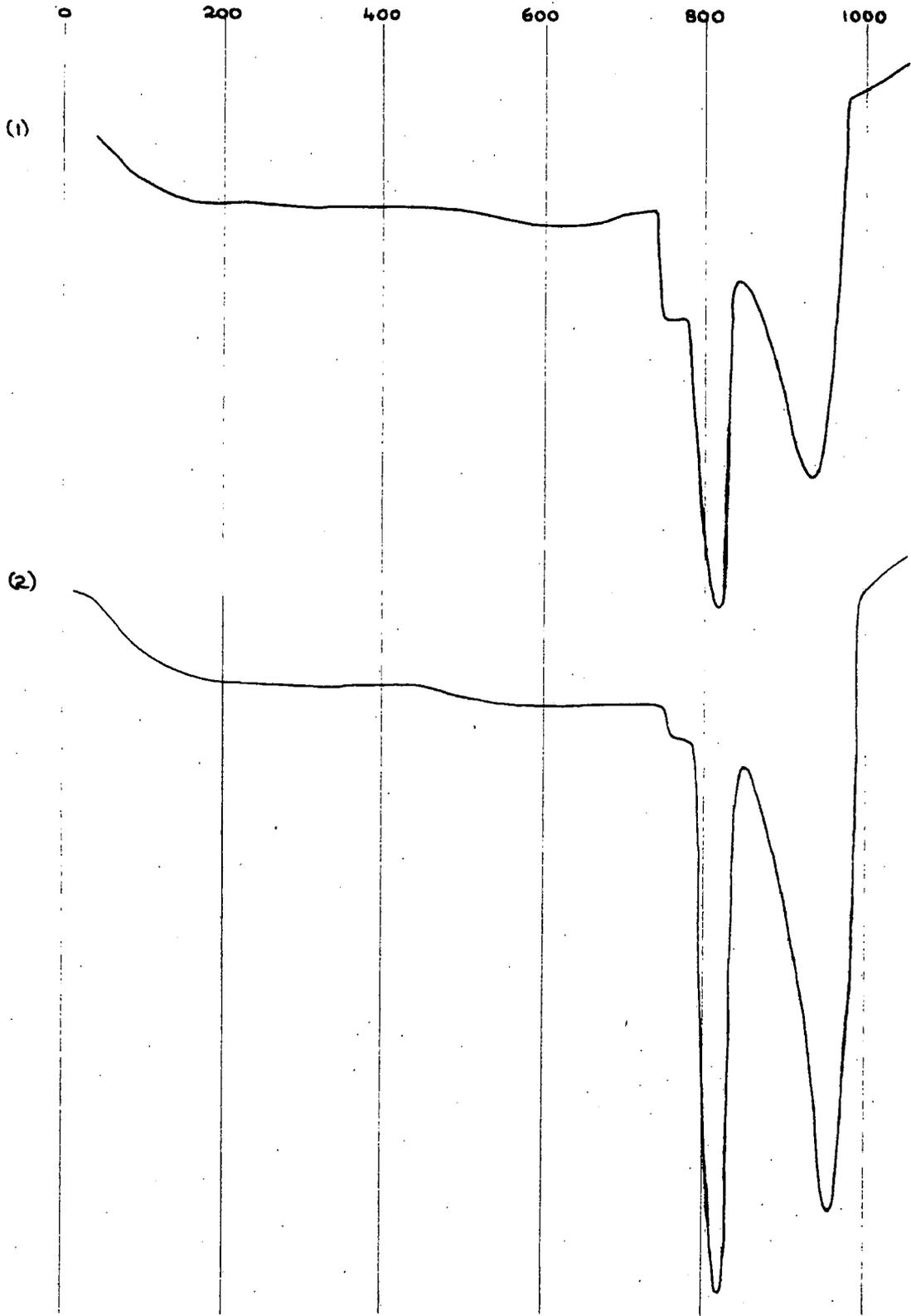
	Before	After
OB/69 (oxidised)	very pale greyish brown	blood red
OB/20	bright yellow	brick red
&	pale pink	reddish brown
OB/21	red	red

The D.T.A. curves for the untreated rock are typical of dolomite in the cases of the pale green and red parts respectively, while that of the

DIFFERENTIAL THERMAL ANALYSES.

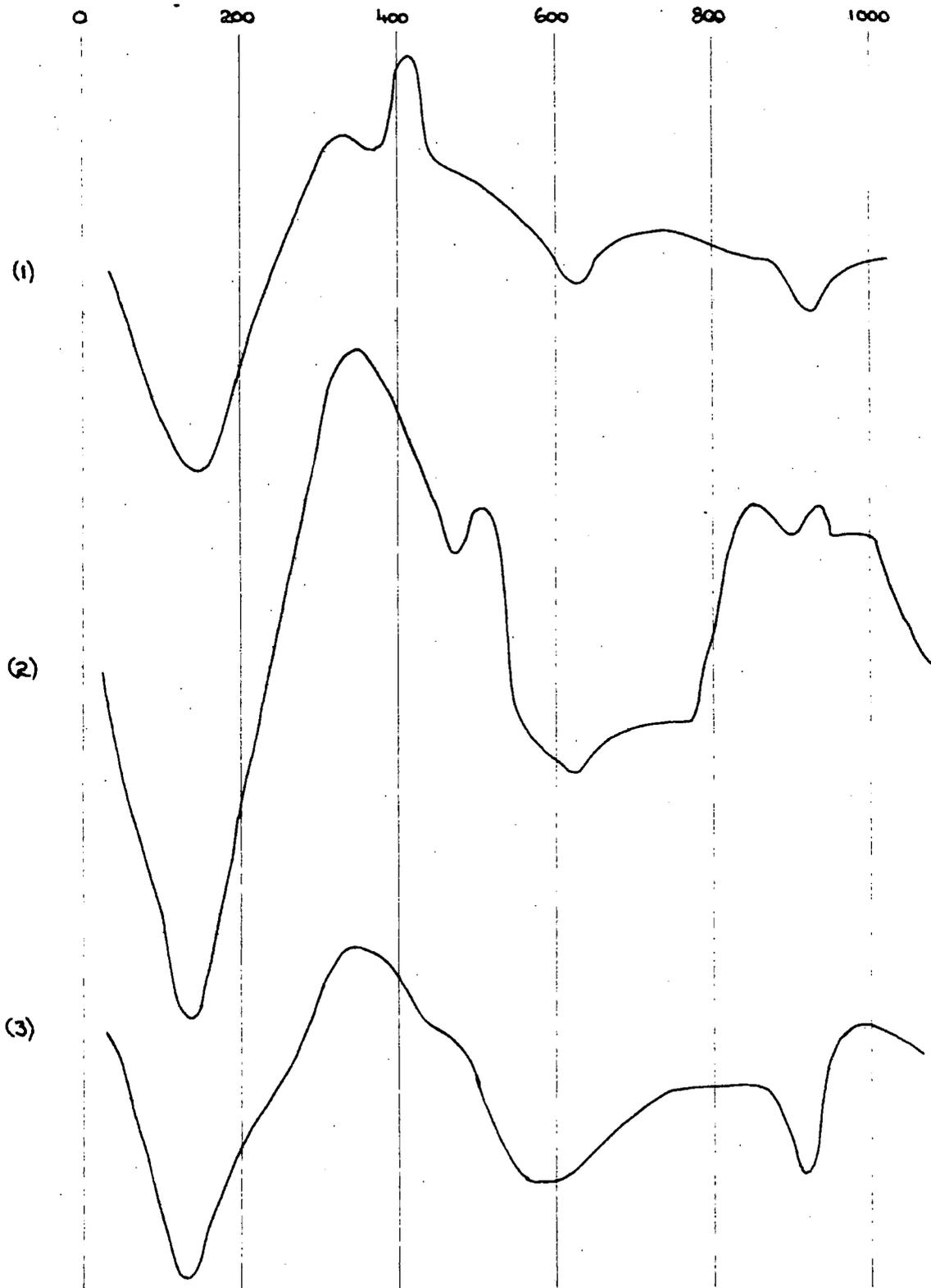


- (1) 08/20 Yellow dolomite, -100 mesh, untreated.
- (2) 08/20 Yellow dolomite, clay fraction.

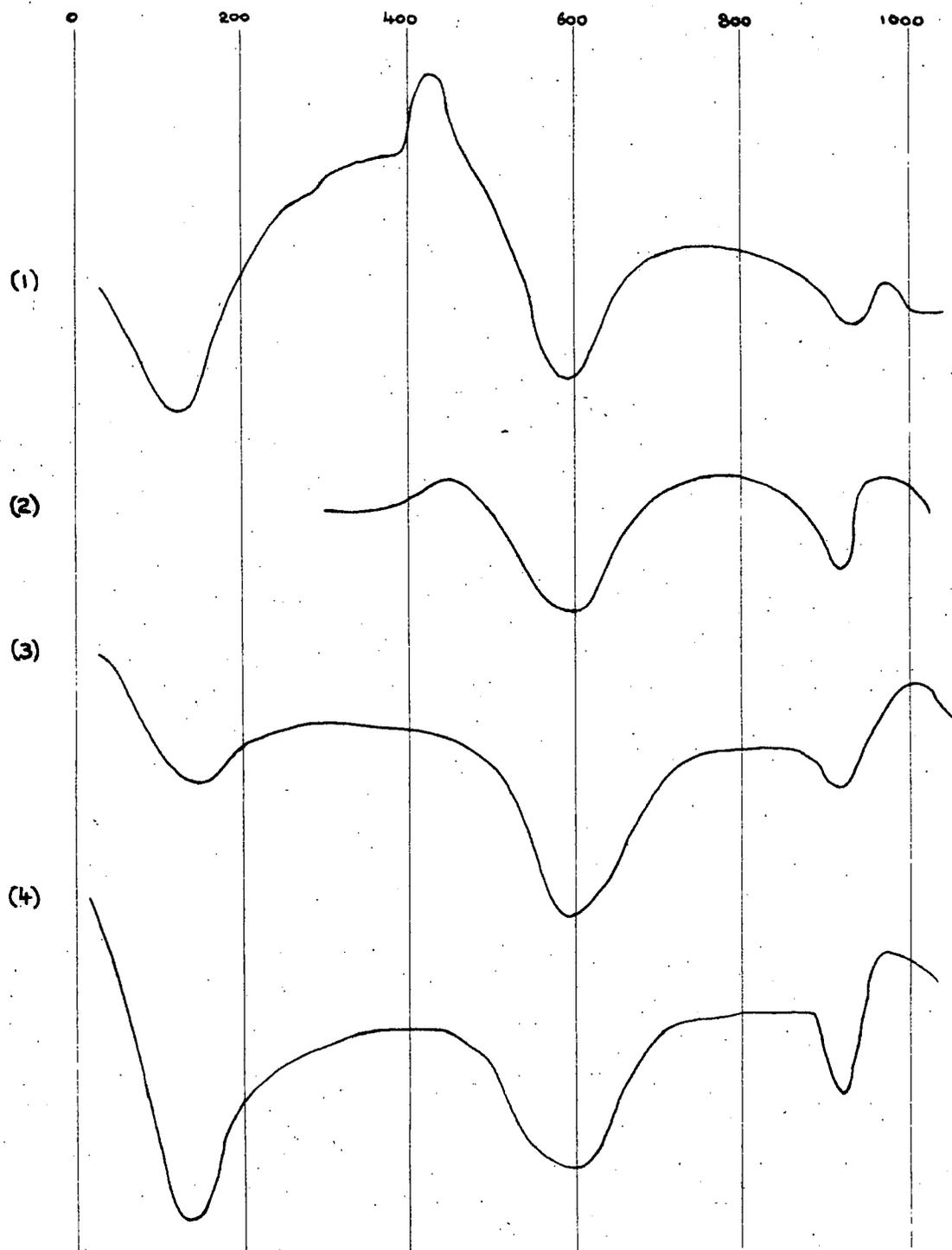


(1) OB/20 & OB/21 Pale green dolomite, - 100 mesh, untreated.

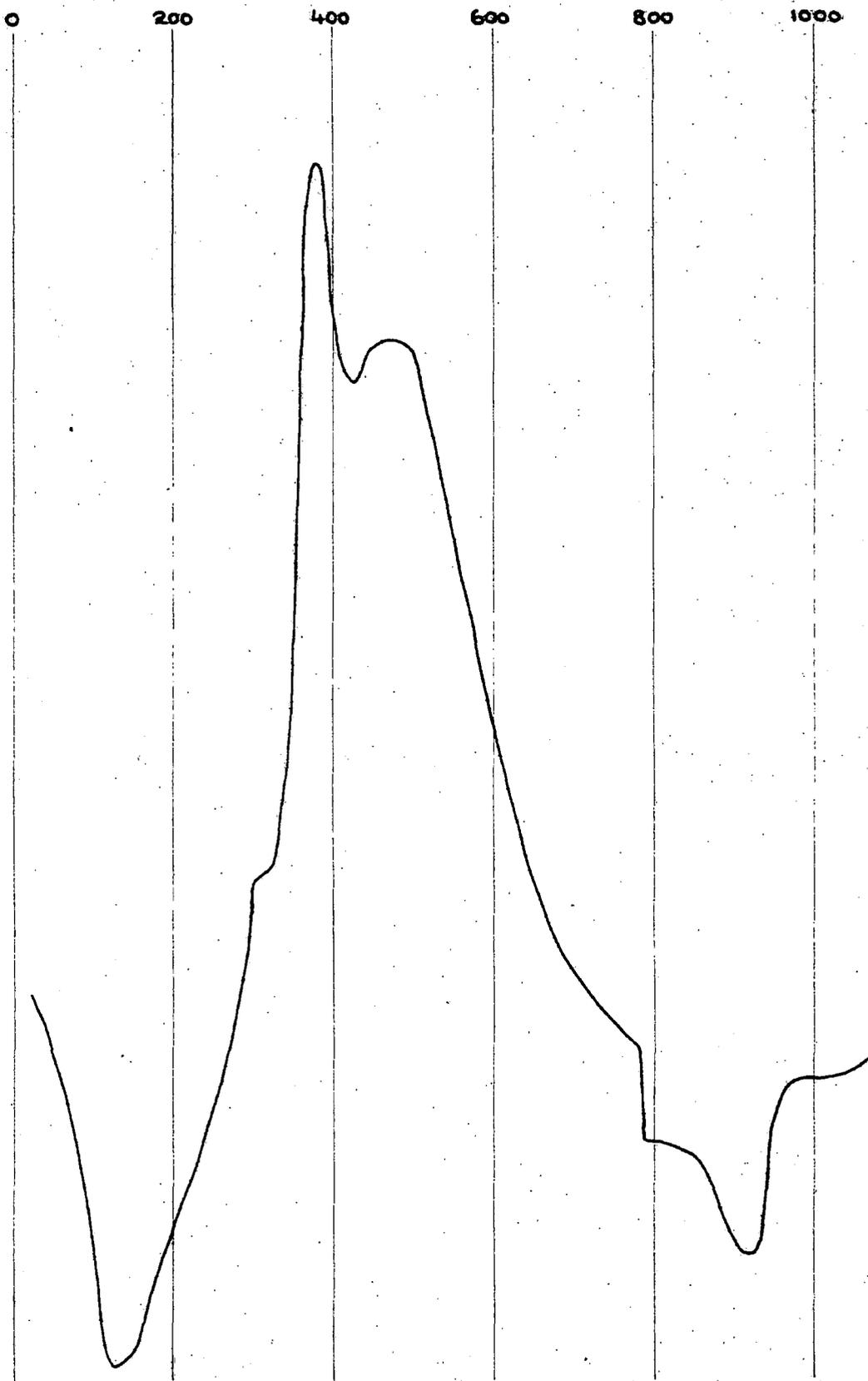
(2) OB/21 Red dolomite, - 100 mesh, untreated.



- (1) OB/69 Grey dolomite, oxidised clay fraction.
- (2) OB/20 Pale green dolomite, clay fraction.
- (3) OB/21 Red dolomite, clay fraction.



- (1) 0B/106 Black siltstone, oxidised clay fraction.
- (2) 0B/108 Red irony siltstone, clay fraction.
- (3) 0B/107 Pale green silty clay, -100 mesh, unwashed.
- (4) 0B/107 Pale green silty clay, clay fraction.



OB/106 Black micaceous siltstone, unoxidised clay fraction.

yellow portion is more reminiscent of a calcite curve. The curves for the clay fraction, while more irregular than those for the clay fractions of the siltstones, show some similar characteristics in that they indicate the presence of illite with a little kaolin; again this is with the exception of the sample from the yellow portion, which shows some resemblance to a calcite curve.

(ii) Contrast with surface oxidation.

The hypothesis has been put forward in the past that the ores owe their present oxidised state to alteration by deep weathering from a previous reduced condition. It is true that with the deeply dissected topography and the semi-arid climate obtaining at Om Bogma complete oxidation of a deposit of iron and manganese carbonates might be expected to some depth, and it is therefore necessary to examine this question in some detail.

(a) Position and extent of the oxidised halo.

The oxidised halo is very widespread; it extends in greater or lesser thickness over the whole area of the ore deposits. No carbonaceous rock has ever been recorded resting directly on the Sandstone Pavement: there is always a layer of red rock separating them, at least half a metre thick in the clay facies and much more than this in some of the more permeable rocks. The Lower Sandstone may indeed be a part of the oxidised halo, since it is almost invariably stained, often heavily so, with iron oxides, although the lack of carbonaceous matter in the upper part of the formation is only to be expected in that type of lithology. Underground exposures of the higher part of the Limestone Series are much less frequent than those of its base as the practice was to keep the mine workings as far as possible on the Sandstone Pavement. However in certain circumstances the top of the Series was penetrated, particularly in prospect rises put up to test for mineralisation in the higher parts of the thinner developments of the Series. It was found that there is also a layer of red iron-stained rocks at or near the top of the Limestone Series, but the overlying beds at or a little above the base of the Upper Sandstone almost invariably contain a little carbonaceous matter and pyrite with no iron or manganese oxides. In some places the whole of the Limestone Series was found to be within the oxidised zone, but typically a layer within the Series - generally the most

argillaceous part - still retains the diagenetic carbon and pyrite. Where the Limestone Series appears to be absent altogether, as in parts of the East Hills, the lowest part of the Upper Sandstone comes within the oxidised zone. The relations of the oxidised zone and its boundaries to lithology has been described in the previous section. The influence of structure, in particular faults and other fractures is discussed in Chapter 7. It need only be stressed here that the depth of cover bears no relation to the relative development of the oxidised halo. In a part of Gebel Farsh el Azraq this zone is as extensive in association with ore deposits beneath some 200 metres of overlying rocks and more than 500 metres from outcrop, as it is anywhere else in a similar type of country rock. The inclined heading to the south-west of Hill K showed that the bulk of the lowest 50 metres at least of the Upper Sandstone has not been subjected to oxidation even where the underlying Limestone Series has been so affected.

(b) The perched water table.

The disposition of the oxidised halo can only be related to meteoric agencies by means of upward oxidation beneath a perched water table, with the slightly permeable Upper Sandstone forming the aquifer and resting on the locally impervious Limestone Series, which forms the barrier and in turn overlies the porous Lower Sandstone, a relatively "dry" (unsaturated) rock. Such a water table does exist in the mining areas: workings on the Sandstone Pavement are invariably dry, except in places where rainwater runs in from the surface and is held by a layer of mud on the floor, while rises put up through a carbonaceous shaley layer in the Limestone Series often produced a trickle of water, especially under heavy cover or beneath a surface drainage channel. There are examples of this latter phenomenon in both the East Hills and near the middle of Gebel Farsh el Azraq. The circulation of air in the Lower Sandstone is further aided by open fissures, a centimetre or two wide, which are found here and there. During strong winds there is a rapid movement of air in some of these openings, as shown by a fairly strong draught from an opening in the floor of a blind-ending drive, 30 metres inbye.

In the outcrops there is occasionally a slow drip of water from the Limestone Series at the head of a steep wadi (as in Wadi Abu Thor, Map II), but this is rather exceptional as the weathered rocks of this Series are

always permeable in a greater or lesser degree and consequently the lateral limits of the perched water table seldom reach the outcrop. The position of the lower or main water table near the base of the Lower Sandstone is more clearly shown by a "spring line" marked by little tufts of vegetation and an almost continuous line of salt encrustations.

(c) Comparison of the "oxidation fronts."

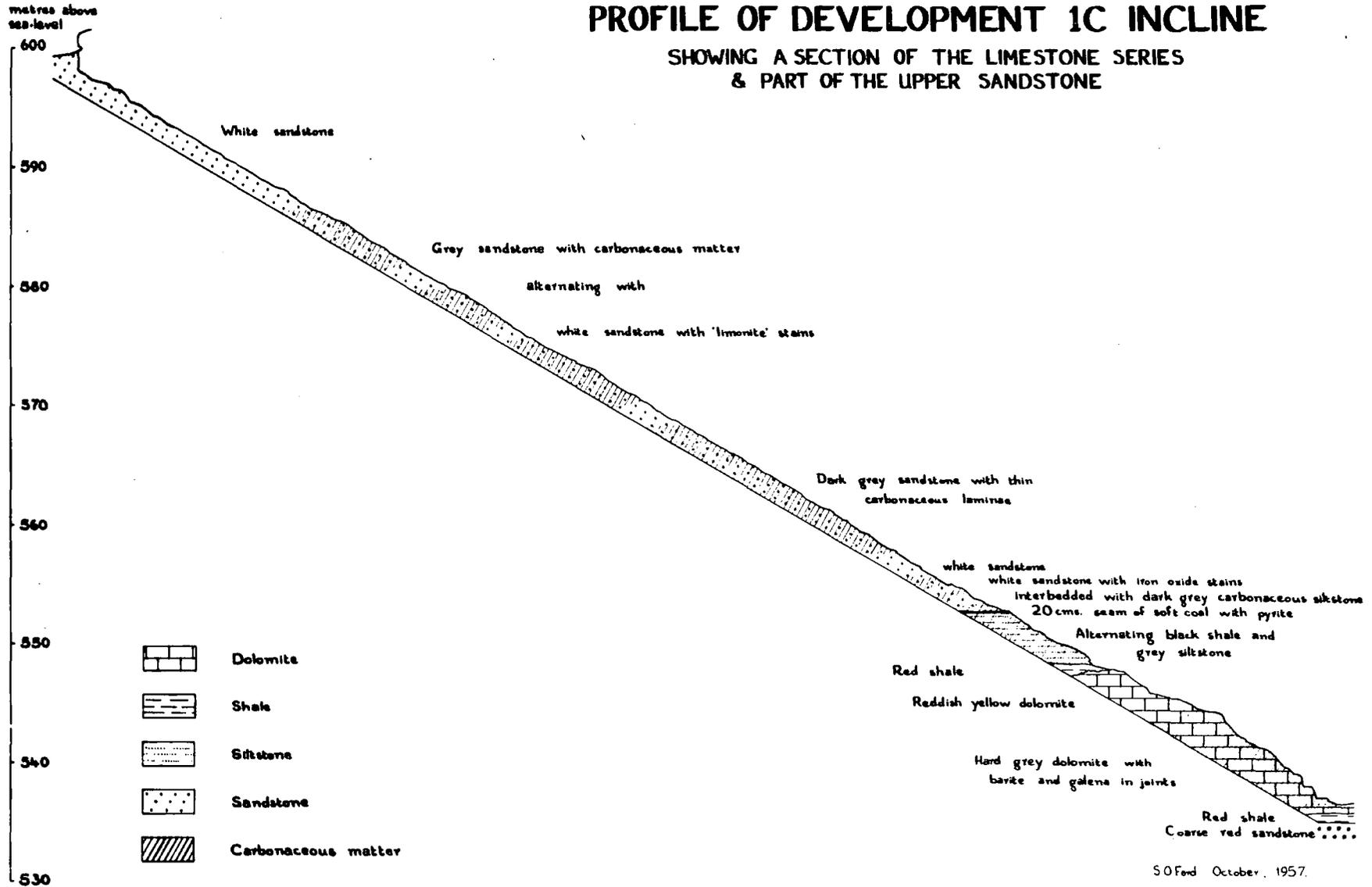
The various depths to which the zone of surface oxidation (deep weathering) normally penetrates in the various rock types were noted in Chapter 5. These are very small (20 metres maximum) when compared with the distances to which these effects would have to penetrate the Lower Sandstone to achieve the results observed in the oxidised halo, when one considers that the alteration is undiminished at 800 metres (the greatest distance reached by mining) from the nearest outcrop of the Lower Sandstone at that level.

The nature of the boundaries of the two types of oxidation also offers a contrast. The lower limit of surface oxidation is very diffuse, with a gradual change from unaltered to weathered rock over a distance of 20 cms. or more. The limits of the halo oxidation, on the other hand, although often extremely irregular, are always very sharp with one single clear boundary line between the unaltered rock and the narrow bleached transition zone and another at the edge of the iron-stained rock.

The chemical changes which have affected the original constituents of the rocks are fundamentally the same in the two cases, i.e. removal of carbonaceous matter, presumably by oxidation to carbon dioxide or carbonate, and complete alteration of all sulphides, principally pyrite but also including chalcopyrite and galena, with oxidation of iron to ferric sesquioxide. The oxidation capacity of both systems has been sufficient to carry these reactions to virtual completion within the zones affected. The differing configuration of the respective fronts however suggests a considerable difference in oxidation intensity. In the zone of deep weathering the indefinite boundary indicates that the rate of advance of the front, which keeps pace, more or less with the rate of erosion, has been greater than the rate of change; with the oxidised halo these conditions were reversed. Not only has there been a more extensive penetration of the rocks under greater confining pressure in the latter case, but the chemical change has been (in the geological time-scale) immediate.

PROFILE OF DEVELOPMENT 1C INCLINE

SHOWING A SECTION OF THE LIMESTONE SERIES
& PART OF THE UPPER SANDSTONE



The most fundamental difference between these two zones of oxidation is in the concentration of the metals, iron and manganese. The weathered zone rocks contain no visible manganese oxides other than the dendritic markings on joint-faces which are found in rocks of all kinds, whether associated with ore deposits or not. They also generally contain no more iron, typically present as "limonite", than is necessary to colour them pale or, more rarely, bright yellow. This contrasts significantly with the occurrence of these metals in the rocks of the oxidised halo, particularly when the same stratum is traced from one zone of oxidation to the other.

(iii) Solution and replacement phenomena.

In addition to the above changes of a largely metasomatic nature there have been other less widespread alterations affecting the physical composition and attitude of the country rocks. These phenomena are more obvious in the outcrops and opencast workings than those connected with the halo oxidation, and consequently they have been described and interpreted (in a number of different ways) by previous workers.

(a) Truncated bedding and collapse structures.

In many places in the mining areas the lower limit of the bedded dolomitic "limestones" can be seen to be very irregular, cutting across individual beds to leave downward projections and dome-like hollows in the underside of the formation (see Plate ~~xxxix~~). The beds above the larger of these hollows have sagged into basin-like structures which gradually die out in the overlying strata of the Upper Sandstone. Elsewhere the beds terminate against an irregular surface of the basal dolomite with only a band of shaley material a few centimetres wide separating the two formations. In these cases the underside of the bedded rocks is clearly a solution boundary, part of the formation having been removed from below.

In other places the beds have been preserved, but they have become flexed to conform to the configuration of the underlying rocks, which include tabular ore bodies and irregular patches of massive basal dolomite (see Plate ~~xxxviii~~). Here the solution has taken place in the basal dolomite, and the inference is drawn that the ore bodies replaced part of this dolomite and were thus able to support the sagging bedded "limestones".

(b) Residual Rock.

Where there has been removal by solution of part of the calcareous beds, particularly in the case of the shaley limestones, there remains a soft friable mass of sandy and argillaceous matter with no recognisable bedding or structure. This material appears to be the less soluble part of the original sediments which remains after the solution of the lime and magnesia, hence the descriptive term "residual rock". This rock is invariably found beneath the bedded limestones which have been attacked by the dissolving media, and its thickness (approximately, and over small areas) varies inversely with that of the remaining limestone, i.e. it varies directly with, but is smaller than, the thickness of bedded limestone which has disappeared. Residual rock surrounds many of the larger ore bodies, but where it overlies them it is separated from them by a "roof", usually 20 - 50 cms. thick, of a harder and more compact iron shale. A more argillaceous and less sandy form of this rock occurs around irregular solution remnants of purer dolomite, often enclosing small rounded fragments of the dolomite to form a kind of "solution breccia". This latter phenomenon can often be seen at the top of the basal dolomite, and also in the upper layer of the oxidised halo.

In addition to the solution remnants of the original dolomite there are also automorphic rhombs of secondary dolomite present (see Section (iv) (a), below).

The residual rock frequently also contains nodules of manganese and iron oxide minerals, particularly in the vicinity of larger ore bodies. Commonly these are composed of closely packed radiating needles of pyrolusite, but sometimes they appear to be an amorphous mixture of the oxides of the two metals. The individual nodules vary in size from one to five centimetres in diameter, sometimes larger, and are generally spheroidal. Frequently they occur grouped together to form botryoidal or reniform clusters, as in some of the larger ore deposits.

(c) Doming in the shales.

Fold-structures similar to those described under (a) above, in which the bedding conforms to the sectional outline of an ore body, can also be seen where ore has been deposited in the soft plastic clays and argillaceous shales. In the latter, however, there does not appear to have been any

removal by solution of previously underlying rock. The field relations here suggest that ore bodies up to three metres or more in thickness have accumulated while squeezing the enclosing rock upwards and outwards, as is inferred in the case of the smaller nodules.

(iv) Secondary mineralisation.

A number of new minerals, not always directly associated with the ore, occur in the zone of halo oxidation. These appear to have developed mainly by re-precipitation of material derived by solution from the original country rocks.

(a) Dolomite rhombs.

These are almost perfect rhombohedra, breaking with the characteristic curved cleavage of dolomite. They range in size from 1 mm. to 15 mm. on an edge, but in any one place they are all of the same dimensions. The crystals normally show clear centres with narrow cloudy outer rims, but the refringence ($n_D = 1.680$) indicates a pure dolomite composition throughout. The appearance of zoning may be due to the incorporation of foreign matter in overgrowths.

These rhombs of dolomite occur as separate individuals and as aggregates of intergrown crystals; they may be sparsely scattered in the residual rock or closely packed into lenticular masses up to 6 m. x 1 m. or more in cross section.

(b) Silica.

Secondary silica occurs in a variety of ways in the Limestone Series or a little above it, and there is some evidence (where it is exposed) of corrosion and partial replacement of part of the underlying Lower Sandstone in the localities affected. The most common occurrence is in a thin bed of medium grained sandstone near the base of the Upper Sandstone formation. The rock is stained various shades of brown and locally even black; it is very hard, resembling quartzite, and on weathered surfaces it shows the high polish of typical "desert varnish". In thin section the original rounded grains of quartz can be seen to be coated with a thin film of opaque matter, probably iron and manganese oxides, and an outer rim of secondary quartz in optical continuity with that of the centre. The interstices have been filled with minutely crystalline quartz, which appears to have

Plate XL

Secondary silica in the Upper Sandstone.
Sp. OB/45 from the base of the Upper
Sandstone on the northern part of the
Central Hills.

Thin section between crossed nicols, x 90.
There is a little secondary growth of quartz
in optical continuity with the sand grains,
and more in tiny crystals between the grains

Plate XLI

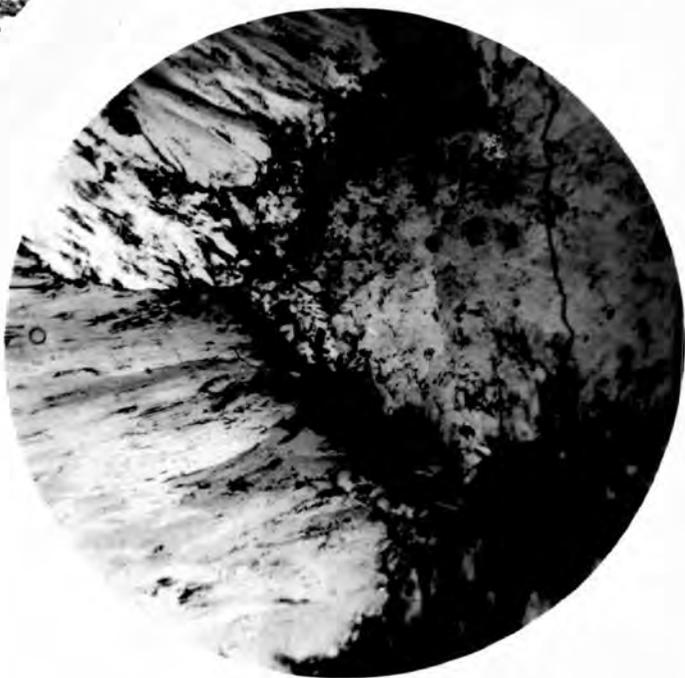
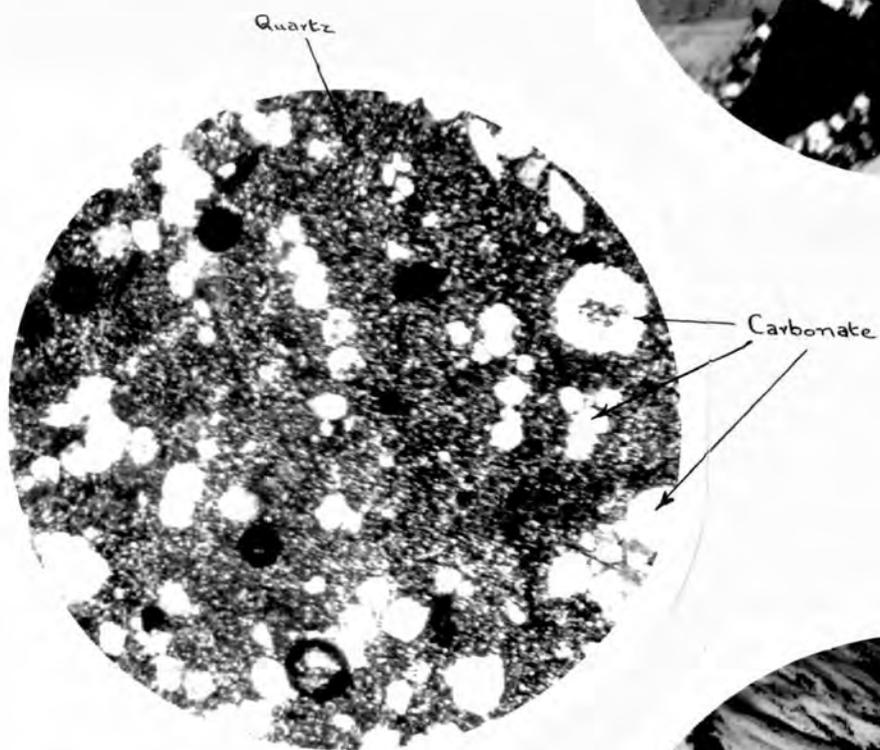
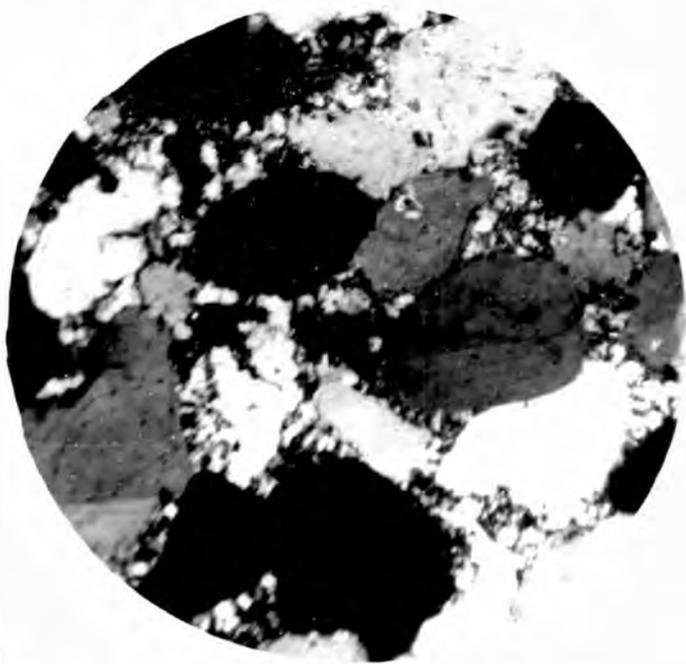
Secondary silica replacing limestone.
Sp. OB/63 from a loose block, S.W. of
Shaft B, North Hills.

Thin section between crossed nicols, x 30.
Irregular crystals of carbonate in a
matrix of micro-crystalline quartz.
An "atoll" of carbonate can be seen on
the right, with its centre replaced by
quartz.

Plate XLII

Secondary silica associated with manganese.
Sp. OB/64 from Dr. 5, North Hills, 1 m.
above the Sandstone Pavement in a pocket-
lined with pyrolusite, within massive
pink dolomite.

Thin section between crossed nicols, x 30.
Fibrous quartz associated with opaque
material.



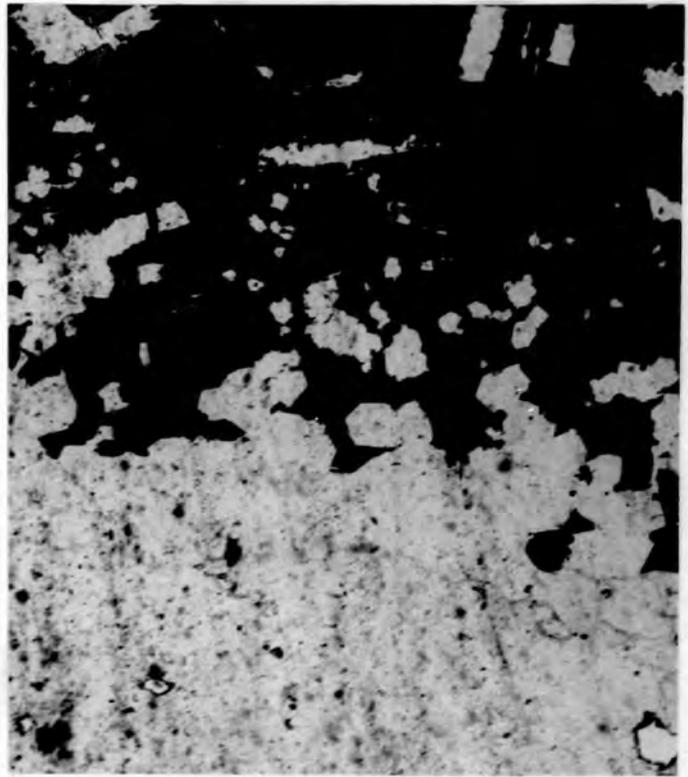


Plate XLIII

Secondary silica associated
with iron.

Sp. OB/46 from the Upper
Dolomite, above Dr. 14,
North Hills.

Thin section in ordinary
light, x 6.

Black: goethite.

Grey: quartz.

Regular lath - and straw
shaped aggregates of quartz
crystals appear within the
goethite.

Plate XLIV

The same, x 30.

Hypautomorphic outlines of quartz
occur at the boundary of the two
areas. Goethite can be seen
growing into the included aggreg-
ates of quartz.

Plate XLV

The same in plane polarised light, x 90.

A group of radiating fibres, and other
single fibres of goethite can be seen
in the quartz. Goethite appears to
be replacing the quartz.

grown outwards from the larger grains. In the darker varieties of this rock there is rather more of the metallic oxides and correspondingly less secondary quartz.

Microcrystalline quartz is also found locally as a replacement of fossiliferous "dolomite", the larger fossils being preserved in the quartz. In hand-specimen this rock has the appearance of chert, and weathered specimens show characteristic desert varnish. In thin section some remnant rhombs of carbonate can be seen at the irregular replacement boundary which have been enclosed in microcrystalline silica and also replaced at the centre by slightly coarser quartz.

Coarsely crystalline quartz sometimes occurs as a replacement of dolomite within the oxidised halo, and it is then often partly replaced in turn by an iron oxide, usually goethite. Quartz crystals have been found up to 5 x 2 cms. in size.

An unusual occurrence of quartz was found in a bed of massive basal dolomite in the North Hills. A closely packed mass of spheroids, each some 2 - 3 cms. in diameter and composed of radiating fibrous crystals of quartz, was enclosed in a thin layer of pyrolusite needles within the dolomite. The identity of the quartz was confirmed by x-rays.

(c) Gypsum and alunite.

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is common as thin bands of satin spar in many of the rocks of the Om Bogma area. It is found in the black carbonaceous clays and shales, in the oxidised shaley limestones and mottled shales of the weathering and halo zones and also, as rather thicker and more extensive sheets, in the larger ore bodies. It also occurs as a "lining" on the hanging wall of the dyke, where this cuts the large ore deposits of the North Hills.

Alunite ($\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$) is sometimes associated with gypsum in the shaley limestones, but it occurs more commonly in the siltstones and shales of the oxidised halo where it is found as little nodules or infilling cracks. This mineral is pure white and so finely crystalline that it has a soapy feel in spite of its hardness of 3.5 - 4. The material collected gave a good x-ray powder pattern and an excellent D.T.A. curve.

A green mineral sometimes found in small amounts associated with gypsum in shales and siltstones of the halo is believed to be brochantite ($\text{Cu}_4(\text{OH})_6\text{SO}_4$).

(v) Conclusions.

The following conclusions are drawn from the foregoing observations and deductions:

(a) Oxidation.

Certain of the rocks of the sedimentary series, notably those in which the oxides of iron and manganese are now found, and rocks adjacent to them, have been subjected to intense oxidation at some considerable time after deposition and consolidation. This oxidation was effected by some means other than meteoric processes.

(b) Changes in composition.

During the oxidation process certain elements, i.e. oxygen, iron and manganese, were introduced to these rocks in quantity from an outside source. Certain other elements, particularly carbon and sulphur, and also calcium and magnesium, which were part of the original rocks, were either removed or redistributed.

(c) Means of access.

The media effecting these changes gained access to these rocks from below, by percolating through the Lower Sandstone.

(d) Physico-chemical conditions.

The configuration of the argillaceous rocks containing nodules, etc., indicates that pressures were relatively high. Solution and re-precipitation of both silica and dolomite indicate a variable, or fluctuating pH. Moderately low temperatures prevailed, leaving a total absence of thermal effects.

(8) DEPOSITION OF ORE IN RELATION TO LITHOLOGY.

Although the deposits of ore are concentrated at the Sandstone Pavement or in the Limestone Series, the iron and manganese minerals are not entirely confined to these limits but are found almost throughout the rock sequence in the area of the mines. When these deposits and their marginal associations are examined in relation to their host-rocks a definite connection can be seen between the nature and magnitude of the mineral deposits on the one hand and the lithology of the country rocks on the other. This connection has been studied for its importance from the economic standpoint as it forms an important aid in prospecting, and it has been interpreted in terms of a lithological control of mineral deposition. It can be described under two heads: the stratigraphical control, affecting the vertical distribution of ore minerals throughout the rock sequence, and the facies control, affecting the distribution of ore and related phenomena within the ore-bearing Limestone Series.

(i) Stratigraphical control.(a) Basement rocks.

There are no deposits of ore in the basement rocks in the vicinity of the Om Bogma mines, but the broken ground of fault zones frequently shows a little red haematite staining. This is most noticeable in the granites in Wadi Samra, Wadi Shellal and in the Nahman Areas.

Vein deposits of haematite and of manganese dioxide ore occur in the crystalline basement rocks in other parts of central Sinai: these are described in another chapter.

(b) Lower Sandstone.

The Lower Sandstone at Om Bogma and in the Nahman Areas, which is generally poor in intergranular clay or other clogging material, is frequently found to contain patches, pipes and layers which have been cemented and partially replaced by the oxides of iron and manganese. These are much more common towards the top of the formation, where the rock is coarser grained, but they are also met with in the lower part of the Sandstone. Weathered fragments sometimes reveal a concentric layered structure in the impregnations, while joints cemented with metal oxides are quite common.

In places a thickness of more than a metre at the top of the Lower Sandstone has been so heavily impregnated with the oxide minerals that it constitutes ore, the bulk of the quartz of the sandstone having been replaced; all gradations of this material are found down to stained sandstone. Replacements in the Lower Sandstone most commonly occur at the base of large ore bodies, but this is not always the case.

In thin section the areas of replaced or impregnated sandstone show definite sharp edges; discrete ramifying strings and veinlets between the grains are virtually unknown.

(c) The Limestone Series as a "host".

The fact that nearly all of the workable ore is found within the Limestone Series in itself implies that conditions in this series have been more favourable to the deposition of the ore minerals than anywhere else in the remainder of the rock-sequence. This appears to be due to the presence of the dolomite, which is the only carbonate rock throughout the rock column in the area of the known ore deposits.

The very widespread invasion of coarsely crystalline dolomites by tiny strings of the oxide minerals is evidence of the relative ease with which it is penetrated compared with the other rocks. Ball's (1916) observations of its generally high manganese content (0.1 - 0.4%) led him to conclude that this element was a primary constituent of the rock, but coupled with the microscopic evidence the analyses he quoted emphasise the ability of the Limestone Series to absorb manganese at some time after its formation.

(d) The Limestone Series as a "blanket".

In addition to its carbonate content the Limestone Series locally contains a much higher proportion of argillaceous matter than is found elsewhere in the rock sequence, and this fact has had a profound effect on the localisation of ore deposition. In a number of places where there is a bed of shale between the Sandstone Pavement and overlying dolomite there has been heavy impregnation of the Lower Sandstone immediately below the Pavement while the Limestone Series remains comparatively uncontaminated. There are examples of this on the western side of Hill "F" and in the lower part of the Wadi Shellal. Where pockets of ore occur in the massive dolomite they are usually found at the top of this formation, immediately underlying a shaley layer.

In every case observed workable ore bodies have been overlain by a "roof" of shale or argillaceous siltstone, which has apparently been impervious to the colloidal oxides of iron and manganese, while in many cases it has allowed the passage of active solvents to overlying calcareous beds, giving rise to the truncated bedding, residual rock and collapse structures described in the previous chapter, (see Plate XXXIX). The roof shale has thus acted as a semi-permeable layer, and its presence in this role gives strong support to the argument that the ores have been introduced by means of ascending solutions. By contrast the presence of "Pavement shale" beneath the ore although often noted is by no means a general rule.

The most significant indication of the "blanket" effect of certain strata in the Limestone Series is the fact that the Upper Sandstone above the largest concentrations of ore generally shows little or no staining by manganese or iron, while above more patchy mineralisation within the Limestone Series the Upper Sandstone is typically comparatively heavily impregnated with these oxides. These phenomena cannot be related to differences in the Upper Sandstone, which shows little or no lateral variation, but they can be shown to depend upon the composition of the Limestone Series, as described in the next section on facies control of ore deposition. Examples can be cited in the North Hills, where the largest single ore-body was found under a hill of white to pale brown Upper Sandstone, and in Hill 'D' where rather poor concentrations of ore are found under a hill of black-stained sandstone.

(e) Upper Sandstone.

In Wadi Buda and generally to the north-west of Wadi Baba where the Limestone Series is thicker and contains a relatively smaller proportion of argillaceous matter there are few concentrations of ore within the Series, while the lowest part of the overlying Upper Sandstone is often heavily stained and impregnated with iron and manganese oxides. No examples are known, however, of complete replacement of any part of the Upper Sandstone by iron or manganese oxides.

Elsewhere the Upper Sandstone typically shows dark staining confined to fault planes and vertical joints, and occasionally in a thin bed of rather coarser sandstone. By means of this staining fractures can be traced very easily from the air or from neighbouring higher ground. The

inference is drawn that because of its finer grain and inter-granular clay the Upper Sandstone was less susceptible to permeation by the oxides of iron and manganese than the other sedimentary formations. In the two small hills to the east of Gebel Marahil (map II) the Limestone Series is absent, and there is no sign, such as slumping or brecciation in the Upper Sandstone, of a pre-existing carbonate rock formation having been removed by solution, but the boundary between the Lower and Upper Sandstones is clearly marked by a thickness of about a metre of black very heavily impregnated sandstone. Taken with the foregoing evidence this appears to reinforce the view of the Upper Sandstone tending to localise the deposition of the metallic oxides which penetrated the Lower Sandstone from below.

This localising effect, both in the Upper Sandstone and in the Limestone Series may be due to the clay matrix acting as a physical barrier to colloidal material, or it may be due to chemical action of their carbonaceous content (see Chapter 11), or more probably to a combination of these.

(ii) Facies control.

(a) Ore distribution in relation to facies.

The lateral variations in thickness and lithology of the Limestone Series have been discussed in Chapter 5, illustrated by Map III and Figure III. A comparison of Maps III and IV will show that the occurrence of ore of workable thickness is quite independent of the development of the various facies types in the Limestone Series as a whole.

It is only when we examine the association of ore with the individual members of the Limestone Series that we see the effect of the various lithological divisions on the deposition of the iron and manganese oxides. In the thicker developments of the Series ore is almost invariably confined to the basal dolomite, and where this has been entirely replaced the ore appears in the upper dolomite layer, leaving the intervening shaley bedded "limestone" virtually unattacked. There is no record of this "upper bed" ore occurring where there is still some undissolved basal dolomite.

In thinner parts of the Series where there is no basal dolomite ore may appear in either the bedded facies or the upper dolomite. In the absence of a calcareous host, and in some cases where the lower part of the

series is very argillaceous, the ore may be concentrated at the base of a compact shale.

To the south-east of Ain Abu Hamata (Map II) there are several small lenses of coarse sandstone, surrounded by siltstone, which have been partially or almost entirely replaced by ore. In this case the ore-bringing media have evidently more easily penetrated the larger pores of the coarser grained rock and have been able to attack this host more strongly than they have done in the case of the finer siltstone.

(b) Relations of the ore bodies to their host rocks.

This subject has already been touched upon in the previous chapter on marginal phenomena; it will be further discussed here in terms of cause and effect.

It appears that the active fluids were able to penetrate the dolomite very readily for considerable distances during the first stages of oxidation and impregnation, before the later stage of replacement took place. All stages of the metasomatic process can be seen, up to complete replacement of the dolomite by the metal oxides, sometimes only a small kernel of dolomite remaining to reveal the nature of the rock which has been replaced. Generally only small pockets of the ore minerals have been produced in this way, as these conditions result in a tendency to dissemination rather than concentration of the metals, except where the original dolomite was only moderately developed.

The process of colloidal deposition of the oxides after the previous solution of the carbonate host, especially where a semi-permeable "blanket" of roof-shale is involved, has led to the accumulation of the largest single ore bodies in Sinai, for example the large tabular deposits of the Central, East and North Hills. Two factors have brought this about, firstly the removal of the dolomite or limestone provided the space necessary, or rather it relieved the confining pressure which would otherwise tend to inhibit the accumulation of large compact solid bodies, and secondly the auto-catalyzing effect (Zapffe, 1931) of the deposition of manganese would lead to a concentration of the metal in a single body, and even to the extension of deposition beyond the limits of the original dolomite bed. The latter effect appears to be a reason for the observed extension of some of the large ore-bodies of the North Hills downwards into the underlying Lower Sandstone.

Generally deposition of ore after the prior solution of calcareous rock has resulted in ore high in joint metals (i.e. a high tenor of iron plus manganese) and low in silica and other contaminating substances. In prospecting therefore dolomite and bedded "limestone" are considered favourable hosts for large bodies of "clean" ore.

By contrast the ore deposits associated with a siltstone or sandy host rock are usually irregular in shape and often very "dirty", with numerous patches and bands of country rock mixed with the ore. An example of this occurs to the south of Hill D in the Kahman Areas where the total thickness from Sandstone Pavement to Roof Shale of 9.4 metres compares favourably with the greatest thickness of 8 metres found in the large ore-bodies associated with a carbonate host in the North Hills, but the joint metal value is only 46.9%, compared with nearly 60% in the North Hills.

Where ore has been deposited in softer, more argillaceous, rock the tenor is again fairly high, but the ore-bodies are usually thin and often small in lateral extent, as in the southern parts of the East Hills. It would appear that these finer-grained rocks could neither be readily penetrated by the ore-bringing media nor easily dissolved to make room for the ore, but have been bodily displaced by the precipitating oxides.

(c) Influence of host-rocks on ore mineralogy.

The various types of ore and the minerals of which they are composed have been described in another chapter. During the routine work of recording the geology of the mines careful note was taken of the character of the ore in addition to noting the lithology of the host-rocks. The most striking observation which resulted from this comparison was that while goethite is quite common in the ore of the "limestone" and dolomite areas, it is rarely seen closely associated with a siliceous (siltstone or shale) host. Haematite is virtually the only iron mineral found associated with the traces of residual sand or silt found in the larger ore-bodies or in the shales or siltstones immediately surrounding them. The associations of the manganese minerals with the host rocks are not so definite, but there is a strong tendency for the "hard blue" type of ore, chiefly composed of the psilomelane (s.l.) group of minerals, to occur more commonly in the siltstone and shale areas.

These findings agree with the observations of G.A.Thiel (1924) in the

Cuyuna Range near Lake Superior, who found that soft pyrolusite was associated with "ochreous limonite" in the low silica, high phosphorus ores, and that haematite occurred with "hard crystalline manganite and massive dark blue dense psilomelane" in the high silica, low phosphorus ores.

The ratio of manganese to iron does not appear to obey any rules in the limestone areas, where it is usually very variable both laterally and vertically. Occasionally, as in the Central and Eastern Hills, a layer of almost pure manganese dioxide has been found beneath a thick layer of massive goethite, with sometimes another layer of high grade manganese ore above the iron. In the "no limestone" areas, however, iron ore often forms a widespread "halo" around a body richer in manganese. Iron was apparently able to penetrate the finer grained rocks more easily than was manganese - possibly the haematite was deposited directly from true solution as it is finely granular and rarely shows colloform textures. Goethite on the other hand may have crystallised from colloidal ferric hydroxide.

(9) RELATION OF THE ORE TO THE IGNEOUS INTRUSIONS.

The association of many of the ore-bodies with the Om Bogma Dyke has led to speculation on a possible causal relationship in their proximity to one another. It is therefore necessary to examine more closely the relations of the ore mineralisation with the basic igneous intrusions to confirm or deny a possible genetic connection between them.

(i) Mineralisation associated with the igneous rocks.

The association of dark purple and black stains in the country rocks with adjacent basic igneous rocks has been mentioned in Chapter 4. These stains are not always obvious, but locally they are very marked. They occur both above and below the dolerite sill at the north-east corner of Gebel Farsh el Azraq, where the Upper Sandstone has been altered in contact with the igneous intrusion. In a thin section (OB/95, see Plates XLVI & XLVII) the altered rock immediately above the sill shows closely packed irregular quartz grains, in parts corroded and recrystallised, with a little secondary growth on some of the original grains. There has also been corrosion and replacement of the quartz by a translucent dark brown mineral, almost certainly goethite, which occurs as a veinlet and also spreading outwards as an impregnation of the sandstone. This mineral shows the rounded outlines typical of colloidal deposition, especially where it has apparently grown into a free space. This space has subsequently been filled by quartz showing irregular extinction, tending towards a fibrous texture.

The recrystallisation appears to have taken place more or less contemporaneously with the introduction of the dark mineral. The black staining of all this hardened sandstone is due to iron and manganese oxides, but the source of these minerals in this context is doubtful. They may be part of a mineralisation associated with the intrusive dolerite, as suggested by Westerveld (1948) for similar minerals in the Mesozoic rocks of Morocco.

(ii) The ore deposits and the Om Bogma Dyke.(a) The intrusive contacts.

Wherever the dyke traverses ore-bearing ground it cuts cleanly through the ore deposits and country rock alike with a sharp line of contact

(see Plates VIII & XXXIX). No evidence has been seen of a penetration of the dyke rock by the oxides of iron or manganese, either in the field or under the microscope, but veins of the chilled dolerite varying in width from two centimetres to nearly half a metre have been found extending from the dyke into both the country rock and the ore. At the edge of an ore-body, as in the North Hills, the flexed bedding of the overlying shale can be matched from one side of the dyke to the other, and also the boundary of the oxidised halo can be seen to correspond on one side of the dyke to its position on the other side.

(b) Effect of the dyke on the ore.

The dyke is typically bordered by a layer of fibrous gypsum (satin spar) up to 3 cms. thick in the lower part of the Limestone Series, and this mineral also occurs in the numerous joints within the ore adjacent to the dyke. The ore in a zone from one to five metres wide on either side of the dyke is almost invariably in the form of "Hard Blue" ore which is a nearly homogeneous mass predominantly composed of the α series of manganese dioxides (Chapter 6, (ii), (h)), the width of this zone apparently being in direct relation to the amount of gypsum in the ore. Outside the Hard Blue zone the ore has the usual nodular or banded texture typical of the larger deposits.

The inference is drawn that active fluids associated with the dyke have attacked the ore, forming a colloidal solution of iron and manganese (possibly as the hydroxides) and the associated gangue, these being re-precipitated in situ almost immediately with typical colloform texture. The manganese has apparently incorporated foreign ions (e.g. barium) into its structure to give the impure α dioxides. The numerous joints would be formed in subsequent shrinkage. to be filled later by gypsum derived from the overlying pyritous limestones.

A series of specimens of the bedded limestone overlying an ore body were collected respectively in contact with the dyke and at distances of 30 and 90 cms. away from it. They show contamination and replacement by the ore minerals close to the dyke, becoming progressively weaker away from it. The amount of this secondary migration of the ore is very small indeed compared with the size of the ore body.

(c) Age relations.

It is clear from the above observations that the ore and its accompanying oxidation halo was in place much as it was found in recent times at the time of the intrusion of the dyke. It is therefore assumed that there is no direct genetic connection between the ore and the intrusion of the basic magma. The coincidence in position is interpreted as being due to factors which have influenced the distribution of both the ore and the dolerite. These will be discussed further in the next chapter.

The presence of the dyke is an extremely useful, and conclusive, guide to the age of the ore, and in particular the age of its associated oxidation phenomena. As the dyke outcrops over a distance of at least 18 kms. and does not connect with any surface extrusion of lava it must have been intruded well before erosion cut down to its present level. Hence possible oxidation of the ore, and the formation of the associated oxidised halo cannot be the result of meteoric activity.

Plate XLVI

Partially recrystallised and mineralised sandstone from the contact with a dolerite sill.

Sp. OB/95 from the roof of the sill at the extreme north-east corner of Gebel Farsh el Azraq.

Thin section in plane polarised light, x 15.

Secondary growth of quartz can be seen on the sand grains, locally embayed and corroded by the opaque mineral.

Plate XLVII

The same, between crossed nicols.

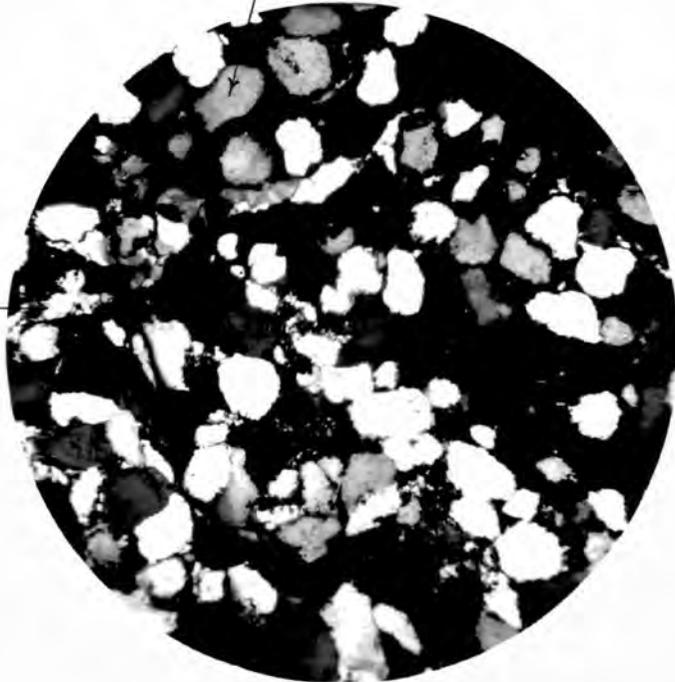
A new growth of quartz can be seen in a cavity in the oxides.

Corroded sand grains



Secondary quartz

Quartz grains with overgrowths



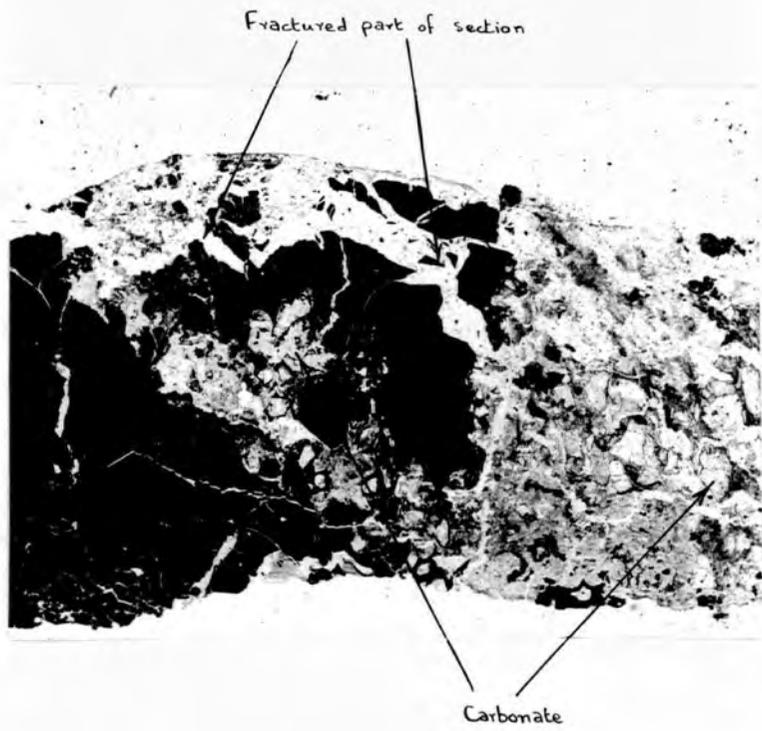
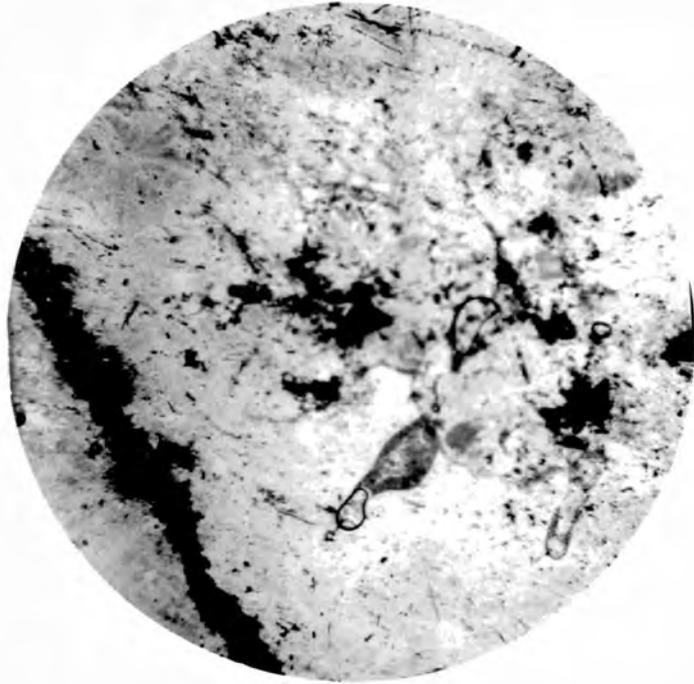


Plate XLVIII

Manganese mineral veining and replacing an igneous dyke.

Sp. OB/105 from a fine-grained pink dyke, transversely cut by a group of closely spaced veins of manganese oxides. Wadi el Akhdar, about 45 kms. E.S.E. of Om Bogma.

Thin section in plane polarised light, x 40.

The rock is a felsite, with a veinlet, left, filling a joint.

There are signs of corrosion of the felsite by the vein material, and this has also invaded the rock for some distance away from the vein.

Plate XLIX

Manganese oxide in the basement complex.

Sp. OB/101 from the contact of a vein of manganese oxides with the country rock, Wadi el Akhdar deposit.

Thin section in ordinary light, x 6.

Black: manganese, and possibly some iron, oxides.

Light grey: principally carbonate grains of the country rock (a much altered and decomposed gneissic rock).

Dark grey: finely granular matrix.

Towards the top of the picture the section has been broken during preparation.

(10) THE ORE DEPOSITS IN RELATION TO STRUCTURE.

The distribution of ore and sub-economic mineralisation projected on to a horizontal plane agrees more closely, both in general and in detail, with the tectonic pattern of the area than it does with any lithological divisions. This aspect of the ore deposits will accordingly be described in relation to the structural elements.

(i) Distribution of the ore-deposits.

(a) Extent of the ore-field.

The western limit of the ore-field is the largest of the rift faults forming the boundary between the central Sinai block and the Clysmic area. Beyond this fault the basement rocks and the lowest sediments which elsewhere act as host to the ore minerals are buried beneath thousands of metres of younger deposits. Any concentrations of iron and manganese oxide minerals which may occur there would be of no economic interest on account of the difficulty and expense of location and extraction, hence any geological speculation in this direction is never likely to be proved.

To the north the host rocks disappear beneath a gradually increasing thickness of younger sediments, and concentrations of minerals in them would become unworkable on this account, but apart from this effect there is a decrease in the size and frequency of workable ore deposits towards the northern limits of the area in which the host-rocks do outcrop. Only the higher priced manganese dioxide would repay working anywhere to the north of Wadi Baba although ferruginous manganese deposits do occur. In the region of Gebel Mukhul in the north-west, and in Wadi Buda, some four kilometres north-west of Gebel Um Rinna, no concentrations of ore minerals are known to occur at all, only some chemical analyses quoted by Ball (1916) revealing a probable increase in the iron and manganese content of the dolomites.

To the south and east small scattered ore-deposits and occurrences of ore-minerals have been reported up to and beyond the farthest development of the Limestone Series. The sedimentary rocks have been considerably eroded away in this part of the peninsula, so that the original southern and eastern limits of the ore-field can only be determined with refer-

ence to the basement rocks.

(b) Locus of thicker deposits: axis of the ore-field.

The overall distribution pattern of the ore can only be seen satisfactorily in respect of the larger deposits of ferruginous manganese ore. These are aligned in a south-west to north-east direction, from the lower part of Wadi Shellal, close to the great rift fault, through the Om Bogma hills, the hills flanking Wadi Abu Hamata and Wadi Abu Thor (the ore being less continuous here), the long hill and the V-shaped hill flanking Wadi Lahian to Gebel Um Rinna near to the northern limit of the Limestone outcrop. This line of outcrops is twenty kilometres long and although it has a maximum width of five kilometres, if one includes the deposits near Bir Rekeis to the north-west and those of the head of Wadi Nasib to the south-east, it is generally much narrower than this.

The axis of the greatest concentrations of ore is thus parallel to the strike of one set of joints. For most of its length it is also coincident with the Om Bogma dyke. The only noticeable departure from the dyke is in the area of Gebel Um Rinna. The line of the dyke traverses an outcrop of basement rocks east of Wadi Zobeir and continues along the floor of Wadi el Sih, which is covered with loose sand. This is some two kilometres south-east from Gebel Um Rinna. There are, however, several other similar dykes in the neighbourhood, one of which, outcropping to the west of Wadi Um Zerdab at its junction with Wadi el Sih, has iron and manganese oxides associated with it where it cuts the Limestone Series.

(c) Association of ore with N.E. - S.W. fractures.

The primary dependence of ore distribution on the north-east to south-west structure lines is amply confirmed by a study of aerial photographs in the light of knowledge previously gained from the ground. Structure lines, in the form of joints, faults and dykes, show up very clearly as straight, or nearly straight, lines which can often be traced intermittently or continuously for long distances across the very rugged topography.

In the Wadi Himeira to the north-east of the northern hill at least three clearly incised lines can be seen eroded into the granite basement in a direction roughly parallel to that of the Om Bogma dyke. These joints are in line with the three most clearly defined belts of ore found in the

northern hill. Two of them are also opposite known ore-bodies in Hill F.

The directional trend of the ore deposits is most strikingly exhibited in the long hill and the V-shaped hill between Wadis Nasib and Zobeir. The ore here occurs in two fairly narrow and nearly parallel belts, 500 metres apart. The more south-easterly one of these coincides with the line of the Om Bogma dyke, although the dyke does not outcrop continuously across these hills. The bands can be followed for two kilometres, and would apparently be continuous had they not been dissected by erosion.

(ii) Association of ore with faults.

(a) Major faults.

Most of the larger individual ore bodies are found to occur in close association with the major faults described in Chapter 3. The most important examples of this connection occur along the fault-system which traverses the ore-field from Wadi Shellal northwards along Wadi Um Sakran, crossing the eastern and northern hills, where some of the biggest single ore bodies are found, thence continuing northward to cross the Wadi Baba near Bir Rekeis, close to another fairly large ore-body, to pass up Wadi Kharig and disappear under the loose sand to the north-west of Gebel Hazbar. Another example can be seen in Wadi Nasib, a channel which has been eroded along part of one of the biggest faults (thrown 200 metres) in the ore-field. Not only are the largest ore-bodies along the major axis associated with these faults, but the only large deposits which occur to either side of this, associated with parallel fractures, are found to be adjacent to them or in their immediate neighbourhood.

(b) Branching faults.

As noted in Chapter 3 the major faults may occur as a single plane of displacement with no sympathetic fracturing of the rocks on either side, or they may be accompanied by a broad zone of fractures. In the former case the rocks are devoid of ore and the mineralisation and accompanying oxidation of the country rocks are comparatively restricted; in the latter case there are frequently moderate or large ore bodies to be found. Examples of this are to be seen in the west side of that tributary of Wadi Abu Hamata which runs northwards from the pass at the head of Wadi Rekeis, on

the eastern face of Hill 'D'. There is a big fault running along the wadi which at two places brings the Limestone Series against the basement rocks with no apparent subsidiary fracturing of the ground; at these places no ore was found. Elsewhere along its length this fault throws off a number of "flyers" into the sediments on the downthrow side, and it is in this disturbed ground that deposits of ore occur.

The best example of a broad fracture zone is in the northern hill where a major fault has split into two, each with a throw of 35 -40 metres, which are separated by a 250 metres wide belt of ground with numerous small faults with throws varying up to 5 metres. There is a very large body of ore in this area and to either side of it, where there are also a few sympathetic faults.

It is in the strongly fractured ground of broad fault zones that mineralisation in the form of staining and impregnation, with partial replacement, is most frequently seen in the Lower Sandstone. This is also true in some cases where the overlying dolomite is devoid of ore, as on the western face of Hill 'F', to the north-east of the northern hill of Om Bogma.

(c) Divergence from the faults.

Although there is a definite association of ore with the faults there are also cases of a divergence of ore bodies from the exact line of faulting. One feature of the big ore body in the northern hill which is particularly striking is the presence of a number of barren areas associated with the small faults thrown in the opposite sense to the larger ones: generally the small faults thrown in the same sense as the larger ones have a greater than average thickness of ore associated with them.

There are some significant exposures in the workings along the fault which extends south-eastwards from Ain Abu Hamata. This fault throws off a number of "flyers", and these, rather than the main fault, appear to form the loci of ore deposition. In some of the cross-cuts to the principal fault the fault plane is seen to be marked by a band of black carbonaceous clay gouge some 5 - 10 cms. wide with oxidised rocks, either stained red with haematite or bleached by the removal of carbon and pyrite, on each side.

It would appear that the gouge has formed an impervious barrier which has inhibited the passage of oxidising and mineralising fluids in the fault plane while the broken and more porous rocks on either side have not been so protected from these effects.

(iii) Agreement with the joint pattern.(a) Shape and orientation of the ore bodies.

These features are best seen in the smaller ore-bodies as the larger ones are generally bounded, at least in part, by the limits of erosion at the hill sides. The small ore-bodies are often fairly long and narrow, or irregular with elongate apophyses in a number of directions. These narrow belts of ore may extend along a fault line, as is the case with the northern extension of the main ore body in the northern hills, but more often they do not coincide with any noticeable line of displacement. They may be apparently independent of faulting, as in the middle of the northern hills, or they may cut across a series of faults or run parallel to a fault but separated from it by barren ground, as in the eastern hills.

(b) Correlation between surface staining and hidden ore.

In at least two cases in the northern hills joints marked by heavy dark staining of the adjacent rocks can be seen on the surface directly over an ore-body and coinciding with its direction of elongation. By carefully noting such stained joints and fractures on the surface of the ground it has been possible to predict the extension of a known ore-body, which has subsequently been proved by mining development. It has also been possible to predict the presence of an entirely unexposed ore-body which has since been proved to exist by churn drilling.

An examination of surface staining is not, however, an infallible guide to the economic possibilities of an area. Often there is little or no staining in the rocks overlying the largest ore bodies, whilst investigations below some very prominent surface stains, as in Hill K in the western Nahman Areas, have revealed either comparatively small concentrations of ore minerals or only dispersed deposits in the Limestone formation. Nevertheless it is true to say that where there are signs of mineralisation along a fracture above the Limestone there are also abundant signs of mineralising activity within the rocks of the Limestone Series where they are intersected by the ~~same~~ fracture, even though ore may not be present in commercial quantities.

(c) Isopachytes.

The larger ore-bodies are tabular rather than lenticular in outline, tending to terminate abruptly at the edges so that a "bed" of ore up to four metres thick may cut out altogether in a very short horizontal distance.

The lower surface generally conforms more or less to the Sandstone Pavement, although there may be up to a metre of intervening Pavement Shale, or a metre or two of the Lower Sandstone may have been replaced. The upper surface is much less regular, so that there are considerable variations in the thickness of a large mass of ore.

In the larger ore deposits of the northern hills vertical measurements of the thickness have been made at intervals of about twenty metres, the results plotted on the mine plans and isopachytes drawn for 6 metres, 4 metres and about 1 metre (i.e. the commercial "cut-off"). The resulting isopachyte plan shows a number of ridges of thick ore, each one either extending outwards from a fault or running along a fault. The directional trends of those ridges which do not coincide with faults are significantly parallel to the strike of the joint systems described in Chapter 3. The most prominent of these belts of thick ore is parallel to, but not coincident with, the Om Bogma Dyke.

(c) Ore-grade maps.

For commercial purposes the grade of the ore is expressed in terms of the percentage of manganese metal which it contains, but as the combined content of manganese and iron is typically constant between 57% and 60% the manganese percentage is in effect an expression of the ratio of manganese to iron. The observation made by earlier workers that the ore is richer in manganese adjacent to the faults, although applicable in some cases, is by no means the rule. The ore is essentially an inhomogeneous mixture of the higher oxides of iron and manganese with sudden and marked vertical and lateral variations in the Mn : Fe ratio. In places a layer of iron ore very low in manganese has been found above, or sandwiched between, manganese ore of chemical grade, while elsewhere the manganese was relatively more concentrated at the periphery of a large ore-body.

(iv) Interpretation: structural control of ore deposition.

The agreement in distribution between the ore and the effects of mineralising activity in general on the one hand and the various fractures on the other can leave no doubt that the former was dependent upon the latter, and this leads to the conclusion that the metals were actually introduced by means of the fractures, which acted as channels for their transporting medium. The wide extent of mineralising activity suggests

that the metals were derived from a large source area. It seems likely, however, that they commenced their journey in comparatively few channels, spreading out into the increasing number of fractures and fissures which exist nearer to the surface of the earth.

This hypothesis agrees with the following deductions made from a consideration of the larger deposits of western Sinai. The alignment of these deposits with the Om Bogma Dyke suggests that the mineralising fluids began their journey by passing through the series of fissures which are now occupied by the dyke, or others closely related to them. As they continued their passage they began to spread laterally along the larger of the N.W. to S.S.E. trending faults, and thence into the smaller faults and joints, moving more easily through shattered ground and by-passing the "tight" fault-planes. On entering the sediments part of the fluids was able to infiltrate into the rock on either side of the fractures, especially in the coarser part of the Lower Sandstones and in the dolomites, while in some cases further passage in the fault-planes was prevented by argillaceous gouge which rendered them impervious.

(11) THE ORIGIN OF THE OM BOGMA ORES.(i) Earlier hypotheses.

A number of hypotheses concerning the origin of these ore deposits have been advanced in the past, but when these are examined in the light of the data presented here a number of them must be rejected immediately, while some contain features which are still acceptable and others which are not.

(a) Sedimentary origin.

This hypothesis was put forward by Barthoux (1923) and later by Evans (private report, 1929).

During the deposition of the Limestone Series and also part of the Upper Sandstone the rocks of the basement complex are assumed to have been exposed to weathering and erosion in the land-mass lying to the south-east of Om Bogma. A humid climate is supposed to have supported abundant vegetation the products of whose decay provided the reducing conditions necessary to dissolve, and maintain in solution, iron and manganese from the crystalline rocks. On reaching the sea these metals would be precipitated in the oxidising environment, either as carbonates or oxides, in the former case to be oxidised by meteoric waters after the uplift and deep erosion of the strata in which these deposits are found.

A number of objections to this theory can be raised immediately, even on a casual acquaintance with the ore deposits. These are, briefly:

- (1) Irregularity. Sedimentary deposits found by chemical precipitation are typically regular or varying gradually in thickness, at least over fairly small areas. The iron and manganese ores of western Sinai are intermittent and irregular in thickness, with abrupt lateral terminations.
- (2) Inhomogeneity. Chemical sediments are usually uniform in composition and texture, or showing regular variation within narrow limits over small areas. The deposits under discussion are extremely variable in composition as regards the ratio of manganese to iron, and often very variable in texture over quite small distances.

- (3) Associations with structural elements. The relations of the ore deposits to post-depositional fractures of the sedimentary strata were recognised by the earliest workers in the area.
- (4) Solution phenomena. Evidence for the solution of the country rocks in proximity to ore deposits was also recognised and accepted from the earliest times.

To account for these apparent inconsistencies the protagonists of the sedimentary hypothesis have had to propose a number of post-depositional changes. Barthaoux suggested solution and recrystallisation with segregation of the iron and manganese, but he did not discuss the means of solution. Evans postulated a strong north and south compression which

".... caused the hard Carboniferous Limestone to be thrust over and through the softer underlying manganese ore and the shale and sandstone on which it rested. This will explain some of the rapid cutting out of the ore."

The detailed examination of the ground which has been undertaken in recent years has brought no evidence to light showing thrusting on the scale implied here, although there is some evidence of compression (see Plate XXXVII).

Evans also attempted to explain the intermittent nature of the ore "beds" by means of valley bulges:

"Where it lies beneath a considerable thickness of superincumbent strata, this exerts a heavy pressure upon it, but in the vicinity of the vertical sides of a wadi, it has no lateral pressure to support it, and as it is less resistant than the rocks above and below, it is slowly squeezed outwards. This will account for the fact that there is often a fair show of manganese on the surface of the slope that is soon lost when it is followed into the hill."

This hypothesis, mentioned by Groves (1938), was put forward to account for a statement by the mining engineers to the effect that ore is more abundant in and near the outcrops than it is beneath a great depth of overburden. More extensive underground exploration has shown that the engineers' belief was unfounded (see Maps II & IV). There is in fact no support for lateral movement of the ore, nor for the contention that it is less resistant than the rocks above and below.

Evans dismissed the association of ore with fractures:

"The faults throw the manganese as well as the rocks in which it occurs. This clearly negatives the suggestion which has been made that they represent the channels by which the manganese found its way to the position in which it is now found."

This argument is not conclusive; it would be more correct to say that the ore occurs at a particular horizon regardless of the displacement of this horizon by faulting.

The strongest evidence against a syngénetic origin for the ores is to be found in the carbonaceous matter and very low manganese content of the unaltered host rocks coupled with the presence and configuration of the oxidised halo associated with the present distribution of the oxide ore minerals. The rocks of the Limestone Series indicate a long, fairly narrow offshore zone of shallow water in which oxidising conditions ($E_h > 0$) prevailed. There was also a nearby large land mass, probably containing exposed igneous rocks, and it is most likely that humid climatic conditions prevailed. These are the conditions under which iron and manganese oxide deposits might be expected to accumulate as chemical precipitates (see Chapter 5, (iii), (d)). For the deposition of beds averaging five metres in thickness there would have to be rapid deposition of the iron and manganese with slow deposition of other material which might contaminate the ore. The preservation of carbonaceous material in the strata being deposited in oxidising conditions on the other hand requires rapid deposition and burial. (Chapter 5, (iv), (a)).

The very low manganese content of these rocks containing carbonaceous matter is very strong evidence against the sedimentary origin of the ores. It is inconceivable that under conditions of open circulation a chemical precipitate could be concentrated on certain parts of the sea bed and at the same time be almost absent on adjacent parts. This argument is even more convincing when it is added that there can be no correlation between ore deposition and depth of water or sedimentary facies variation.

The direct connection between the oxidised halo and the ore minerals is indisputable, (see Chapter 7, (i) & (ii), and Plates XIX - XXII, XXXIII, XXXV & XXXVI). There can be no doubt that the formation of the halo was a post-diagenetic change, and the inference can be made that the ore is an epigenetic deposit.

(b) Concentration of a disperse deposit.

Ball (1916) proposed the view that the ores of Om Bogma are residual deposits concentrated by the solution of the host (the dolomite) of a disperse deposit. He described the process as follows:

"Intense faulting during the latter part of the Miocene period gave rise to an up-flow of heated subterranean waters in the fault fissures. these waters acting on the dolomitic limestones, dissolved the carbonates of lime and magnesia which form the main constituent of the dolomite, leaving the less soluble carbonates of iron and manganese, and the siliceous impurities, largely unattacked. The carbonates of iron and manganese were subsequently oxidised, and underwent a process of segregation to form the ore bodies near the faults, while the siliceous matter forms the sandy shales which nearly always occur above the ores."

Ball supported this contention by quoting a number of analyses of dolomite collected from several widely scattered localities, which gave an average content of 0.24% MnO. He calculated that

"a single square metre of pure manganese ore a metre thick represents the total possible yield of some thirty square metres of the dolomitic strata."

Although the deposits are not "pure manganese ore" they average considerably more than a metre in thickness over quite large areas. The largest ore body in the North Hill had an average thickness of about 5 m. over an area exceeding 3 hectares, with an average content of 21% Mn. (c. 33% MnO₂). This would represent the total yield of some 150 hectares, assuming all the dolomite were dissolved, which is by no means the case. Clearly this source would be insufficient to supply the quantity of manganese required.

The hypothesis is even less tenable when we consider the origin of the manganese in the dolomite. Ball's specimens were of the pink massive dolomite, which on close examination (see Chapter 7, (i), (a)) shows the presence of manganese oxide in tiny veinlets which have invaded the rock after post depositional dolomitisation (see Plates XXIII - XXV). It seems more reasonable to suppose that the manganese of both the ore deposits and the pink dolomites was introduced during the same mineralising activity.

In an attempt to solve these quantity relations Fenine (1930) suggested that the manganese was derived from the igneous rocks of the basement complex, being dissolved by thermal waters rising through fractures. Assuming the solution removed all the manganese from a width of half a metre on either side of a fracture, and allowing a (generous) average manganese content of 0.2% Mn. in the igneous rocks, then to yield the same 3 hectare ore body, fed through a 200 m. length of fracture, the thermal waters would have to traverse a thickness of about 40 kms. of rock. Taking Goldschmidt's (1954) average of 0.1% Mn. for the igneous rocks

this becomes something of the order of an 80 km. depth of origin for the heated waters. When depths of this magnitude are envisaged it would be more reasonable to assume that the manganese was derived from a more concentrated source, or that it was an integral part of the original thermal solutions.

(c) Oxidation of a protore.

The arguments against the sedimentary deposition of large oxide deposits in the Limestone Series apply also to the accumulation of large deposits of rhodochrosite, or even alabandite, under similar conditions. A sedimentary protore, oxidised at a later date, can therefore be ruled out. There remains the possibility of a hydrothermal carbonate deposit, oxidised on the depression of the water table consequent on deep erosion in Pleistocene and Recent times. This is one of two alternative possibilities put forward by Schnellmann (private report, 1951). The objections to this mode of oxidation have been discussed in Chapter 7, (ii) & (v), and Chapter 9, (ii), (c), (q.v.). However such an oxidation could have been effected there is a very strong objection to the previous existence of a protore in the complete lack of any unoxidised remnants, in spite of the preservation of diagenetic pyrite (which requires a lower potential than rhodochrosite for its oxidation) in the unaltered country rocks.

(d) Deposition from circulating meteoric waters.

Deposition of the ore from descending solutions has not been put forward as a serious hypothesis by any worker in this area. The most serious difficulty would be to find a suitable source rock able to yield sufficient quantities of manganese. It is true that the Upper Sandstone contains some local deposits of manganese oxide cementing the sand grains, but this is concentrated most commonly in the fault-planes, where leaching would be expected to be strongest if the manganese were being removed in solution. By analogy with the strata exposed in the scarp of Gebel el Tih and along the gulf margins, the rocks formerly overlying the Carboniferous beds of Om Bogma were not manganiferous enough to have provided sufficient material for the formation of the ore deposits.

Another severe difficulty would be the necessary changes in the physico-chemical conditions. For the leaching and retention in solution of the manganese during transport reducing conditions are necessary, as

discussed in Chapter 5, (iv), (c), while the precipitation of the higher oxides, (not to mention the organic matter of the host rocks) would require removal of oxidising conditions. Percolating meteoric waters would not show a sudden and spontaneous rise in Eh with increasing depth in this manner, and certainly not so in rocks where strongly reducing conditions previously prevailed, as indicated by the co-existence of pyrite and dolomite.

(e) Mineralisation in association with the igneous intrusions.

The distribution of the largest ore-bodies along the strike of the Om Bogma Dyke has led a number of mining engineers to conclude that the deposition of the ore and the intrusion of the dyke were intimately connected. Westerveld (1948) concluded from his work in Morocco that the large masses of dolerite associated with the Mesozoic rocks of that country were sills, and that the adjacent manganese deposits owed their origin to emanations from the igneous magma before it solidified.

That this cannot have been the case with the large ore deposits of the Om Bogma district is shown by the fact that the ore was in place before the intrusion of the dyke (see Chapter 9, (ii)).

(f) Hydrothermal deposition of the oxides.

Deposition of the oxides of iron and manganese from ascending hydrothermal solutions was proposed by Schnellmann as the probable mode of origin. He suggested a mechanism of metasomatic replacement, the hydrothermal solutions gaining access to the Limestone Series by means of the faults. He pointed out that in many cases solution of the host rock had gone beyond the limits of the zone of replacement, leaving an intermediate zone of residual shaley material between the ore and country rock (cf. Chapter 7, (iii)).

The present investigation has confirmed that the ore was deposited from rising solutions (Chapter 8, (i)) and has also shown the importance of the various structural elements as channels for the introduction of ore-depositing fluids (Chapter 10).

(ii) Conclusions from present investigation.

(a) Mechanism of ore formation.

From the discussion of evidence presented in earlier chapters, and in the first section of this chapter it will have become apparent that the

mechanism of ore formation in the Om Bogma manganese deposits which is being advanced in this thesis is, briefly, as follows:

During a long period of tectonic quiescence following the planation of the basement complex a sequence of continental deposits, with at least one thin marine intercalation, followed by marine sediments was laid down. These reached a total thickness approaching 2000 m. by the end of the Eocene period, by which time a phase of tectonic activity had commenced. During this activity considerable faulting occurred, with the formation of one or more sets of N.E. - S.W. fractures, penetrating to considerable depth but not characterised by any significant lateral or vertical displacement (shown by the corresponding levels and facies on either side of it in the Limestone Series). There was thus no tendency for the fractures to fill by mutual attrition of the two walls.

Mineralising fluids carrying iron and manganese were able to escape by this means and made their way towards the surface. On reaching the lowest marine sedimentary formation, containing reactive dolomite associated with layers of impervious argillaceous rocks, the bulk of the iron and manganese was deposited as the higher oxides. At the same time certain constituents of the host rocks in contact with these deposits (organic matter and pyrite in particular) were removed or altered by strong oxidation. According to local variations in facies and the fractures some of the iron and manganese was deposited before reaching the Limestone Series, while some was carried beyond it into the Upper Sandstone.

After the mineralising phase of activity basic magma was forced into one set of these same fractures, solidifying into a dyke of dolerite. On the evidence of Ball (1916) the dyke is of Miocene age, hence the ore must have been formed in the Miocene period or earlier. At that time the Limestone Series would have been buried beneath 1500 m. or more of superincumbent strata.

The unusual feature of this hypothesis is that it requires oxidation by juvenile fluids. The next step is therefore to attempt to deduce the nature of those fluids.

(b) Conditions in the host rocks.

The conditions obtaining in the host rocks before mineralisation give the environment of ore deposition. In particular a consideration of the variations in these conditions in the vertical sequence may yield important

information on the reason for precipitation at one horizon (i.e. it may explain the stratigraphical control of ore formation).

Temperature would be higher than at the surface, but not markedly so. Little variation would be expected from one rock type to another.

Pressure. At a depth of 1500 m. the confining pressure on the rocks would be fairly high, and would tend to close such openings as fissures, joints and other fractures unless these were under tension in competent strata (e.g. during earth movements). Hydrostatic pressure in such openings as could still allow access of ground water would be of the order of 150 atmospheres, increasing with depth.

Permeability would depend on the number and state of the fractures, and on porosity (the size and shape of the pores rather than percentage porosity). In the basement rocks permeability would be confined to fractures, while the Lower Sandstone, being coarse to very coarse grained and rather poorly cemented, would be virtually permeable throughout. In the Limestone Series permeability would vary considerably with facies in both the solid rock and in the fractures (see Chapter 8, and Plate XXXIV). Permeability in the Upper Sandstone would be much lower than in the Lower Sandstone because of the generally smaller grain size and the interstitial clays. Passage would be virtually confined to the fractures and to a few coarser grained beds in the solid rock.

pH and Eh in the sediments would depend on the conditions of diagenesis. The conditions in the basement rocks would depend principally on the nature of the ground waters, the rocks themselves would not be expected to contain any strongly reactive components which could influence either pH or Eh. The bulk of the Lower Sandstone, with its ill-sorted coarse-grained texture, was laid down in conditions of shallow and turbulent water. In such strongly oxidising conditions it is unlikely that any organic matter would be preserved to give a reducing or acid diagenetic environment on burial and the consequent exclusion of oxygen.

The diagenetic environment of the Limestone Series has been discussed in Chapter 5, (iv). On the data of Krumbein & Garrels (1952) the presence of some calcite (in the impure dolomitic limestones) together with pyrite indicates a pH of at least 7.8 and an Eh of less than -0.2. The pH of the Upper Sandstone at this time is less precisely fixed, as calcite is not known to have been present in that formation before ore-genesis, but the

Eh must have been -0.2 or less to have allowed the preservation of pyrite.

(c) Conditions of mineralisation.

The colloform textures and the absence of any sign of thermal effects in the host rocks indicate no great increase in temperature with the rise of the mineralising fluids.

For the fluids to rise in quantity, as indicated by the size of the deposits, they would have to be under a greater pressure than that of the column of ground water already present in the rocks. On this reasoning the minimum absolute pressure would depend upon the depth of origin, and although this would fall off with increasing distance from the source one would still expect pressures of the order of several hundreds of kilograms per square centimetre. Pressures of this order of magnitude might account for the distortion noted in the clays and shales associated with mineralisation (Chapter 7, (iii), (c)).

Another possible explanation for this distortion is the force exerted by growing crystals (Becker & Day, 1916). The unmineralised clays and shales retain their plasticity to the present; in places they have even yielded to explosive charges by compression rather than rupture.

pH during the mineralisation was in the range where both silica and dolomite are soluble, approximately between 6 and 8. The solution and re-deposition of both of these substances may have been due to fluctuations in pH, but it is more likely to have been the result of local variations in the concentration of the solutions.

The most striking change which occurred in the physico-chemical conditions with the arrival of the mineralising fluids was a sharp increase in Eh. In the Limestone Series this was from less than -0.2 to more than zero (indicated by the removal of carbonaceous matter). Within the zone affected by these fluids the oxidising intensity was high, as shown by the sharp line of demarcation at the boundary of the altered zone. The oxidising capacity of the system was also considerable, being at least sufficient to oxidise all the previously reduced components of the country rock.

(d) The nature of the mineralising medium.

The colloform textures in the ore indicate a low-temperature aqueous solution. The conclusions of Duffell (1937) concerning diffusion in

relation to ore deposition suggest that the colloids were not formed until the Limestone Series was reached, the transported material being in true solution during its passage through the underlying rocks. The presence of colloidal matter in the Limestone Series explains the role of the roof shale immediately overlying the three ore bodies as a "semi-permeable membrane" separating part of the solute from the solvent, but it would be difficult to explain the general lack of this activity in the Lower Sandstone if one assumed transport of the ore material in the colloidal state.

The aqueous solution contained iron, manganese and oxygen in considerable quantity, part of the oxygen being "available" to react with substances encountered in the country rocks, e.g. carbonaceous matter and pyrite.

Also present, but in much smaller quantity, were barium, magnesium and lime. The solution was saline, as shown by the small amounts of rock salt which appear as encrustations on the ore and red iron shales.

In tracing the course of the mineralising activity we find that a strongly oxidising aqueous solution ascended through the rock column with very little reaction until it encountered a reducing environment, when it reacted strongly with organic matter and sulphide minerals, depositing colloidal ferric oxide and manganese dioxide in the process. From the chemical point of view it is necessary for some component of the invading solutions to have been reduced in such a reaction in order to absorb electrons from the iron in the oxidation of pyrite, and to provide oxygen for the oxidation of carbonaceous matter and sulphur. Manganese is the only substance known to have been introduced in quantity which could have existed in a higher state of oxidation than that in which it is found in the ore deposits.

(iii) Further investigation.

(a) Hydrothermal oxidation.

The subject of hydrothermal oxidation of manganese minerals was investigated by Trengrove (1936), who experimented on the thermal dissociation of manganese carbonate in the absence of oxygen. He found that there was no oxidation below 170° , but some manganese dioxide was produced at higher temperatures, being unstable above 300° . The reaction was

retarded at high pressures and in the presence of carbon dioxide. His findings do not apply to the case under discussion, since there is no evidence for a previously existing deposit of manganese in the form of carbonate, and a high pressure is inferred.

In a short review of the literature Trengrove (*ibid.*) noted a number of deposits, in varying environments, in which there appears to be evidence for the oxidation of manganese well below the water table.

The deductions made in the previous section lead to the suggestion that manganese was present in solution in a higher state of oxidation, and that it was precipitated by reduction rather than by oxidation. The possibility deserves consideration that a part of this element was present as the manganate, or even the permanganate ion. This at once raises the question of the formation of such ions at the source of the mineralising fluids. The existence of such strongly oxidising conditions as would be required in a natural environment at considerable depth is contrary to the general trend of geological thought, and cannot therefore be accepted without very critical examination and more comprehensive investigation than has been undertaken in the present work. It has been mentioned here as the logical conclusion to the observations and deductions made during the examination of the Om Bogma ore deposits. No attempt is being made at present to explain the formation of the mineralising fluids.

(b) Examination of the permanganate hypothesis.

When considered in more detail it is found that the presence of permanganate would explain the action of the mineralising medium as shown by the evidence in the field. In normal laboratory conditions permanganate is unstable; it decomposes spontaneously with evolution of gaseous oxygen. This reaction would be inhibited at high pressures, such as those inferred during the formation of the Om Bogma ores (Le Chatalier's Principle).

Permanganate is a strong oxidising agent. It reacts with organic compounds and carbon, breaking down to the dioxide in the process. Under certain conditions the manganese oxide is produced in colloidal form (e.g. when manganous salts are treated with permanganate - Partington, 1937).

Ferric oxide also forms colloidal solutions in the presence of organic matter. Permanganate oxidises ferrous ions, but would be stable in

the presence of ferric ions; these could co-exist in acid solution. Part of the iron may have been present as undissociated ferric chloride, since there is evidence (in efflorescent rock-salt on exposed ore faces) to suggest that chloride ions were introduced with the ore.

A low pH would account for the virtual absence of corrosion of silica in the granitic basement rocks and the lower part of the Lower Sandstone. Neutralization of the solutions by reaction with the carbonate rocks in the Limestone Series could explain this activity close beneath the Sandstone Pavement, and also the re-precipitation of the dolomite.

(c) Experiment.

A series of small scale experiments was carried out on a number of rock specimens from Sinai, using a solution of permanganic acid prepared as follows:

A solution of silver nitrate and potassium permanganate were crystallised and the silver permanganate precipitate was decomposed with barium chloride. The resulting barium permanganate was treated with dilute sulphuric acid to give a purple solution of permanganic acid.

1. The solution was decolourised rapidly by coal (OB/72), while pyrite from the same specimen reacted a little more slowly, the decolouration taking a minute or two.
2. Black siltstone (OB/106) decolourised the solution in a few minutes, giving an iridescent oily black film.
3. Pieces of granite (OB/40), black shale (OB/23), red sandstone (OB/78) and grey dolomite (OB/89) were placed in a 200 ml. flask, covered with the acid solution and placed in a warm dark cupboard. The solution decolourised with evolution of oxygen in a few hours, the rocks showing little change. After five months of immersion the granite and sandstone showed a few yellowish brown stains but no other change. The black shale fell to pieces, and whitened a little on drying in air. The grey dolomite changed to a very pale yellowish grey and softened at the surface. There was some local brown staining. Barite and galena in the specimen were least affected. On drying in air the surface became yellow with brown patches. On breaking the specimen it was found that the change had penetrated the rock for 1.5 mm., with a narrow brown line at the limit of oxidation.

(d) Suggestions for further work.

These experiments in themselves are far from conclusive, but a more detailed laboratory investigation, including experiments at higher temperatures and pressures, should yield interesting results. In particular the stability of a solution containing calcium, magnesium and barium with manganate, permanganate and ferric ions in the presence of sodium and chlorine ions should be investigated at high pressures; moderately high temperatures and in the absence of light. The effect on this stability of gradually reducing the pressure and temperature, and varying the pH, and of contact with silica and silicate minerals, carbonates, carbonaceous matter and pyrite should also be investigated.

Other manganese deposits should be examined to see if there is similar evidence pointing to the hydrothermal oxidation of country-rock in association with the formation of iron and manganese oxide ores.

(12) OTHER DEPOSITS IN AND AROUND SINAI(i) Vein deposits.(a) The haematite deposits of Gebel Abu Nimran.

Gebel Abu Nimran (1040 m.) is situated a little to the north-east of Wadi Feiran, about 25 kms. south-east of Om Bogma. The country is composed of granitic rocks of the Basement Complex, intruded by closely spaced parallel north-east trending dykes of purple porphyry. On the western flank of the mountain there are several quartz veins, up to 90 cms. wide, with a little associated grey haematite showing traces of green copper stains. These veins strike approximately east to west. Near the top of the mountain on its south side there is a narrower vein of similar composition and strike, and others have been reported around the summit. In the ravine below the south face (Wadi Abu Nimran) several tumbled blocks were seen with numerous ramifying veins, from one to three centimetres wide, containing quartz and haematite in equal proportions (by volume). These latter veins showed no copper staining.

(b) Wadi Sabra haematite vein.

Blake (1939) reported the occurrence of a vein of "pure haematite", 2 to 12 inches thick, traversing the (Nubian) sandstone to the south of Petra.

(c) Manganese veins near Aqaba.

Blake (1936) notes:

"Both copper and manganese minerals occur in the porphyry intrusions, and veins of manganese ore in calcite occur traversing the granite near Aqaba where all the Palaeozoic rocks have been eroded and the Nubian Sandstone lies directly on the Igneous complex."

(d) The manganese deposits of Wadi el Akhdar.

The country rock in the Wadi el Akhdar area is a granitic or gneissic rock in an advanced state of decomposition, cut by felsite dykes striking a few degrees west of north. There are a few low outlyers of the basal part of the Nubian Sandstone in the neighbourhood, a region of fairly mature topography. The manganese occurs in a group of narrow veins apparently emplaced in a fracture zone. There is, however, no sign of lateral dis-

placement of the dykes, although the veins cut through dykes and country rock indiscriminately. Individual veins reach a maximum width of 80 cms., and the total width of the mineralised zone never exceeds 1.5 metres. There is no visible change in the deposit in the 10 m. depth of the workings. The strike is 65° (magnetic), and the total length of outcrop is about 150 metres. The ore is very similar to some of the higher grade varieties of Om Bogma ore both in texture and mineralogy. Pyrolusite appears to be the predominant mineral, being found in radiating needles up to 5 mm. long and as much finer-grained material. Radiating fibrous goethite in the spherulitic masses associated with colloidal deposition is also found; locally it is brecciated and cemented with gangue mineral.

The gangue is little or no more abundant than in the Om Bogma ores, and includes quartz and dolomite, and possibly also barite and aragonite.

There is clear evidence of replacement of the country rock by the oxides, and the ore minerals also extend as strings along joints in the dyke rock (Plate XLIX).

(e) Origin of the vein deposits.

The origin of these minerals is indicated as being by direct precipitation of the oxides of manganese or iron from active media percolating the rocks along fractures, with some replacement of the country rocks. Hydrothermal mineralisation is indicated in Gebel Abu Nimran, and seems quite likely in the other cases too, although only the low temperature minerals of manganese occur.

(ii) Deposits associated with marine sediments.

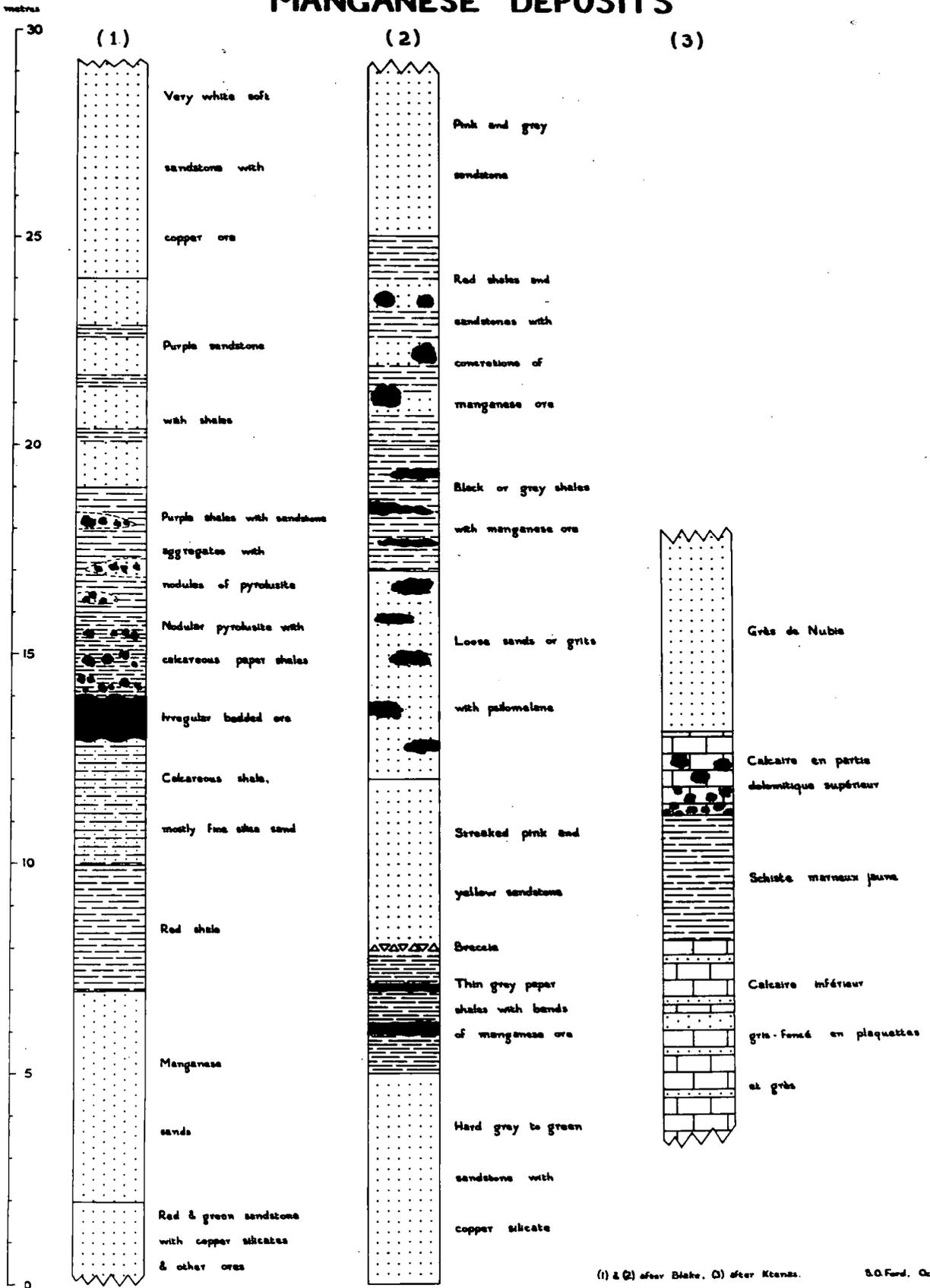
(a) The deposits of Wadi Menayeh.

These deposits have been described by Blake (1930 and 1936) and more recently by Sturm (1953).

Blake gave the following general section:

"Lower Cretaceous	Sandstones	345 metres
	Red shales, purple sst.	5
Carboniferous	Shales & sst. with Mn. ore	10
	Manganese sands	10

SECTIONS OF THE WADI MENAYEH MANGANESE DEPOSITS



	Dark or black lst. with	
Cambrian	<u>Siphonotreta</u> & <u>Obolus</u>	10 metres.
	Bright red sst. with	
	quartz pebbles	30
	Igneous-metamorphic complex	
	(diorite & hypersthene-gabbro)."	

The respective ages of these formations have been disputed (Chapter 2.); Blake correlated these "Carboniferous" beds with those of Om Bogma entirely on the basis of their contained manganese deposits.

More detailed sections are given in the accompanying diagram. These and Sturm's description all emphasise that the manganese occurs as rather nodular and occasionally irregularly bedded pyrolusite and psilomelane at or near the top of a series of rather sandy and calcareous shales, overlain by the higher part of the Nubian Sandstone. Both Ktenas (quoted by Blake, 1936) and Sturm mention the presence of dolomite with which the manganese is associated, but Blake states that he did not see the dolomite. None of these writers mentions the presence or absence of manganese in the underlying dark limestone. The description by Ktenas in particular is reminiscent of ore in the Upper Dolomite overlying shaley bedded limestone in parts of the Om Bogma district.

Sturm noted the following types of emplacement:

- (1) Concretions (nodules) of pyrolusite, 1 mm. to 30 cms. across, in clay; assays showing 28% - 64% MnO_2 .
- (2) Bedded or disseminated manganese oxide in fine-grained sandstone within a red clay zone, and commonly below clay in sandstone and siltstone.
In some places there are alternate manganese rich (4% MnO_2) and manganese poor (1.5% MnO_2) "varves" (Zebra Sandstone), the manganese being concentrated in the fine-grained sandy layers at the expense of the silty layers.
- (3) Recent placers of manganese rich sand.
- (4) Dyke-like structures.
- (5) Irregular spots in limestone or dolomite.
- (6) Small veinlets or crack fillings in layers adjacent to ore-bearing strata.

All of these can be matched with similar occurrences in the Om Bogma area, with slight variation in two cases. Zebra Sandstone found near Ain Abu Hamata in the Nahman Areas was made up of alternate layers of sand grains respectively iron free and coated with bright red iron oxide. Manganese has not been seen distributed in straight parallel banding in this manner at Om Bogma, but concentric diffusion rings of manganese oxide cementing sand grains in the Lower Sandstone have been noted there. The only other difference between the two areas is that "float" ore at Om Bogma takes the form of fragments from 1 cm. in size upwards; there are no recent placers of manganese rich sand (Chap. 6, i, j).

Analyses quoted by Blake (1936) show the deposit to contain higher percentages of CuO (1.29%) and BaO (4%, 3.99% and 4.15% respectively for 3 samples), while P_2O_5 is less abundant (0.05%) than at Om Bogma.

Sturm concluded from the occurrence of the varved and bedded deposits that the ore had a syngenetic origin, being transported and deposited in the solid state. He attributes the concretions in clay and shale to growth in place during compaction of the sediments, while the manganese veinlets filling joints and cracks are, he postulates, due to circulating ground water.

From a study of these descriptions and a comparison with the field evidence at Om Bogma it seems most likely that the deposits in these two areas had a similar origin. The most significant fundamental point appears to be the fact that in each case these deposits are associated with the lowest formation in the rock column that contains calcareous and clay members, the one to act as host and the other as a barrier to rising solutions. Sturm's observation that manganese commonly occurs in sandstone or siltstone below clay is important in this latter connection.

(b) The deposits of Wadi Dana.

Blake (1939) gives a very brief description of these deposits. They underlie 150 m. of purplish sandstone, which is overlain in turn by 300 m. of red sandstone and another 300 m. of white sandstone capped by Cenomanian limestone. Blake's detailed section at the manganese occurrence is as follows:

metres.

Red sandstone	
Grits	4
Botryoidal masses of pyrolusite	3.5
White sandstone and shales	7
Dolomite with psilomelane concretions	4
Pink dolomite with shales	12
Grit	0.5
Red mottled sandstone	

An analysis of a specimen from the deposit showed the copper content (1.80% CuO) to be comparable to that of the deposit at Wadi Menayeh, while the baria (0.05% BaO) and phosphorus (0.16% P₂O₅) are lower than in the Om Bogma ore.

The manganese deposit is associated with pink dolomitic limestone which "resembles that found abundantly in Wadi Hesa." Blake quotes the following analysis of a specimen of this rock:

Insol. in HCl	22.6
CO ₂	32.3
CaO	24.1
LgO	13.5
MnO	5.9
H ₂ O	0.2

98.6

The high manganese content is no doubt the reason for the pink colour; the fact that a similar type of rock is found in Wadi Hesa, some 40 kms. to the north, suggests that manganese mineralisation may be as widespread here as it is in western Sinai.

Again there is a general similarity between this deposit of Wadi Dana and those of the Om Bogma area in the position and associations of the manganese deposits and in the minerals of which they are composed. There is a strong possibility, on the evidence available, that these deposits had a generally similar origin.

(iii) Sinai and Jordan as a manganese province.

From this review of the wider area the picture emerges of a belt of mineralisation extending from near the Gulf of Suez in the south-west to beyond the Wadi Araba depression to the north-east, and possibly farther in either direction (see Map I). There are fundamental points of similarity with the ore deposits of Morocco, where the manganese oxides also occur in veins within the basement rocks and associated with the lowest calcareous marine deposits in the sedimentary sequence. There is a strong suggestion, in the map and plan given by Bouladon and Jouravsky (1952 - facing p. 72), that the distribution of the deposits at Imini is controlled by a fracture in much the same manner as has been deduced in the case of the Om Bogma deposits (Chapter 9). The possibility at once springs to mind of a more or less continuous line of manganese deposits stretching from western Sinai to the Wadi Araba beneath the Nubian Sandstone (s.s.) and the overlying marine Cretaceous beds.

Whether or not this is so one may regard the whole of southern Sinai, the southern part of the Negev and south-east Jordan as a geochemical province abnormally rich in manganese. In addition to the deposits of manganese ore minerals discussed here, and the other occurrences noted in Chapter 1, (v), (d), there is some evidence to suggest that some of the rocks of the Basement Complex contain more than average amounts of this element. The colour of the dark purple porphyry ("Imperial porphyry"), which is a common dyke rock in parts of Sinai, is probably due to the presence of manganese (Evans). More concrete evidence is provided by an analysis of a specimen of pink granite from Wadi Itim, near Aqaba, quoted by Blake (1936). This rock contained 0.5% MnO (0.4% Mn) which is rather high for a granite.

P A R T I I I

COMPARABLE DEPOSITS.

(1) THE MANGANESE DEPOSITS OF MOROCCO.

The quantity and distribution of manganese ore deposits in Morocco, coupled with their varied modes of occurrence and association with rocks of many different ages, justifies the application of the term "manganese province" to the area. The comprehensive description of Bouladon and Jouravsky (1952) (on which these notes are based) shows broadly similar types of deposits and associations to those of the Sinai-Jordan region.

(i) General.(a) Geological background.

The older rocks in Morocco consist of partly metamorphosed pre-Hercynian sediments, with associated igneous rocks. There are three Pre-Cambrian groups and most of the Palaeozoic systems are also represented. These form a basement which is elevated and exposed in the Anti Atlas and in smaller areas in the east and north of the country. The outcrops are bordered by marine sediments of Mesozoic age. There were two major transgressions, during Lias and Cenomanian times respectively, the former reaching to the High Atlas and the latter overlapping it to overstep on to the pre-Hercynian rocks of the Anti Atlas so that in both cases the off-shore deposits near the limits of the transgressions rest on the basement.

(b) The manganese deposits.

As in the Sinai-Jordan area only the oxide minerals of manganese are represented.

Both veins and stratified deposits occur. They are classified by Bouladon and Jouravsky (ibid) on their stratigraphical associations.

(1. Veins.

The veins are mainly in the Pre-Cambrian III in the Ourzazate region of the Anti Atlas, but there are also some veins associated with Palaeozoic rocks in the Oujda area, N.E. Morocco. They are all narrow and discontinuous but of high tenor, exceeding 50% Mn.

(2. Stratified deposits.

These deposits are much larger than the veins, but generally of a

lower tenor. They are found in association with:

Volcanic formations of the Pre-Cambrian III of the Anti Atlas and Upper Viséen of the Oujda region.

Continental formations of the Permo-Trias and Cretaceous.

Meritic facies of the two major transgressions.

It may be of significance that the several types of deposit tend to occur in close geographical association, e.g. in the Oujda region (an area 90 x 30kms.) all these types of deposit occur, while the nearest deposits outside this area (at Bou Arfa) are some 200 kms. distant, and also show several types. These deposits will therefore be discussed here on a regional rather than a stratigraphical basis, with the emphasis on evidence suggestive of the mode of origin of the various deposits. Whilst such a controversial subject as ore-genesis cannot satisfactorily be decided on a second hand acquaintance with an area certain significant facts emerge from the descriptions which should be taken into account when assessing the various possibilities.

(ii) The Oujda region, F.E. Morocco.

(a) Veins in the basement.

Some narrow veins occur in Gothlandian slates (schistes) at Zekkara, but the most important ones are those of Bourdine, occurring in a mass of granodiorite which has been intruded into the Palaeozoic slates and sandstones. The largest of these, 200 m. long and up to 0.5 m. wide, is accompanied by mineralised fractures in the wall rocks (cf. the deposit of Wadi el Akhdar, in Sinai), while one margin is often marked by a layer of ferruginous clay. The vein material is, however, often brecciated, with included diorite fragments. The manganese occurs as braunite, showing alteration to pyrolusite, with a gangue of quartz, dolomite, barite and calcite. The red argillaceous sandstones at the base of the overlying Permo-Trias formations at both of these places are impregnated with psilomelane.

(b) Beds in the volcanic deposits.

At Glib en Nam, 35 kms. E.S.E. of Bourdine, there is a thick flow of dacite at the base of the Upper Viséen, overlain by a series of friable tuffs with some intercalated thin lenses of coarse-grained dolomite, and bands of silicified shale (schistes). The ore is fine-grained braunite in a siliceous cement, resembling banded jasper. It outcrops intermittently for nearly 1 km., reaching a thickness of over 2 m. and is associated with the tuff and silicified shale. Some cracks in the ore have been infilled with white dolomite.

(c) Beds in the continental facies.

At Narguechoum, some 35 kms. W.S.W. from Bourdine, the basement is composed of dacites and granodiorites with indications and veins of manganese. It is overlain by about 20 m. of well cemented sandy conglomerates, followed by 30 m. of arkosic and argillaceous sandstones containing some mineralised beds. These are covered by basalts, 0 - 30 m. thick, the whole sequence being assigned to the Permo-Trias. The basalts are overlain, either directly or with a passage of red clay between, by sandy dolomites succeeded by massive dolomites of Liassic age.

There are two or three mineralised beds, the uppermost and thickest varying between 0.5 m. and 0.8 m., and being characterised by an intermittent roof of red clay. The manganese occurs as braunite and hausmannite with pyrolusite and some psilomelane, in the form of friable aggregates or veinlets in the sandstones. Calcite and barite form the gangue. Locally the ore grades into bands and nodules of iron oxide. Apart from the presence of braunite, and the abundance of barite (5.85% in an assay quoted) the deposit is very similar to those found in a corresponding type of country rock in Sinai (Chapter 7, (i), (d) and Chapter 8, (ii), (b)).

Analogous deposits occur in these Permo-Triassic continental formations in the area between Oujda and Glib en Nam. In Jebel Mahsseur iron and manganese oxides occur in clays and red sandstones above the basalts and 20 m. below the dolomites of the Lias. There are also small amounts of manganese associated with iron oxide deposits in these continental formations in other parts of Morocco.

(d) Beds associated with transgressive marine formations.

At Tanourat the basement (dacite) is directly overlain by 50 m. of basalt, assigned to the Permo-Trias. Above this basalt are some red and green clays, 10 m. thick, with some thin dolomitic intercalations and the lowest mineralised beds at the top. One or two metres of red beds overlie them, including a conglomerate from which some pebbles of the mineralised beds have been reported. Massive white dolomites appear next in the sequence, containing the upper mineralised bed which occurs at the top of a passage of red sandstones. The lower beds show considerable lateral variation; one or two beds may be present, from 0.1 m. to 0.8 m. in thickness. The upper bed is richer and of lenticular appearance, attaining a maximum thickness of 0.6 m. The manganese occurs as needles of pyrolusite, generally very fine but occasionally reaching one or two centimetres in length. White crystalline dolomite occurs in fractures and cavities in the ore. Barite is much less abundant than in the deposits not associated with a dolomite host.

These deposits compare with some ores found associated with a dolomite host in Sinai, particularly in mineralogy.

(iii) Eastern region (Bou Arfa).

No veins or stratified deposits associated with the Palaeozoic rocks were described by Bouladon and Jouravsky at Bou Arfa, but about 70 kms. to the south, at Menabha, there are several veins of manganese in a rhyolite conglomerate. The Bou Arfa district contains the largest manganese deposits associated with the rocks of the Lias transgression.

The basement is formed by ancient schists with altered intrusive rocks, and is overlain by a detrital series more than 100 m. thick, made up of a basal conglomerate, and arkoses and clays with lenses of dolomitic limestone. At the top of this series there are some thin manganiferous beds, 10 - 30 cms. thick, and some passage beds of impure dolomite with nodules and bands of pyrolusite. The detrital series is followed by a "dolomitic limestone episode" whose thickness varies from 180 m. at Ain Beida (north of Bou Arfa) to 30 m. at Hamaraouet, 5 kms. to the W.W.W., increasing to 250 m. at Bassi Fallet, 20 kms. west of Ain Beida. The following succession is given:

Beds of limestone and dolomite with interbedded marl enclosing the ore-body of Ain Beida.

10 m. Detrital facies.

10 - 20 m. Massive pink dolomitic limestone with patches of calcite enclosing the ore masses of Hamarouet.

Bands of dolomite with quartz and mica.

Lower detrital series.

This sequence is succeeded with slight unconformity by a second detrital series, about 250 m. thick, including pink clays with gypsum, arkoses locally stained with manganese and conglomerates with igneous and metamorphic pebbles.

To both east and west these three series thin out and the limestone disappears. They are overlain by a continuous formation of limestones and dolomites attributed to the Dogger.

The tectonics of the region are complex, but the map and sections given by Bouladon and Jouravsky appear to suggest that the manganese deposits are thicker on the crests of anticlines, dying out on the limbs.

At Hamarouet mineralised beds occur at the base of the limestone series, where beds of dolomite contain 1 cm. bands of manganese oxide. Workable ore is found above this in large pockets formed by solution along fractures in the massive dolomites. These masses of ore may be up to 15 m. thick and 10 m. to 20 m. long, with lateral apophyses several metres wide penetrating into cracks in the dolomite. The edges of these pockets, and of dolomite blocks enclosed in the ore, are lined with red clay. (These deposits are analogous to the pockets of ore surrounded by residual rock found in the massive pink dolomites of the Om Bogma district; see Chapter 7, (i), (a) and (iii), (b), and Chapter 8, (ii), (b)). The ore is essentially pyrolusite and psilomelane with local hausmannite. Iron is abundant, crystallised separately from the manganese. Kernels of pyrolusite appear surrounded by radiating concretions of goethite which has been brecciated and re-cemented by a later deposition of pyrolusite (cf. the textures shown by goethite in the Om Bogma deposits, Chapter 6, (ii), (e)).

At Ain Beida the deposit is more regular, being associated with the bedded part of the limestones. The ore occurs in ribbon-like deposits

over 200 m. long in the crests of the folds. The deposits have a lenticular cross section, averaging 10 m. width and 1.5 m in thickness, but locally they attain a thickness of 8 m. They are connected by zones of red mineralised clay (cf. residual rock of Om Bogma). The roof and walls are also lined with clay. The iron and manganese do not occur in separate crystals as at Hamaraouet.

At Ben Zireg, about 80 kms. to the south of Bou Arfa, there are indications of manganese in sandstones of Cretaceous age.

(iv) The Ouarzazate and Imini-Tasdremt region.

To the south of Ouarzazate there is an area, 90kms. from east to west and 50 kms. from north to south, in which there are great numbers of manganese veins in the formations of the Pre-Cambrian III. To the west of Ouarzazate this area is bordered by a line of ore deposits associated with the rocks of the Cretaceous transgression, stretching from Imini in the east to Tasdremt in the west.

(a) Veins in the basement.

The Pre-Cambrian III of this area is made up of a series of rhyolite and andesite lavas, and thick conglomerates and agglomerates, sometimes cemented with dolomite. Locally the volcanic series is terminated by tuffs and red shales with lenses of dolomite. Most of the veins occur in the lavas, and a few in the conglomerates, which have a smaller area of outcrop. There are also rare indications in the granites and sandstones of the Pre-Cambrian II. The veins are nearly vertical, with variable strike, the most common trend being to the north-east. Post-mineralisation fractures are very common.

Two types of vein are recognised:

1. Lenticular, with a dolomite gangue. A vein at Taourat is over 200 m. long and locally 7 m. wide, with a proved depth of more than 40 m.; this is rather larger than the average. Dolomite is abundant, being partially replaced by braunite. Cryptomelane and pyrolusite also occur and hausmannite is found in the dolomite. Iron oxides (haematite and goethite) appear in quantity in some veins. Quartz, calcite and a little barite also occur in the gangue.

2. Narrow and continuous veins, without dolomite. These generally appear in swarms. They are of variable dimensions but always narrow, rarely up to 1 or 2 m. in local swellings. Manganese occurs mainly as braunite, and sometimes as psilomelane, with a sparse gangue of barite and occasionally also of quartz. At the margins the ore is brecciated, with inclusions of country rock. The wall rocks are fractured, containing deposits of ore minerals and gangue in the cracks.

No veins of manganese minerals outcrop in the Cambrian rocks which cover a large part of the area, hence the veins are probably of Pre-Cambrian age.

(b) Beds in the volcanic formations of the Pre-Cambrian III.

The Pre-Cambrian III at Tiouina begins with a 200 m. thickness of rhyolite and andesite lavas, followed by the detrital series and a series of red tuffs with the following succession:

	Beds of dolomite
	Sandstones and conglomerates
	- - - Base of Georgian (G.Choubert)
200 m.	Red tuffs, with narrow siliceous mineralised beds at the base.
20 m.	Barren conglomerates
	Red micaceous tuffs with beds of ore, averaging 0.5 - 1 m. thick.
	Breccia with angular rhyolite fragments and thinner intercalations of microbreccia.
200 m.	Lavas

The lower mineralised zone outcrops for a distance of 800 m. from north to south, with a dip to the east of about 35° . The number and width of the beds is very variable; the maximum number is fourteen and the greatest individual bed thickness is 4 m. There are numerous small faults. The ore passes laterally into the red tuffs, which often form the roof of the ore beds, and also contains quartz grains and fragments of lava showing replacement phenomena. Locally the ore consists of a rhyolite breccia, with a cement of dolomite partially replaced by manganese minerals. Barite is present as gangue. The ore shows variable amounts of silica

(1.75 - 10% SiO_2), baria (1.9 - 13% BaO), potash (trace - 5%) and lead (0.5 - 2%). The principal ore mineral is braunite; psilomelane, cryptomelane, pyrolusite and coronadite also occur.

At Migouden, 4 kms. north of Tiouine, the succession is similar but there are fewer mineralised beds and these are situated in the conglomerates and the tuffs. The Pre-Cambrian III outcrops again to the east on the opposite limb of a syncline, and at Offremt, 7 kms. to the east of Tiouine, there are four mineralised beds outcropping over a length of 400 m. in a series of rhyolite conglomerates with intercalated red tuffs.

(c) Beds in the Middle Cretaceous transgressive marine formations.

The Cretaceous beds in this region rest unconformably on a basement of Pre-Cambrian volcanic rocks, Lower Palaeozoic slates (schistes) or Permian-Triassic sandstones. A series of conglomerates, sandstones and red clays, about 10 m. thick at Imini and thickening to the north, are succeeded by about 10 m. of dolomite of Cenomanian-Turonian age, containing the manganese deposits. This is overlain by a thick red sandstone series with intercalations of red gypsiferous clays and some limestones, of Senonian age.

In the Imini area ore deposits outcrop in a narrow, nearly straight, line more than 25 kms. long, striking in an E.F.E. direction from Tazoult to Tamdakht. Farther to the east there are indications in the neighbourhood of Skoura, (100 kms. east of Imini). The lateral extent of the ore in a north-south direction is very restricted, the width of the deposits hardly exceeding 400 m. At Bou Tazoult there is an apparent duplication of this narrow line of deposits, but even so the total width of the mineral zone is less than 1000 m. (This remarkable alignment of the manganese deposits is much more striking than that noticed in western Sinai, see Chapter 10, (i), (b) and (c)). The quantity and quality of the ore at any place bears no relation to the nature of the underlying basement.

The principal mineralised beds (C_1 and C_2) are always found in the "passage" from the lower sandstones to the dolomite. In its lowest beds (about 1 m. thick) the dolomite contains detrital quartz and occasionally feldspar and muscovite. The higher beds of dolomite are white or pink, generally very pure and only slightly fossiliferous (cf. the nearly pure pink dolomites of western Sinai). Towards or at the top of the dolomites there is a third mineralised bed (C_3), 20 - 40 cms. thick, but sometimes

broken up and re-cemented together with detrital dolomite. These rocks have been affected by a series of folds of 20 - 30 m. amplitude, either with an E.N.E. trend (parallel to the elongation of the ore beds) or trending E.S.E. Enrichment of the mineralised beds does not appear to be a result of this folding.

The two lower beds are regular with a combined thickness varying up to 2.5 m. They are always immediately overlain by a 10 cm. layer of red sandy clay (cf. the "roof shale" of the Om Bogma deposits, Chapter 8, (i), (d)) with many extensions into the ore suggesting that it is in the nature of a "residual" from the solution of the dolomite and its partial replacement by manganese oxides. The floor, even where it is of dolomite, is very regular and only occasionally contains manganese minerals filling cracks. The northern limit is definite; passing from rich ore to barren dolomite in 20 m. To the south the two beds coalesce and thin out, passing progressively into sandstone impregnated with manganese oxides.

The ore is principally composed of pyrolusite, with veins of psilomelane associated with coronadite (the α manganese dioxide containing lead). The upper parts of the beds are formed almost entirely of concretionary coronadite. Analysis showed 0.32% PbO in a sample from Bou Tazoult.

To the west of the Imini group of outcrops the Middle Cretaceous deposits have been largely removed by erosion, but some remnants have been preserved at Haut Tidili and Tifnout showing a poorer mineralisation in thicker dolomite.

Farther to the west the beds again outcrop, over a length of 15 kms., at Tasdremt and Aufour. At Aufour they occur in a basin, 3 x 6 kms., with the mineralisation being strongest at the rim and decreasing towards the centre. The ore here is remarkable for its tenor in lead, which is of the order of 6%. The principal bed (from 0.5 to 0.8 m. thick and rich in lead) is at the top of the dolomite series, cf. the C₃ bed at Imini. There is another bed at the base which corresponds to beds C₁ and C₂. The top of the dolomite series locally resembles a breccia, with angular fragments of dolomite in a dolomite cement. (This may be analagous to the "solution breccia" often seen at Om Bogma, with secondary dolomite, see Chapter 7, (iii), (b) and (iv), (a)).

The overlying sandstone series is composed of arkosic sandstones and conglomerates with rare red clays. The conglomerates contain pebbles derived from the Cretaceous dolomites, and even from the mineralised bed, examples of the latter being cited at Tasdremt with two conglomerate beds situated above the principal ore bed.

At Tasdremt the upper part of the ore bed is the best mineralised and contains vugs lined with barite. The top is irregular and immediately overlain by a roof of sandy material with nodules of manganese oxides and pieces of impregnated dolomite. The lower part of the bed is often formed by three fine bands of manganese oxides in yellow dolomite. The dolomite floor is regular and impregnated with diffuse epigenetic oxides. In the Aufour basin and at Tiranimine some fragments (1 - 5 cms. across) of concretionary coronadite are found embedded in a reddish sandy cement at the top of the ore bed. Sometimes the entire bed is in the form of a breccia with very angular fragments. (But for this angularity this deposit would resemble the nodular and concretionary deposits of ore minerals found near the boundaries of the bigger ore bodies in the Om Bogma district, Chapter 7, (i) and (iii), (b)).

The ore in this western area is composed essentially of psilomelane and coronadite. Both the ore and the dolomite with which it is associated contain 5 - 10% detrital quartz and occasionally some kaolinised feldspar.

(v) Idikel.

Situated in the Anti Atlas about 120 kms. south-west of Tasdremt, Idikel forms the south-west corner of the Moroccan manganese province. The Pre-Cambrian III presents an unusual facies in this area, the rhyolites are absent and the series is represented by schists, sandstones and conglomerates with altered tuffs. Idikel is at the edge of a basin where the whole sequence of the Pre-Cambrian III hardly exceeds 50 m. in thickness. The following succession is given:

- Conglomerates (base of the Georgian).
- 20 m. White tuffs, altered to sericite-schists with thin intercalations of sandstones and conglomerates
- 2 - 5 m. Fine red sandstone containing some fragments of volcanic glass, and enclosing the ore beds and some intercalations of dolomite.

White tuffs, altered to sericite-schists.

15 - 20 m. Massive breccia of schist and quartzite.

Schists (Pre-Cambrian II).

The principal ore-bed outcrops intermittently for a distance of 2 kms. with a width varying between 0.2 m. and 2 m. In the central part of the outcrop, where the width is greatest, there is a second bed 0.2 - 0.4 m. thick above this. Towards the extremities of the outcrop a third bed sometimes appears above the second. At its lateral limits the mineralisation becomes more diffuse and merges into barren sandstone.

The following data are reported from a recent investigation of a suite of specimens provided by Mr. Donald Gill. This information is included by the kind permission of Fergusson Wild & Co. Ltd., through the good offices of Mr. Gill.

Near the surface the ore is soft and friable, being composed of small nodules, a few millimetres across, of manganese oxides with tiny rounded and angular grains of quartz and other minerals, most of them cloudy with decomposition and all coated with red and brown iron oxides. The richer ore occurs as larger spongy masses apparently formed by the leaching of a soluble component of the rock leaving a porous residue of manganese oxides. Below the surface zone the ore is a hard mass of braunite, ankeritic dolomite, brown mica and barite in varying proportions. A little pyrolusite is also present. The soft ore seen at the surface is clearly a residual deposit, or "manganese hat", resulting from the solution of dolomite, and possibly some of the mica, from the hard ore. The soft ore extends for about 100 m. from the outcrop, measured along the dip, which is about 20° to the east. It can also be seen in small patches at greater depth, associated with fractures.

Manganese occurs in the hard ore almost entirely as automorphic braunite, which has been identified in reflected light by its crystal form, comparatively low reflectivity and very weak anisotropy. The identification was confirmed by means of an x-ray powder photograph. In the coarser parts of the bed, up to 1 mm. in grain-size, ankeritic or manganese bearing dolomite (refractive index $n_0 \approx 1.690$) can be seen to have partially re-

placed the braunite, leaving embayed crystals, "atolls" and residual rims showing the automorphic outlines of braunite. This dolomite also occurs as veinlets in the rock, while larger veins (2 - 3 cms. wide) consist of purer dolomite ($n_D \approx 1.675$). Barite can also be seen in the hand specimen as greenish crystalline layers ($n_B \approx 1.645$) on some joint faces.

A specimen from the floor of the ore bed showed a fine-grained laminated texture. Layers up to 1.5 mm. thick of granular quartz, dark brown mica and a little carbonate up to 0.1 mm. grain size are interstratified with rather intermittent layers of a fine to coarse-grained opaque ore mineral associated with dark mica, barite and a little plagioclase. In other specimens the coarser ore and gangue mixture cuts across the fine-grained layered part of the rock, apparently replacing it.

The rock of the ore bed has undergone a number of phases of alteration since original deposition. It is not considered possible on the evidence examined to deduce the precise nature of the original rock. An epigenetic origin for the manganese can by no means be ruled out.

(vi) Comparison with the Sinai deposits.

(a) Points of contrast.

The volcanic formations (tuffs and agglomerates) of the Pre-Cambrian III and Upper Viséen of Morocco are not paralleled by any similar deposits in Sinai, hence there can be no comparison of the two regions on the basis of manganese deposits associated with them.

The vein deposits of Morocco are far more numerous than those of Sinai and Jordan, and here the difference is reflected in the country rocks with which the veins are associated. Most of the veins of the Ouarzazate region of Morocco are found in lavas, a few occur in conglomerates while there are rare indications in granites and sandstones, the types of lithology most widespread in Sinai.

There is another difference in the mineralogy of some of the deposits. Braunite is the predominate mineral in most of the Moroccan veins and also in the deposits associated with continental formations, but it was not recognised in the Wadi el Akhdar and has not been reported from any other deposit in Sinai.

The reported presence of conglomerates above some of the ore beds of Morocco containing pebbles derived from the ore is in striking contrast to the situation in Sinai, where no conglomerates are found directly above any of the known ore occurrences.

(b) Points of similarity.

In both areas there is a generally similar succession of continental formations, principally sandstones, with intercalations of transgressive marine beds overlying an ancient basement which in the immediate areas of the manganese deposits at least is composed almost always of igneous or metamorphic rocks. Taking the regions as a whole we find that the ore deposits are not confined to one formation, or to rocks of any particular age: in Sinai and Jordan the ores occur in the basement and associated with marine transgressions of Cambrian (Wadi Dana) and Carboniferous (Om Bogma) ages, while in Morocco they also occur as veins in the basement and associated with two marine transgressions of different ages. In every case of an ore deposit associated with a marine transgression it is also true that the ore occurs in the lowest marine formation above the basement, and usually in the lowest (original) carbonate rock; it may be that the latter point is of more significance than the former. In neither region, however, is the ore confined to one particular facies; there are occurrences in continental and non-carbonate rocks in both regions.

In specific areas we find, both in Morocco and in Sinai and Jordan, that where ore deposits are present at one horizon there are usually also indications of mineralisation at other levels and in rocks of very different age in the same general area.

There is a general similarity in the mineralogy of the deposits in the two provinces, apart from the occurrence of braunite in Morocco. The manganese is always found in the oxide form, and there is no evidence whatever in either case that it was not originally deposited as the oxides. The associated gangue minerals too are similar, namely barite, dolomite, calcite and quartz. Copper and lead show a slight, and sometimes considerable, relative concentration in the ore deposits as compared with the average proportions of these elements in the crust.

Replacement phenomena have been noted wherever a dolomite or limestone host has manganese ore minerals associated with it. The general prevalence of a roof of red shale or clay separating the ore from the over-

lying dolomite should also be noted here. The frequent presence of a pink colour in dolomite close to ore deposits is another common factor; this has been noted at Bou Arfa and Imini, and at Om Bogma and in Wadi Dana.

There is a noticeable association between the distribution of ore and structural features in some of the Moroccan deposits, as there is in Sinai. This is most striking in the Bou Arfa area, but the shape and orientation of the Imini deposits is also very suggestive, especially when taken in conjunction with the strike of numerous veins of barite in the Lower Palaeozoic slates outcropping between Sainte Barbe and Bou Aggioun. There is also the fact that the subsidiary line of deposits to the south of Bou Azzar closely follows a fault, (see the map and section given by Bôuladon and Jouravsky (1952), facing p. 72).

Lastly there is the apparent association between the manganese deposits and the emplacement of basic igneous rocks. Westerveld (1951) has emphasised the proximity of these deposits in parts of Morocco, and has deduced a genetic connection between them. In western Sinai the association of the larger ore deposits with the Om Bogma dyke appears on the surface to be coincidental (Chapters 9 and 11, (i), (e)), but it might possibly have a deeper significance. Blake (1939) noted the presence of "a small extinct volcano connected with a fault of pronounced structural features" in the area of the Wadi Dana manganese deposit.

(vii) The origin of the Moroccan manganese deposits.

The theories advanced to explain the genesis of these deposits are numerous and varied, there being a tendency for most workers to support a sedimentary origin for the stratified deposits and to explain discordant features and replacement phenomena in them by subsequent solution and re-precipitation. It is not proposed to discuss the pros and cons of the various theories here, or to propose a new hypothesis, but the foregoing comparison with the deposits of the Sinai and Jordan region will have shown the close similarity of the deposits as a whole and that between corresponding individual deposits. This suggests that the possibility of a common mode of origin for deposits of like nature in both of the regions deserves careful consideration.

In particular the deposits of Imini and Om Bogma, which contained the

bulk of the ore in their respective provinces, are closely comparable from this point of view. It has already been noted that the remarkable alignment of the deposits, which is so suggestive of a structural control of deposition, is much more precise at Imini than in the Om Bogma district. If a hydrothermal origin were to be proposed for the Imini deposits this difference could be readily explained by the difference in the thickness of the sandstone between the basement and the dolomite host rocks. This sandstone is only 10 m. thick at Imini as opposed to 130 m. at Om Bogma. At Imini this lower sandstone locally rests on "Permo-Trias" basalts which overlie the basement, but for this argument the effect is virtually the same as if the sandstone were resting directly on the basement. In the Om Bogma district the hydrothermal solutions are supposed to have been confined to the fractures in the basement rocks but to have percolated through the rock on reaching the porous sandstones, spreading outwards and away from the fractures to a greater or lesser degree. By analogy the departure from the structure lines would be much less in similar circumstances at Imini.

(2) THE MANGANESE AND IRON ORE DEPOSITS OF POSTMASBURG, UNION OFSOUTH AFRICA.

These deposits outcrop in and around the Gamagara Hills, in northern Cape Province. The geological succession is as follows (Boardman, 1952):

Quartzites	}	Gamagara Series - Matsap System
Shales		
Conglomerates		

Erosion and strong unconformity

330 m.	Various Upper Griquatown beds	}	Transvaal
1000 m.	Andesitic lavas - Middle Griquatown		
	Thin tillite bed		
660 m.	Banded ironstones and jaspers	} Lower Griquatown	System
1300 m.	Dolomite Series		

The erosion of the Transvaal System along a N. - S. anticline in the area north of Postmasburg exposed large areas of the Dolomite Series before the deposition of the Gamagara strata. A zone of overthrusting extends north and south through Postmasburg and along the Gamagara Hills. The lowest thrust fault in particular has resulted in the formation of thick and variable breccias where dolomite forms the sole of the thrust. Two distinct types of breccia are present. The lower of these, known as the "manganese marker", is in contact with the dolomite and consists of a leached and silicified thrust fault gouge with pockets of high grade and siliceous manganese ores. The higher breccia phase, called the "Blinkklip breccia" is composed of brecciated Lower Griquatown banded ironstones. Subsurface solution of the dolomite floor has resulted in the slumping of large masses of the breccias, tongues of manganese ore descending into the dolomite in many places. Huge masses of haematite, forming high grade iron ore also occur associated with the thrust zone, as replacements of the lenses of basal conglomerates and the shales of the Gamagara Series, or replacing the "Blinkklip breccia". The reserves of these iron ores are estimated at 1000 million tons (Boardman, *ibid.*).

The ores outcrop in an almost continuous line along the Gamagara Hills from Beeshoek, near Postmasburg, to Sishen, about 60 kms. to the north. Beyond Sishen the zone of overthrusting is hidden by superficial

deposits, but the mineral deposits appear to continue, as there is another outcrop of iron and manganese ores at Black Rock, 112 kms. north of Sishen. To the south of Beeshoek the ground is rather better exposed, but only an isolated outcrop of iron ore at Koedoeskloof, 88 kms. from Postmasburg, is reported. To the west, at Aucampsrust and Kameelhoek the ore zone is brought up in an anticline within a tectonic window, while to the east, particularly in the Klipfontein or Breccia Hills, there are several erosional remnants of the sheet-like ore zone.

The manganese ore is massive and hard, composed essentially of pyrolusite, manganite and bixbyite, with wad, rhodonite, barite, diaspore, lithiophorite and opaline silica.

Du Toit (1933 & 1954) interpreted the manganese ores as hypogene replacements of chert, breccia, conglomerate or shale by waters bringing up manganese and iron through solution of the supporting dolomite (cf. Ball's hypothesis on the origin of the Om Bogma ores, Chapter 11, (i), (b)). The Dolomite Series of the Transvaal System commonly carries small proportions of manganeous carbonate, and weathering of the rock in various places has led to the formation of manganiferous earth or to the production of lateritic manganese ores (Du Toit, 1954).

Boardman (ibid) noted a tendency for the Gamagara shales to become impregnated with, or altered to, manganese ore where they are in contact with dolomite, and to form iron ore bodies where they overlie or have been infolded into the banded ironstones. He confirmed the hypothesis of metasomatic replacement and enrichment for the origin of the iron ores, but he could see no sign of an abstraction of iron from the banded ironstones and so concluded that iron was introduced from an outside source. He suggested this might have been derived from iron-bearing rocks in the region (including the Dolomite Series) by weathering in the period following the post-Matsap orogeny. In particular he stressed the intense oxidation which accompanied the mineralising processes.

This mechanism is not altogether satisfactory since it appears to require solution of the metals at the surface, where they were partly in the form of carbonate and therefore in the reduced state, followed by transport underground and eventual deposition in strongly oxidising conditions below a shale formation which is supposed to have formed a "trap".

Strauss (1952) disputed the above interpretation of the structure, preferring to regard the so-called thrusts as normal faults with post-humous movement in the reverse direction. He regarded the ore-bodies as secondarily enriched deposits formed by the removal of silica and alumina from originally iron-rich sediments.

Du Toit's hypothesis of concentration by hydrothermal agencies is preferable for both iron and manganese, but it seems likely from a brief consideration of the enormous quantities of ore present that part at least of these metals may have formed an integral part of the original hydrothermal solutions. These deposits would thus become directly comparable, from a genetic point of view, with those of Om Bogma.

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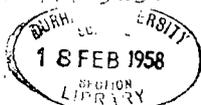
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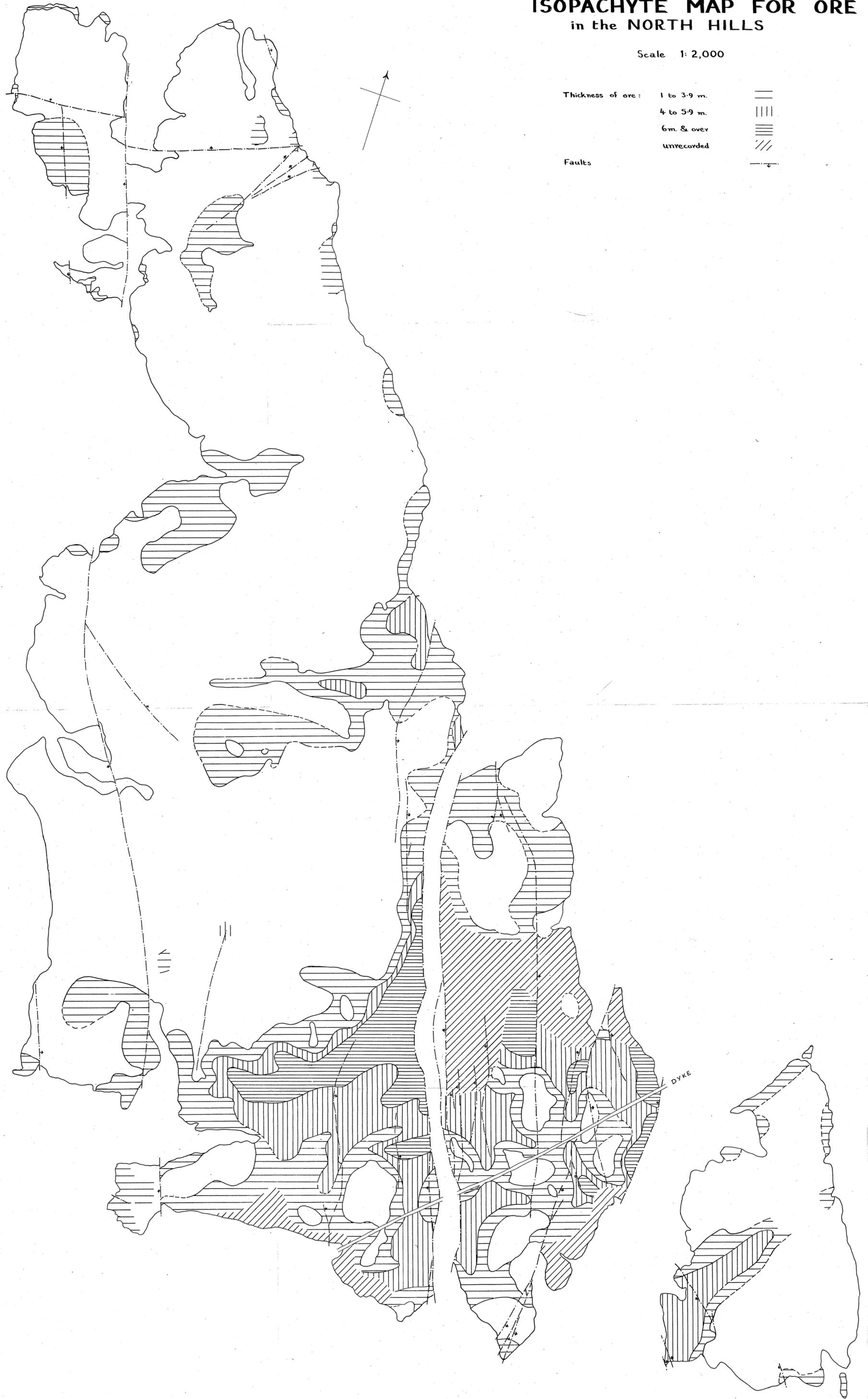
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ISOPACHYTE MAP FOR ORE in the NORTH HILLS

Scale 1: 2,000

- Thickness of ore:
- 1 to 3.9 m. 
 - 4 to 5.9 m. 
 - 6 m. & over 
 - unrecorded 
- Faults 





**PAVEMENT CONTOUR MAP for part of
the NORTH HILLS**

Scale 1:2,000

- Contours on the Sandstone Pavement, numbered in metres above sea level — 627 —
- Outcrop of the Sandstone Pavement
- Faults ———|———
- Principal development headings DR 34

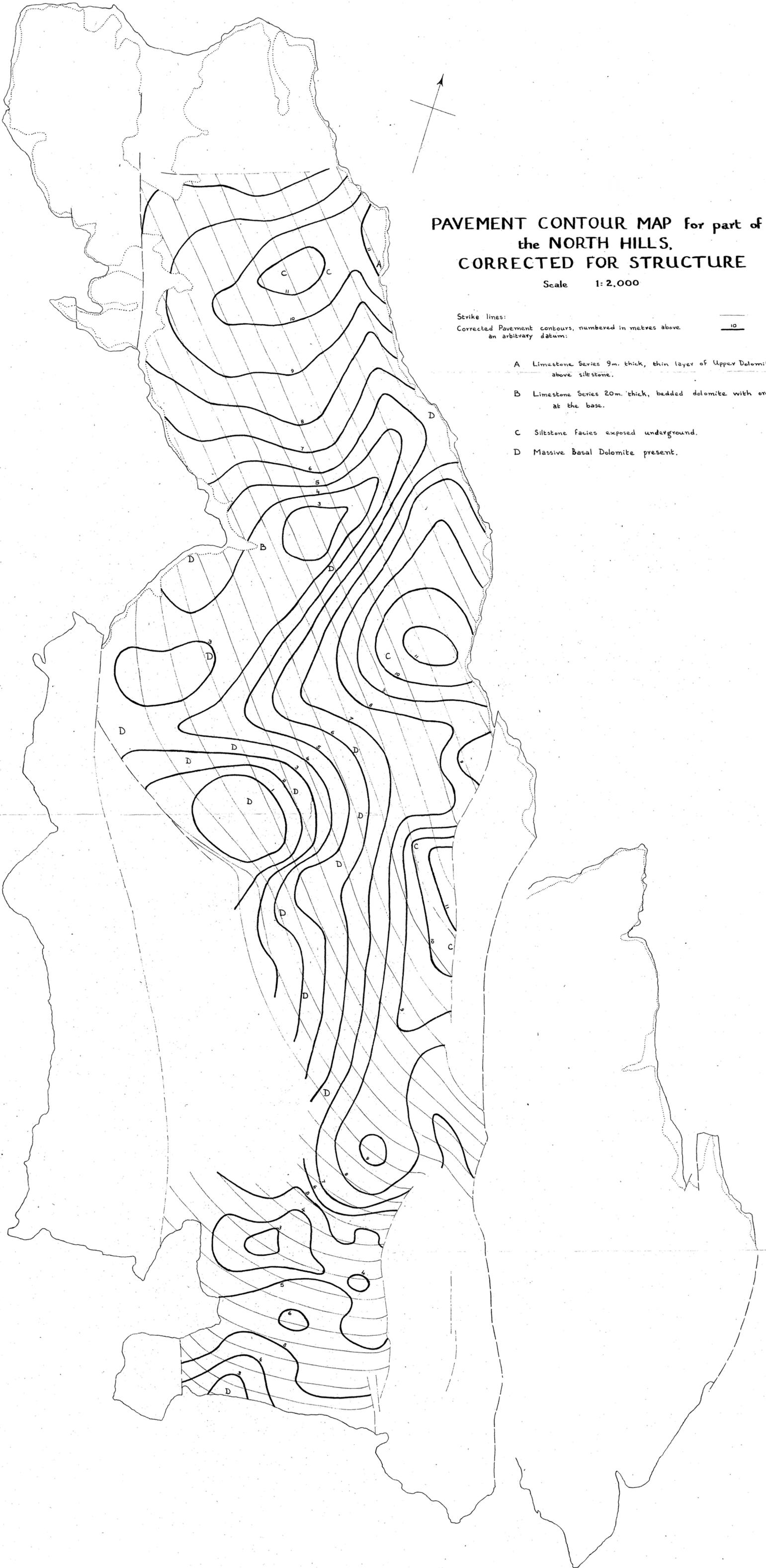
PAVEMENT CONTOUR MAP for part of the NORTH HILLS. CORRECTED FOR STRUCTURE

Scale 1:2,000

Strike lines:
Corrected Pavement contours, numbered in metres above
an arbitrary datum:



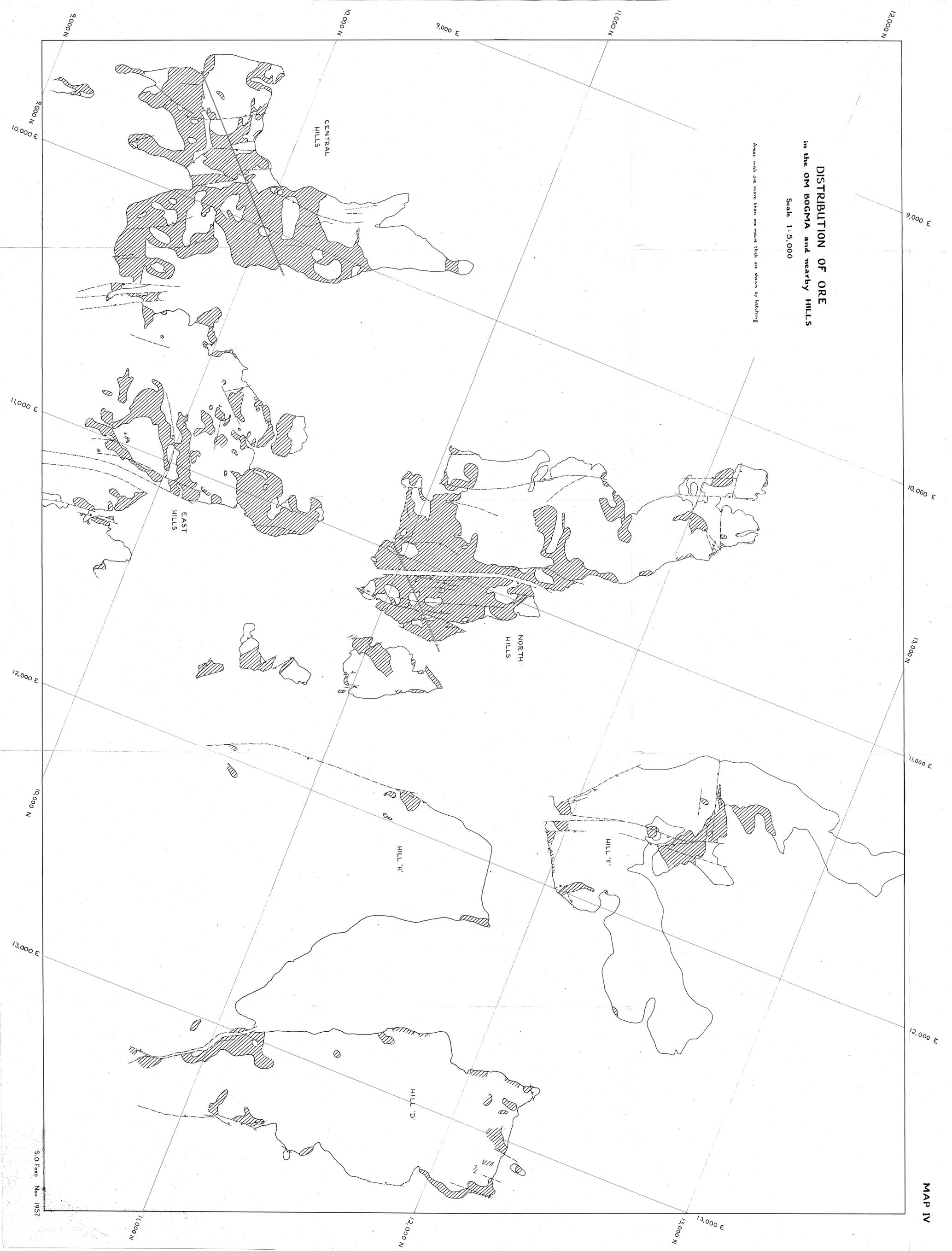
- A Limestone Series 9m. thick, thin layer of Upper Dolomite above siltstone.
- B Limestone Series 20m. thick, bedded dolomite with ore at the base.
- C Siltstone facies exposed underground.
- D Massive Basal Dolomite present.



DISTRIBUTION OF ORE
in the OM BOGMA and nearby HILLS

Scale 1:5,000

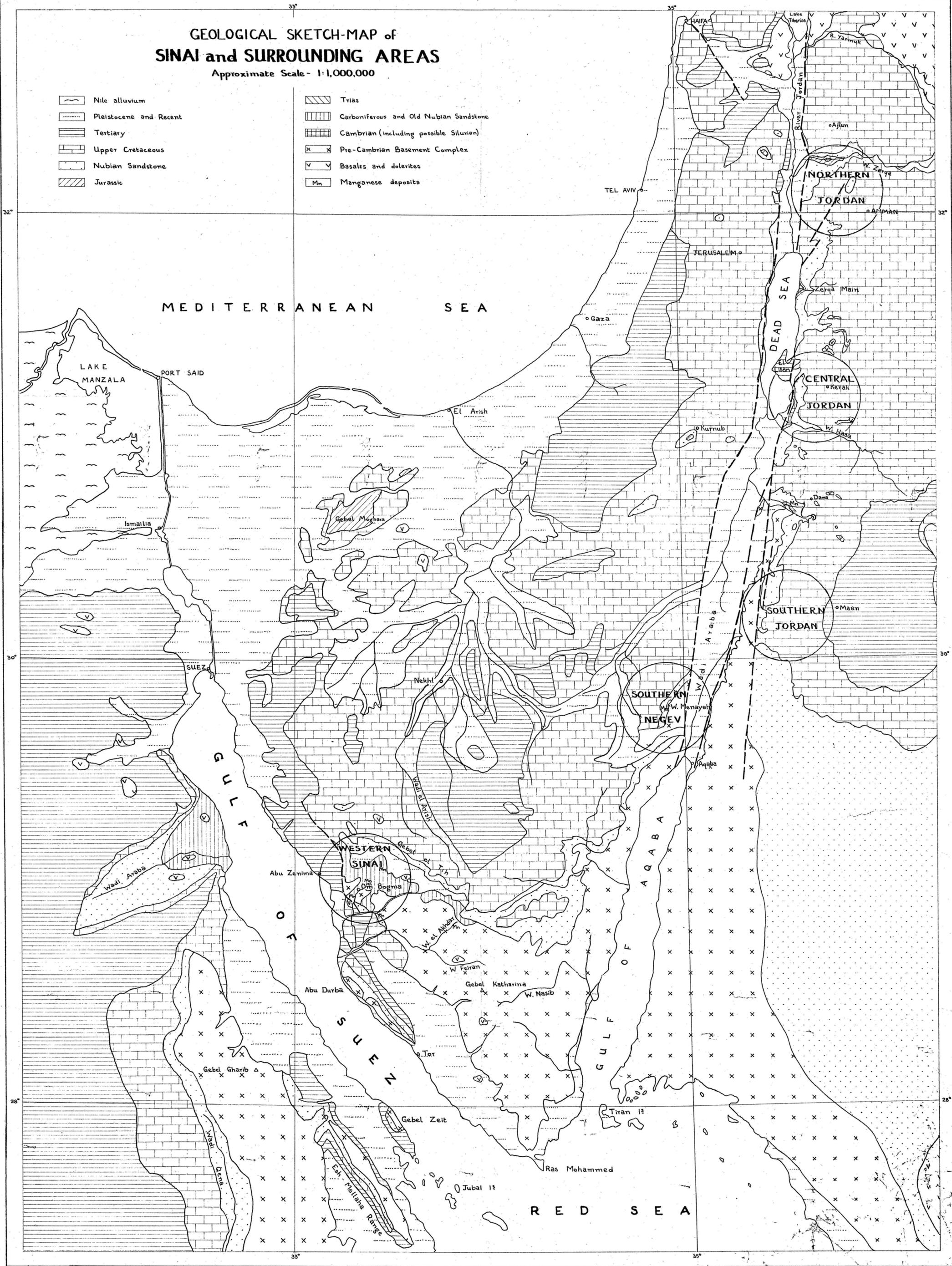
Areas with ore more than one metre thick are shown by hatching.



GEOLOGICAL SKETCH-MAP of SINAI and SURROUNDING AREAS

Approximate Scale - 1:1,000,000

- | | | | |
|--|------------------------|--|--|
| | Nile alluvium | | Trias |
| | Pleistocene and Recent | | Carboniferous and Old Nubian Sandstone |
| | Tertiary | | Cambrian (including possible Silurian) |
| | Upper Cretaceous | | Pre-Cambrian Basement Complex |
| | Nubian Sandstone | | Basalts and dolerites |
| | Jurassic | | Manganese deposits |



Based on Hume, Blake & Little.

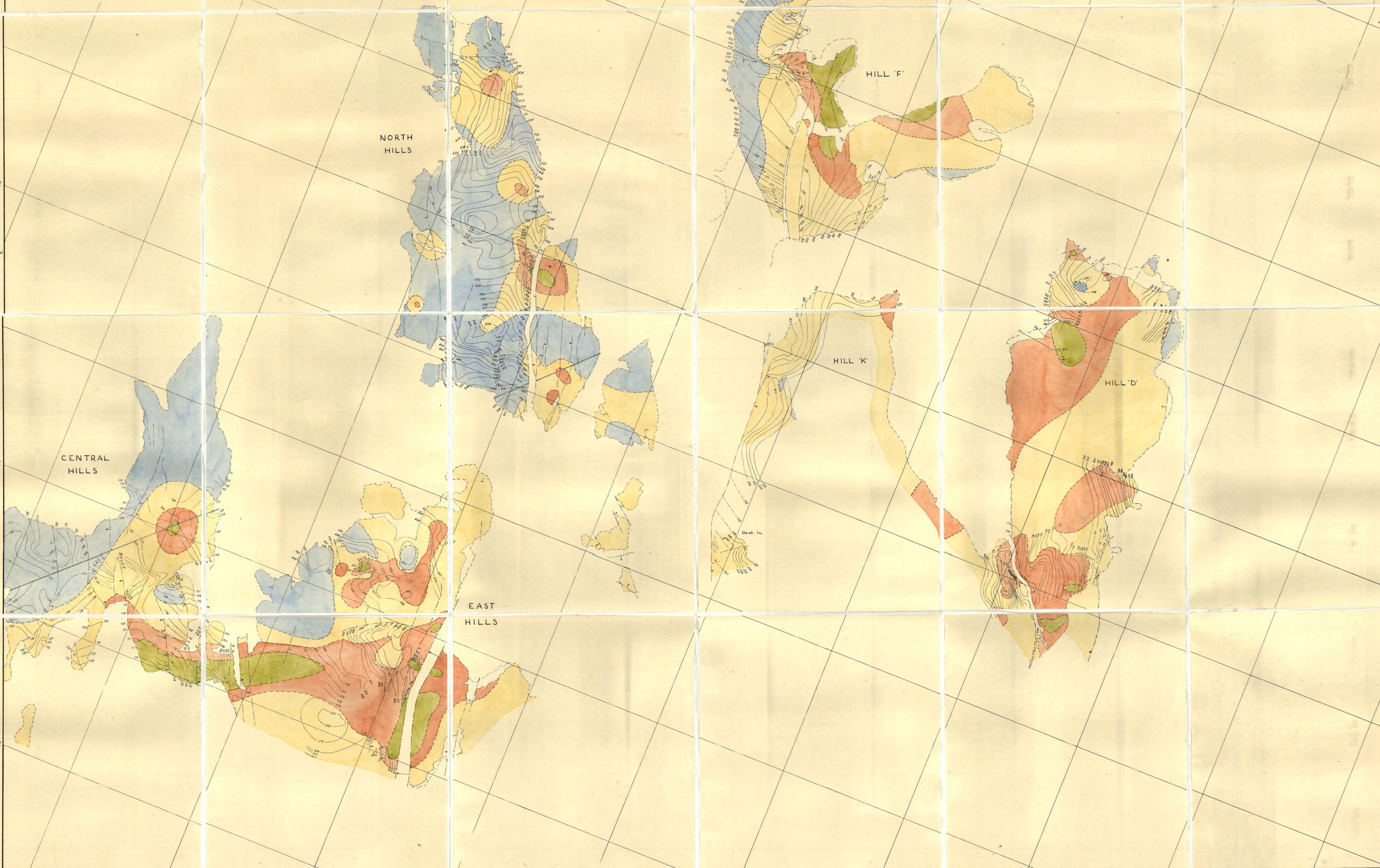
LITHOFACIES MAP
of the OM BOGMA and nearby HILLS
with CONTOURS on the SS' F. PAVEMENT
Scale 1:5000

Approximate thickness and facies of the Carboniferous Limestone Series:

More than 15 m., massive basal dolomite typically developed	Blue
8-15 m., shaly bedded limestone or lenticular dolomite	Yellow
0-8 m., shale and siltstone facies	Red
Upper Sandstone resting directly on the Sandstone Pavement	Green

Pavement contours, in metres above sea level

-72-



GEOLOGY OF OM BOGMA, WESTERN SINAI

HORIZONTAL & VERTICAL SCALE 1:12,500
VERTICAL INTERVAL 50 Metres.

