J. Coll. Sci., Univ. Riyadh. Vol. 11, pp. 171-188 (1980)

The Opaque Minerals of the Jabal Sha' Layered Intrusion, Saudi Arabia

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The opaque minerals in the Jabal Sha' intrusion, Saudi Arabia consist of intercumulus magnetite, ilmenite, pyrrhotite and minor pentlandite and chalcopyrite. Electron microprobe analyses and measurements of reflectivity were used to study the chemical and physical variations from the bottom to the top of the exposed section of the intrusion. The equilibration temperatures and oxygen fugacity were determined from the electron microprobe analyses of the coexisting oxides. The Jabal Sha' oxides last equilibrated at temperatures 150° to 250° below those for the Skaergaard intrusion but with higher oxygen fugacity.

The Jabal Sha', a layered gabbro intrusion, is located in the Khybar area, (42° 53' long. and 18° 45' lat.,) within the northern edge of the high Asir Province mountains, just South of the Khybar village, in South Western Saudi Arabia (Fig. 1) (Almohandis 1974, Coleman *et al.*, 1977).

The Jabal Sha intrusion consists mainly of plagioclase-augite-olivine mesocumulates, plagioclase-augite mesocumulates and a noritic-ferrodiorite. The opaque minerals; magnetite, ilmenite, pyrrhotite with minor pentlandite and chalcopyrite make up to about 6 percent of the rocks, and may be as low as 0.5 percent in some rocks. They are considered to be chiefly of primary origin, although secondary magnetite occurs as an alteration product of ferromagnesian minerals, especially olivine. The opaque minerals occur as anhedral grains and small droplets between the pre-existing cumulus silicate minerals.

The object of the present paper is to investigate the textural relationships of the opaque phases by polished sections and also to apply the method of Buddington and Lindsley (1964) to estimate the temperature and oxygen fagacity when the oxides last equilibrated from the Jabal Sha‘ rocks.

Electron microprobe analyses and measurements of reflectivity were made of 11 samples which were used to investigate the change in composition of the opaque phases from the bottom to the top of the exposed section of the intrusion.

The Opaque Phases

The opaque phases of the Jabal Sha‘ intrusion include magnetite, ilmenite, and sulphides which are represented by pyrrhotite and minor pentlandite and chalcopyrite.

Magnetite is more abundant towards the bottom of intrusion and it is absent in some rocks towards the top of the intrusion. The amount of sulphides increases towards the top of the intrusion.

Most pentlandite $(Ni, Fe)_9 S_8$ is altered and replaced probably by bravoite, which has less reflectance and less nickel content. No electron probe analysis was made of this mineral due to alteration and the poor polished surfaces.

Chalcopyrite ($CuFeS_2$) was found in three polished sections as very small blebs and exsolution lamellae in the pyrrhotite.

Textures of the opaque minerals

The magnetite occurs as anhedral grains moulded on the pre-existing cumulus silicate phases. It has generally fine and coarse exsolution lamellae and blebs of ilmenite. The width of such lamellae ranges from a few microns to 0.2 mm. These exsolution lamellae are almost parallel to the octahedral planes (111) (Plate 1). Magnetite sometimes shows partial or complete martitization. Ilmenite also occurs as individual anhedral grains and as minute blades, possibly of exsolution origin (Plate 2). However, some ilmenite is intergrown with magnetite; the latter can be identified within ilmenite.

Some extremely fine lamellae (probably ulvöspinel) were found in some magnetites, but no further identification of this phase was made.

Hematite has been identified in one specimen, where it develops within the magnetite along octahedral cleavage planes and at the margins due to incipient weathering.

Symplectic texture (Plate 3) is not uncommon. It shows irregular grains of magnetite and ilmenite enclosed by discrete grains of both minerals together with sulphides.

Most of the sulphides have rounded form as droplets (Plate 4) and this suggests an immiscible origin of the sulphide liquid. However, some of the sulphides have an irregular shape as discrete grains (Plate 5). Small oval grains of pentlandite can be observed between discrete grains of pyrrhotite.

Fine exsolution lamellae of pentlandite inside pyrrhotite are not uncommon, while very small blebs and lamellae of chalcopyrite inside pyrrhotite can be observed.

The average grain size of the oxides is variable and ranges from minute grains (0.1 mm) to large discrete grains (2.5 mm). The average grain size of the sulphides ranges from 0.1 mm to over 1.6 mm.

Reflectivity measurements

The measurement of reflectivity of the opaque minerals is of great importance not only for mineral determination but also for study the variation in composition and zonal structures.

Reflectivity measurements of the opaque minerals were carried out using a Zeiss microscope with an attached Photomultiplier and galvanometer. The theory and practice of such measurements have been discussed by Bowie (1967), Bowie and Taylor (1958), Cameron (1961) and many others.

All the reflectivity measurements were made using a white light source, using silicon carbide (SiC) as a reflectivity standard. The standard was used to check accurately the validity of the reflectivity measurements. Five to six measurements were made for each mineral on each of polished sections to get the maximum and minimum reflectivity of the minerals.

The results of reflectivity measurements are summarized diagramatically in Fig. 2, 3 and 4.

The range of reflectivity in magnetite is fairly constant but slightly wider towards the bottom of the intrusion probably due to compositional variations in the magnetite near the bottom or due to the variable amount of TiO_2 in the magnetite near the bottom of intrusion. It is also of interest to note that there is a general trend towards increasing the minimum reflectivities for the magnetites towards the top of the intrusion.

The range of reflectivity in ilmenite is variable from section to section, but it seems that the range is very slightly wider towards the bottom of the intrusion. The range of reflectivity in pyrrhotite is also variable from section to section, but it is clear that the range towards the bottom of intrusion is wider. The reflectivity of pyrrhotite is much greater than magnetite or ilmenite.

X-ray examination

Powders of the strongly magnetic fraction of three rock specimens (NSH_{10}, NSH_7 and NSH_5) were used for X-ray identification of the Fe-Ti oxides. Cok_{α} - iron filtered radiation at 22kV and 20 ma settings were used on Philips high angle X-ray diffractometer. Relatively sharp peaks were obtained for ilmenite, while magnetite gave broad peaks, probably due to the compositional variations within each sample.

The X-ray data indicate that the unmixing phenomenon between magnetite and ilmenite is common towards the top area of the intrusion. This phenomenon is represented by the fine exsolution lamellae of ilmenite inside magnetite.

Chemistry of the Opaque Minerals

Analyses of the Jabal Sha' oxides and sulphides were carried out using a Cambridge Geoscan II microprobe, at 2.4×10^{-8} A beam current, using a beam width of about 3 micron in diameter. Accelerating potential was fixed at 15 kV. About 3-5 counting intervals of 20 seconds duration were made at each spot. Raw count data were corrected for drift, background, fluorescence, absorption, dead time and atomic number effects using the Fortran IV computer program of EMPADR VII, written by Rucklidge and Gaspirini (1969). The standards and minerals for analyses were previously carbon-coated. Standards used were natural minerals and pure metals.

Four polished sections representing the top and bottom area of the Jabal Sha' intrusion were selected (Sample No. NSH_3, NSH_{10}, ESHL and NSH_2). Six discrete magnetite grains and seven discrete ilmenite grains were analysed for six elements. The results of electron probe microanalyses are presented in Tables 2 and 3 together with the recalculated analyses, corrected after Carmichael (1967). The recalculated analyses were done by a computer program written by Dr. J. Ludden.

Table 1 shows the magnetite analyses recalculated on the ilmenite and ulvospinel basis together with the end member compositions, while Table 2 shows the ilmenite analyses recalculated on the ilmenite basis with the end member compositions.

Magnetite

FeO in magnetites shows no definite trend with the structural height of the intrusion. MnO and Al_2O_3 show an increase towards the top of intrusion. TiO_2 shows various concentrations, from 0.2 percent to over 5 percent which is probably due to the fine exsolution lamellae of ilmenite within the magnetite grains. MgO is undetected in most analyses, except in one case, where it reached 0.6 percent due to the fine exsolution lamellae of ilmenite within the magnetite grains. Cr_2O_3 is almost constant (about 0.1 percent) in most of the analyses except in two samples where it reached about 0.6 percent.

Ilmenite

FeO, MnO, Cr_2O_3 and Al_2O_3 in ilmenite increases generally towards the top area of the intrusion. However, TiO_2 and MgO show no definite trend with the structural height of the intrusion.

Sulphides

The sulphides (pyrrhotite) in two specimens (NSH_{10} and NSH_3) from the bottom and the top area of the Jabal Sha' intrusion were analysed for six elements.

The result of the analyses is presented in Table 3.

The analyses of pyrrhotite shows that it consists mainly of Fe and S. The proportions of the two major elements do not give the stoichiometric formula (FeS), but there is a deficiency of Fe, such that the formula can be written ($Fe_{1-x}S$). The amount of nickel and copper increases slightly towards the top area of the intrusion, although the amount of Co and Mn increases towards the bottom of the intrusion.

Equilibration Conditions

The equilibrium temperature and the oxygen fugacity have been calculated according to Buddington and Lindsley (1964) diagrams. The data are presented graphically in Fig. 5, together with data from Skaergaard intrusion (Buddington and Lindsley 1964).

The Jabal Sha' oxides appear to be equilibrated under higher oxygen fugacity and temperatures 150° to 250° lower than the Skaergaard oxides. This conclusion is compatible with the fact that the high water content in the Jabal Sha' magma probably promotes the equilibration at lower temperatures and exerts higher F_{O_2} than a relatively anhydrous Skaergaard magma.

Buddington and Lindsley (1964) have also shown that there is a correlation between the temperature and distribution of MnO between coexisting magnetite and ilmenite. They showed that this distribution may be a function of equilibrium temperature. The MnO% in magnetite and that for ilmenite are plotted against each other in Fig. 6. It is clear according to this figure that the Jabal Sha' oxide lie within the field of acid plutonics, similar to that of the upper layered series, Kap Edvard Holm, East Greenland (Elsdon 1972). This is because the temperatures of equilibrium are probably near to liquidus temperatures for water saturated acid plutonics. The equilibration temperatures of the Jabal Sha' oxides are close to 630°C.

Discussion

The opaque minerals of the Jabal Sha' intrusion crystallized mainly as intercumulus phases within the silicate minerals. The crystalization of such minerals was due to the concentration of Fe^{3+}, Fe^{2+}, Ti, S and Ni and Cu in the magma.

The high amount of magnetite at the bottom of intrusion indicates a high P_{O_2} during the emplacement of the Jabal Sha' intrusion. However, the increase of ilmenite towards the top area of intrusion is due in part to the late crystallization of ilmenite from basaltic magmas generally.

The decrease in the amount of sulphides towards the bottom of the intrusion, probably suggests that the sulphides were not present in the magma at an early stage of differentiation as solid particles or because of the increasing of the partial pressure of oxygen (P_{O_2}) which decreases the content of sulphur (Skinner and Peck 1969). However, P_{S_2} increases towards the top of the intrusion giving sulphides mainly as droplets. The form and dominating phase of pyrrhotite as the major sulphide in the Jabal Sha' rocks suggest that it crystallized from an immiscible sulphide liquid consisting mainly of iron sulphide with small amount of nickel sulphide and very small amounts of copper sulphide, oxides and silicates.

The formation of ilmenite lamellae in magnetite is an oxidation process involving the oxidation of magnetite/ulvospinel solid solution to form magnetite (solid solution) and ilmenite (solid solution):

$3\ Fe_2TiO_4 + O \rightarrow 3FeTiO_3 + Fe_3O_4$ (see Buddington and Lindsley, 1964).

The oxidation exsolution of ilmenite from the Jabal Sha' magnetite may be due to (Anderson 1968):

(a) excess oxygen contained in titaniferous magnetite.
(b) trapped oxidising agents.
(c) hydrogen loss from trapped water.
(d) introduction of an external oxidising agent.

Electron-probe determinations of coexisting oxide compositions indicates that equilibration in the Jabal Sha' oxides occurred at temperatures 150° to 250° below those for the Skaergaard intrusion and at a higher oxygen fugacity.

Acknowledgements: I am indebted to Dr. A. C. Dunham for discussion and encouragement and to Mr. F. C. F. Wilkinson for driving lessons on the electron probe microanalyzer.

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Table 1. The Jabal Sha' Intrusion

Microprobe analyses of magnetite						
	NSH_3		NSH_{10}		ESHL	NSH_2
FeO	90.830	90.480	89.620	89.540	92.900	84.830
MnO	0.140	0.060	0.080	0.030	0.110	0.950
TiO_2	0.460	0.660	4.730	3.850	0.210	5.220
MgO	0.000	0.000	0.000	0.000	0.000	0.590
Cr_2O_3	0.110	0.100	0.110	0.100	0.550	0.310
Al_2O_3	0.510	1.360	0.580	0.330	1.200	2.340
Total	92.350	92.660	95.120	93.850	93.97	94.240
Corrected analyses (after Carmichael 1967)						
Ilmenite Basis						
Fe_2O_3	66.59	65.89	62.96	63.59	68.58	59.53
FeO	30.91	31.18	32.96	32.32	31.19	31.26
Total	99.02	99.26	101.42	100.22	100.64	100.20
End Member Compositions						
Mol.% TiO_2	1.10	0.95	5.44	5.35	0.30	7.05
Mol.% Fe_2O_3	48.90	49.05	43.56	44.65	49.70	42.95
Mol.% FeO	50.00	50.00	50.00	50.00	50.00	50.00
Ulvospinel Basis						
Fe_2O_3	66.08	65.46	59.81	61.02	68.44	56.05
FeO	31.36	31.58	35.79	34.63	31.31	34.39
Total	98.97	99.21	101.11	99.96	100.62	99.85
%Usp	2.22	1.91	13.45	11.10	0.60	14.80
End Member Compositions						
Mol.% TiO_2	1.10	0.95	6.30	5.26	0.30	6.89
Mol.% Fe_2O_3	48.36	48.58	40.55	42.12	49.55	39.66
Mol.% FeO	50.55	50.47	53.15	52.63	50.15	53.44

Table 2. The Jabal Sha' intrusion

Microprobe analysis of Ilmenite							
	NSH_3			NSH_{10}	ESHL	NSH_2	
FeO	44.720	44.200	44.300	44.370	46.050	46.500	46.200
MnO	1.790	0.870	0.830	1.760	0.840	1.820	1.800
TiO_2	51.830	52.670	52.920	52.300	52.070	51.060	51.920
MgO	1.230	1.600	2.020	0.650	1.040	0.410	0.340
Cr_2O_3	0.040	0.130	0.070	0.010	0.030	0.060	0.040
Al_2O_3	0.020	0.100	0.110	0.010	0.050	0.020	0.060
Total	99.630	99.57	100.25	99.19	100.070	99.87	100.36
Corrected analyses (after Carmichael, 1967)							
Ilmenite Basis							
Fe_2O_3	2.35	0.63	1.28	0.31	1.24	3.51	2.16
FeO	42.60	43.63	43.15	44.09	44.93	43.34	44.26
Total	99.86	99.63	100.38	99.12	99.90	100.22	100.58
% R_2O_3	2.29	0.87	1.42	0.31	2.01	3.41	2.16
End Member Compositions							
Mol.% TiO_2	49.42	49.78	49.64	49.92	49.49	49.13	49.45
Mol.% Fe_2O_3	1.16	0.44	0.72	0.16	1.02	1.73	1.09
Mol.% FeO	49.42	49.78	49.64	49.92	49.49	49.13	49.45

Key to samples

NSH_3 — Plagioclase-olivine-augite mesocumulate, about 1440 m from the bottom of intrusion.

NSH_{10} — Plagioclase-augite-olivine mesocumulate, about 143 m from the bottom of intrusion.

ESHL — Plagioclase-2 Pyroxenes — olivine mesocumulate, about 70 m from the bottom of intrusion.

NSH_2 — Plagioclase-augite-olivine mesocumulate, about 1716 m from the bottom of intrusion.

Table 3. Pyrrhotite Compositions

Microprobe analyses					
Rock No.	**NSH_{10}**		**NSH_3**		
	1	**2**	**1**	**2**	**3**
Spot analysed					
Fe	61.15	60.79	62.31	62.25	61.16
Mn	0.05	0.05	0.01	0.04	0.02
S	38.72	39.44	37.67	37.88	38.05
Ni	0.05	0.10	0.32	0.26	0.46
Cu	0.16	0.07	0.01	0.10	0.23
Co	0.40	0.61	0.15	0.17	0.21
Total	100.53	101.07	100.48	100.70	100.12
Molecular Proportions (Cations Per 1S)					
Fe	1.095	1.089	1.116	1.115	1.095
Mn	0.001	0.001	0.000	0.001	0.000
S	1.208	1.230	1.175	1.181	1.187
Ni	0.001	0.002	0.005	0.004	0.008
Cu	0.002	0.001	0.000	0.002	0.004
Co	0.007	0.010	0.003	0.003	0.004

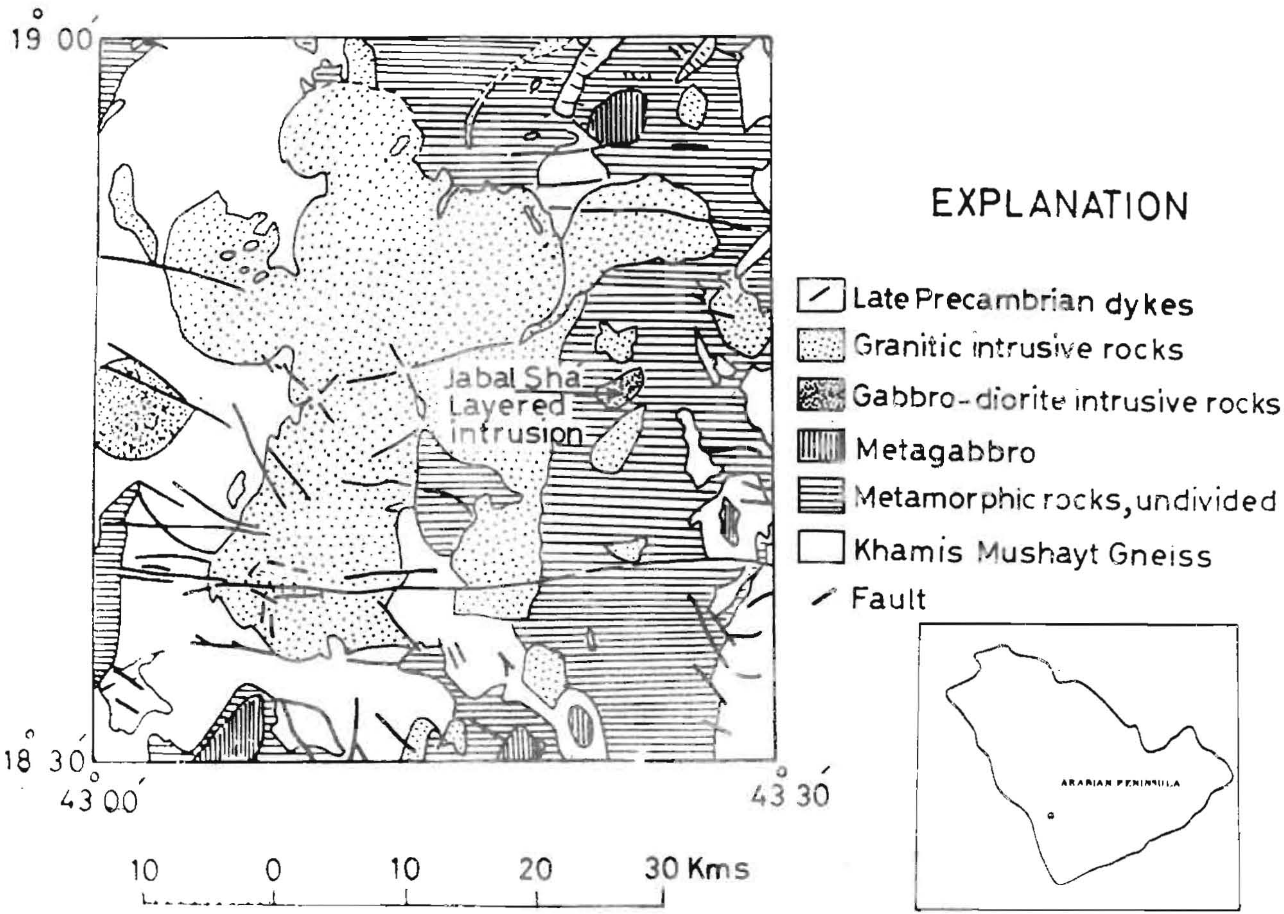

Fig. 1. Generalized geological map of the Khybar area showing the Jabal Sha' layered intrusion (modified after Coleman *et al.* 1977).

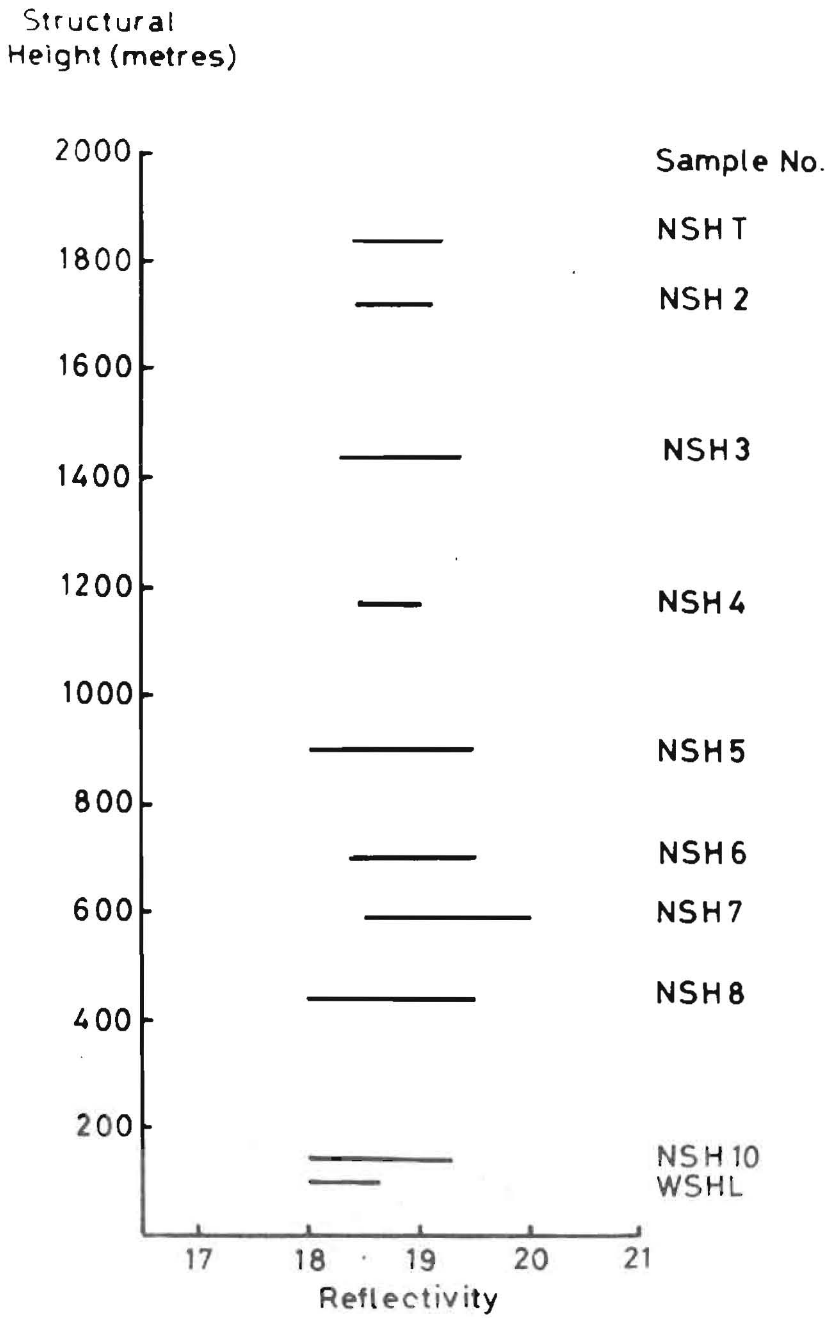

Fig.2. Variation of reflectivity in magnetite with the structural height of the instrusion.

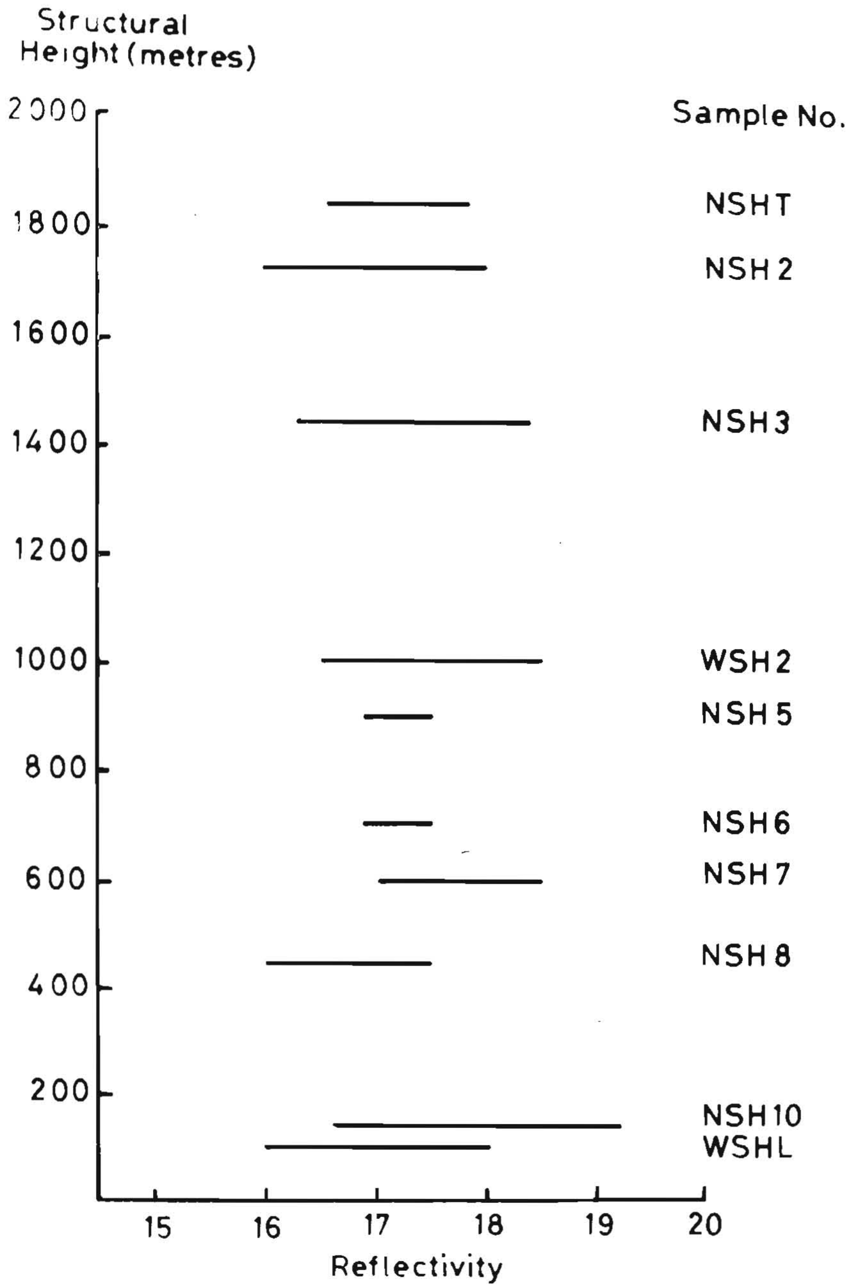

Fig. 3. Variation of reflectivity in ilmenite with the structural height of the intrusion.

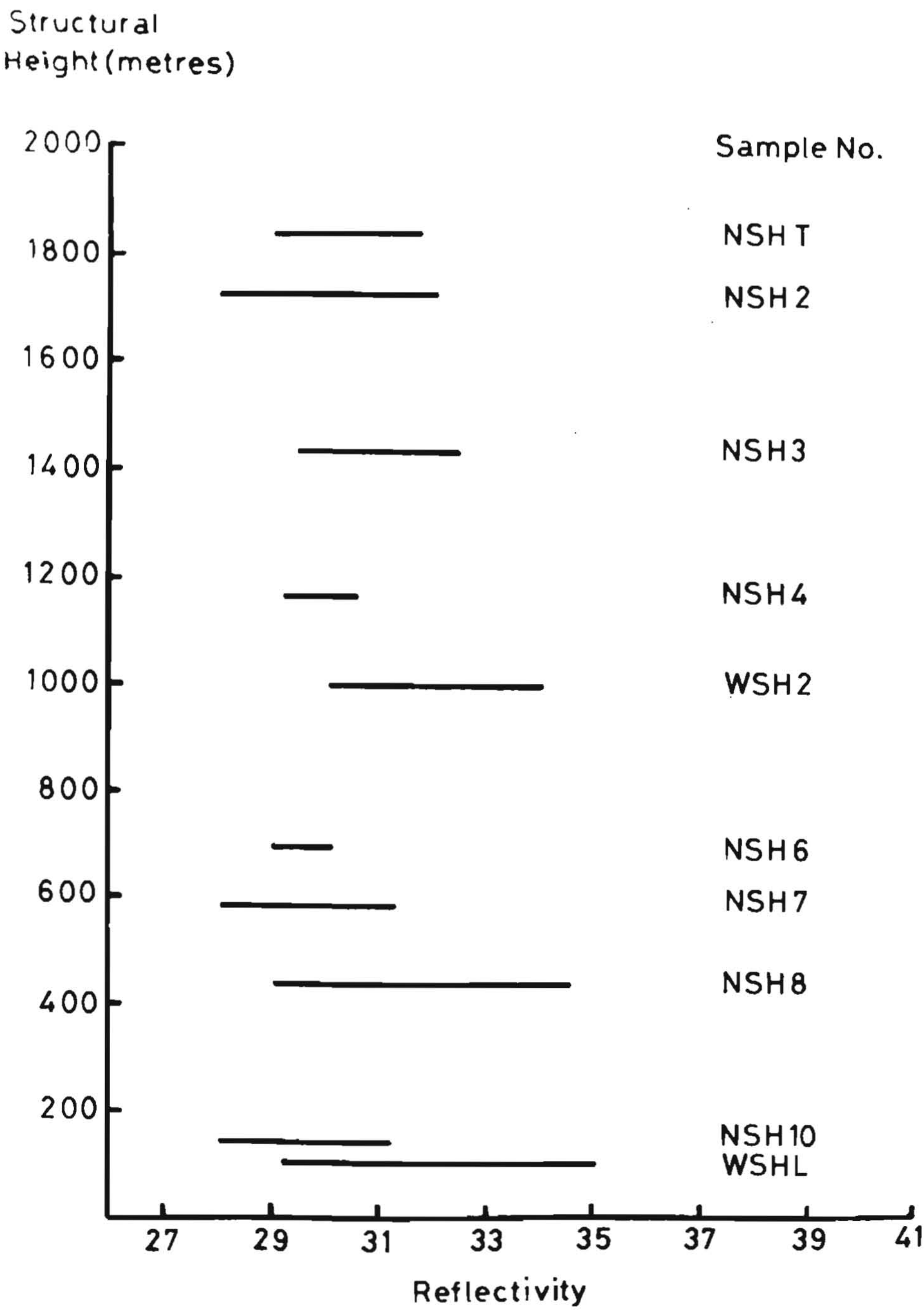

Fig. 4. Variation of reflectivity in Pyrrhotite with the structural height of the intrusion.

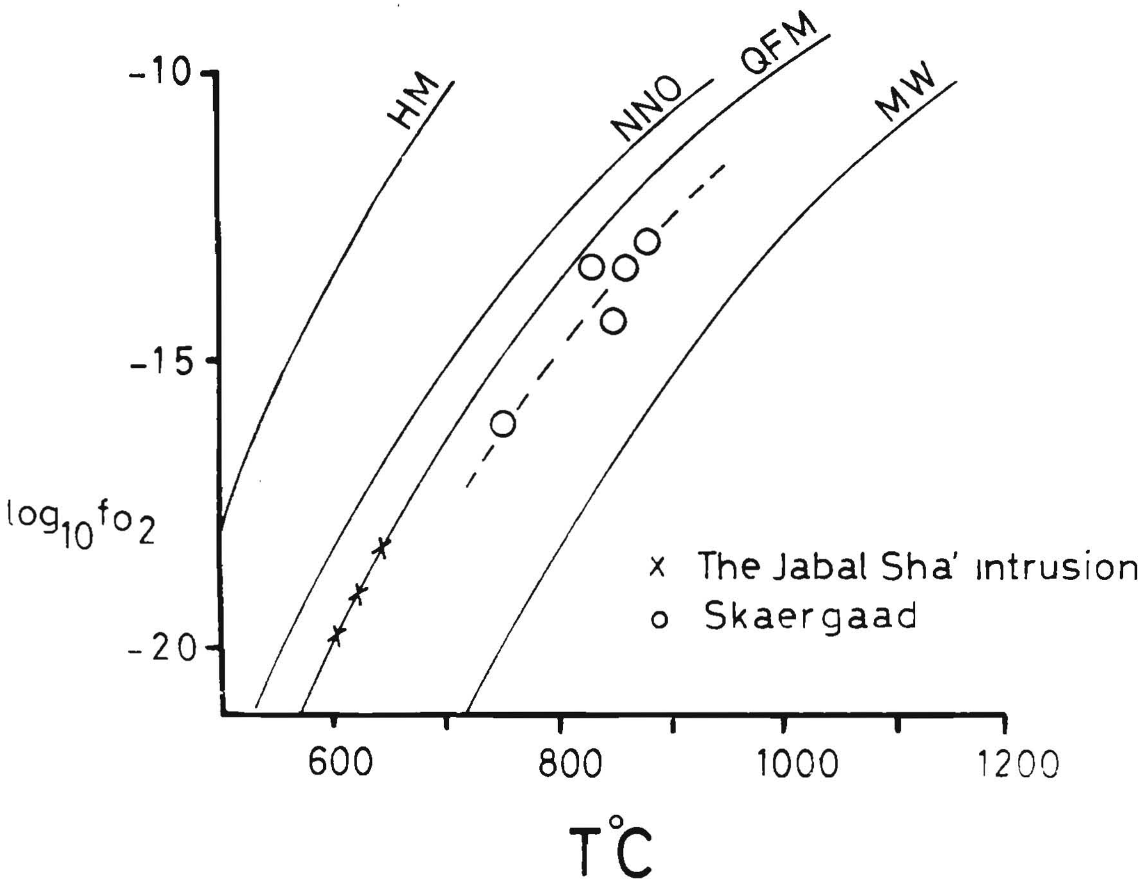

Fig. 5. $T\text{-}F_{O_2}$ relationships of the Jabal Sha' Fe-Ti oxides, compared with data from the Skaergaard intrusion (Buddington and Lindsley 1964). Full curves indicate buffer assemblages; NNO, nickel-nickel oxide; QFM, quartz-fayalite magnetite, MW, magnetite-wustite; HM hematite-megnetite.

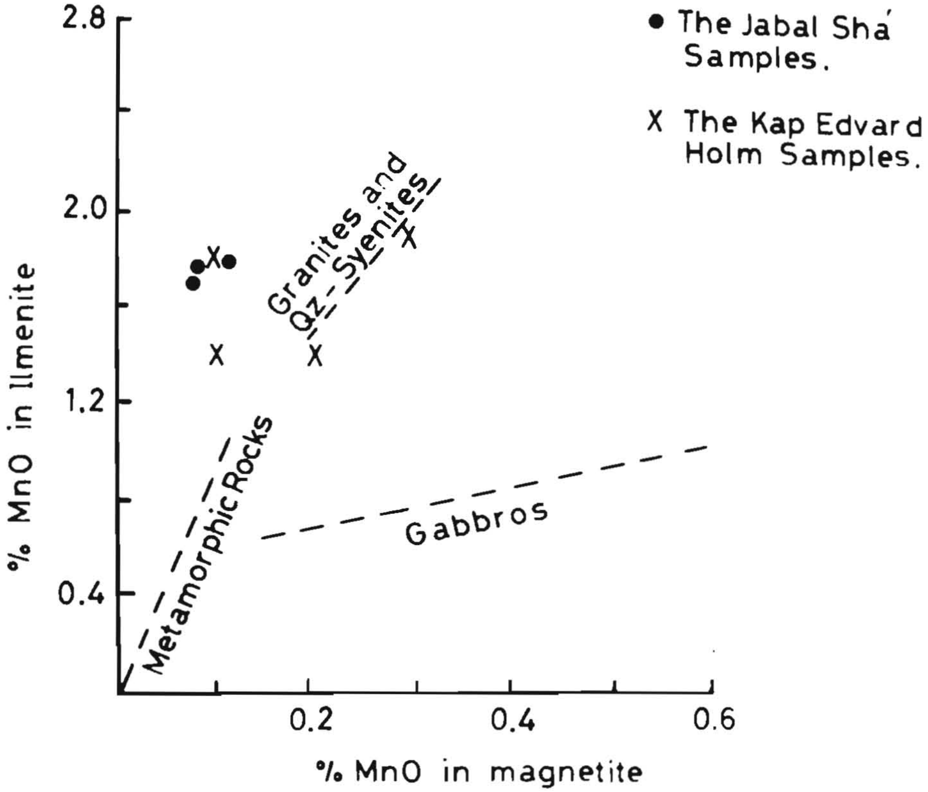

Fig. 6. Plot of % MnO in magnetite against % MnO in ilmenite. Dashed curves indicate trends for mafic and salic igneous assemblages and metamorphic assemblages (Buddington and Lindsley 1964).

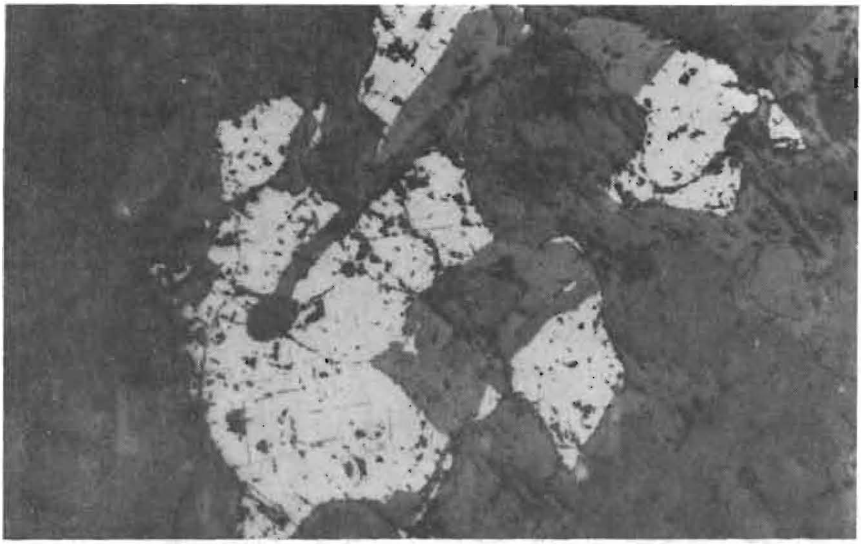

Plate 1. WSHL — Photomicrograph showing exsolution lamellae of ilmenite in magnetite. X 32.

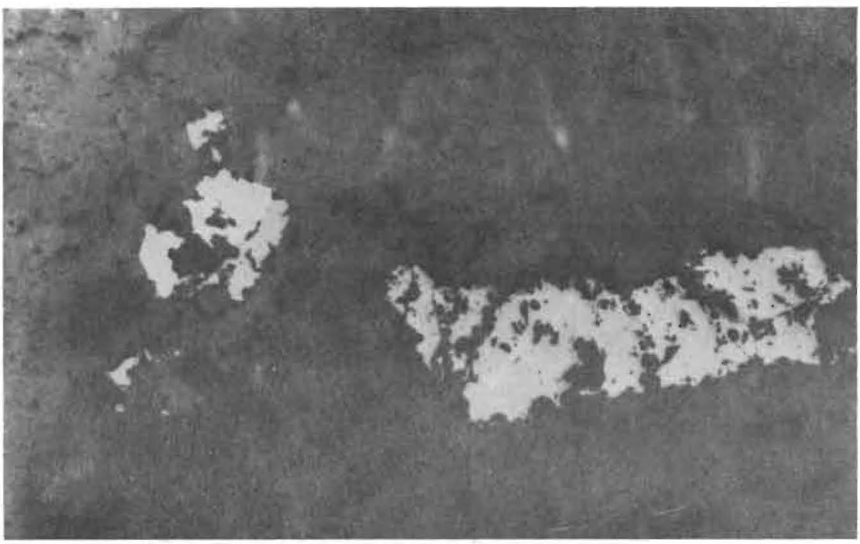

Plate 2. WSH7 — Photomicrograph showing magnetite (grey) associated with ilmenite (clear gray). X 32.

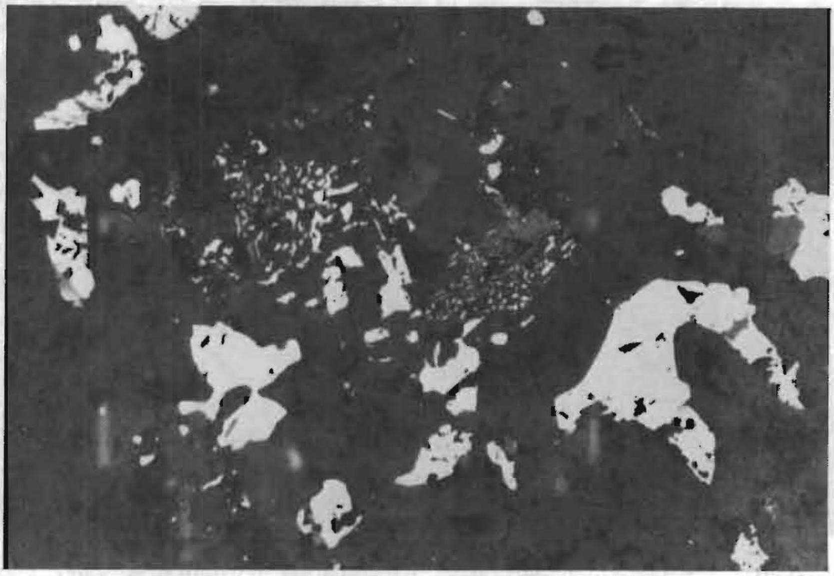

Plate 3. NSH8 — Symplectic texture, showing the intergrowth between magnetite (grey) and ilmenite (clear grey) enclosed by large discrete grains of magnetite (grey), ilmenite (clear grey), and sulphides. X 32.

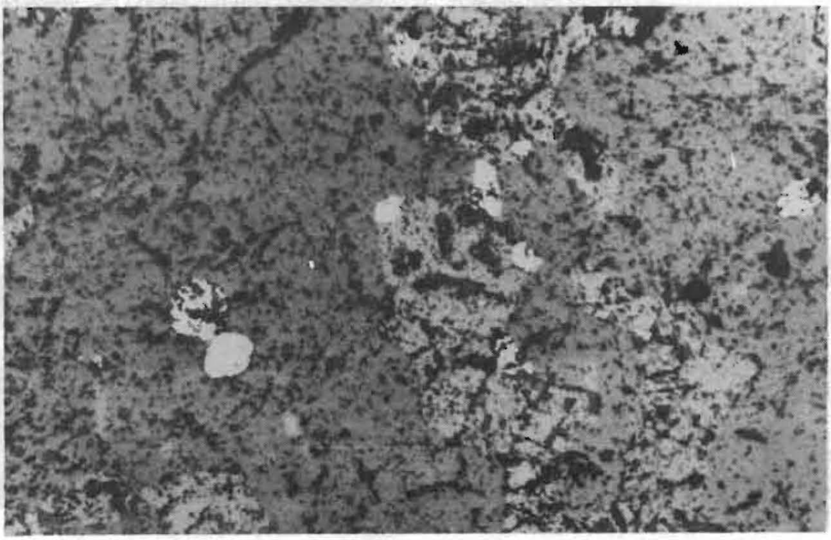

Plate 4. NSH2 — Small droplets of sulphides, mainly pyrrohotite in silicates. X 32.

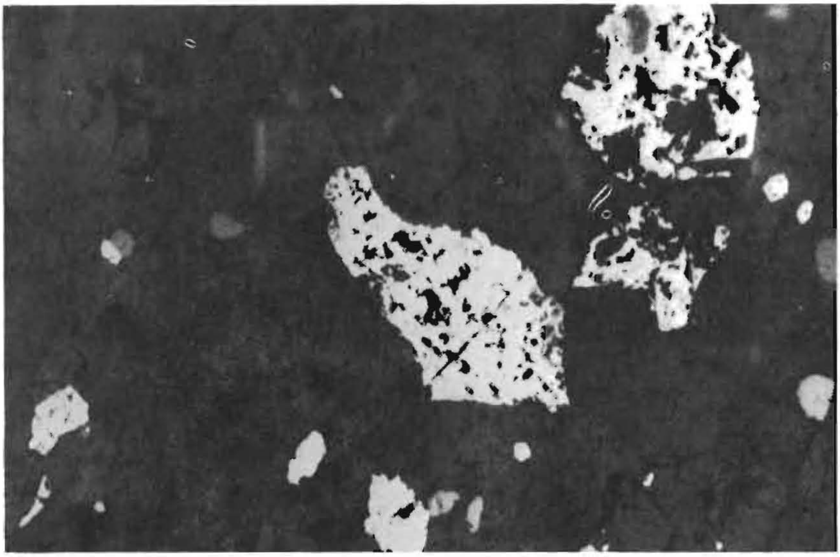

Plate 5. WSH3 — Large discrete grains of Pyrrhotite (clear grey) in silicates. X 32.

المعادن القاتمة لجبل شاع المتطبق بالمملكة العربية السعودية

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قسم الجيولوجيا ، كلية العلوم ، جامعة الرياض ، الرياض ، المملكة العربية السعودية ·

إن المعادن القاتمة في جبل شاع المتطبق بالمملكة العربية السعودية تتكون من الماجنيتيت والإلمنيت والبرهوتيت وقليل من البنتلانديايت والكالكوبيرايت وكلها معادن ذات طبيعه بين تراكميه · ولقد استخدمت تحاليل المعادن بواسطة تقنية المجس الالكتروني وكذلك قياس الانعكاسات وذلك لدراسة التغيرات الكيميائية والفيزيائية من قاع الجبل المتطبق الظاهر إلى قمته · وقد تم قياس درجات الحرارة الاتزانية ومقدار إنطلاق الأكسجين للأكاسيد المتواجدة معا · إن أكاسيد جبل شاع القاتمة قد وصلت إلى حالة الاتزان الحراري الأخير عند درجات حرارة أقل من درجات الحرارة التي وصلت عندها الأكاسيد القاتمة من معقد سكيرجارد بحوالي ١٥٠ إلى ٢٥٠° ولكن مع زيادة في مقدار إنطلاق الأكسجين ·