THE GEOLOGY OF THE DWARS RIVER FRAGMENT AND THE ORE-MINERALS OF THE MAGNETITE-DEPOSIT ON KENNEDY'S VALE 361 KT.

EASTERN TRANSVAAL

by

WILLEM CORNELIUS JANSE VAN RENSBURG.

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A. Sulphide Minerals/...

A. Measurement/....

FRONTISPIECE:

Northeast view of the Magnetite-deposit on Kennedy's Vale 361 KT.

A B S T R A C T.

During the field-seasons of 1960 and 1961 an area of 60 square miles was mapped in the vicinity of Kennedy's Vale, District Lydenburg. The information so acquired is presented on the map.

The Dwars River Fragment, a mass of metamorphosed rocks of the Pretoria Series, is present in the western part of the area. The Fragment consists of quartzite, hornfels, metamorphosed dolomitic limestone and mafic rocks forming sills, belonging to both the Lydenburg and Maruleng types as defined by Willemse (1959, p. xliii). These rocks have been folded into a doubly plunging anticline and a syncline plunging south.

The Fragment is to be explained in one of three ways. It either represents a "bulge" in the floor of the Bushveld Igneous Complex, a xenolith or a horst between two downfaulted blocks of plutonic rocks.

Mafic and Ultramafic plutonic rocks of the Bushveld Complex were also investigated.

A mineragraphic description of the ore-minerals of the Merensky Reef is included and an attempt is made to determine the temperature range of formation of the sulphides. Microscopical evidence and X-ray diffraction data point to a range from above ~~700~~ 670°C. The lower limit is not known.

Maghemite and martite are only present at or near the surface of the magnetite deposit on Kennedy's Vale. The existence of intermediate stages in the magnetite-maghemite series is indicated by the experimental data, and the oxidation of magnetite

resulted/.....

resulted in the formation of predominantly "maghemite" at temperatures below about 500°C, whereas martite formed in minute quantities below 700°C and more extensively above this temperature.

A study of the sulphide minerals associated with the ultramafic pegmatoid showed that they should be classified with the pegmatitic ore-deposits, as defined by Niggli (1954, p.513) as far as their association with rocks of definite pegmatoidal origin is concerned. Regarding their temperature of formation, they do, however, resemble ortho-magmatic deposits. It is proposed that such an assemblage be referred to as pegmatoidal.

A statistical investigation of the accuracy and reproducibility of values obtained with a CdS - photocell reflectometer indicates that this instrument is a ~~handy~~ useful aid in ore-mineral identification. By means of quantitative reflectivity and micro-indentation hardness measurements, the presence of intermediate members of the magnetite-maghemite series was established.

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I. INTRODUCTION.

The farms Kennedy's Vale 361 KT, Tweefontein 360 KT, Spitskop 333 KT, Frischgewaagd 359 KT, Zwakwater 377 KT and part of Annex Grootboom 335 KT are covered by this investigation (Geological Map).

The area is situated at the intersection of longitude $30^{\circ}7\frac{1}{2}'$ and latitude $24^{\circ}52'$. The Kennedy's Vale magnetite-deposit is about 50 miles by road from Lydenburg.

In 1908 Hall investigated the area as part of geological sheet 8. In his well-known work on the platinum deposits of South Africa, Wagner (1929, p.157) incorporated also the deposits on Dwarsrivier 373 KT and Tweefontein 360 KT. In more recent years, in 1951, Genis and Taylor mapped part of Tweefontein 360 KT, and in the same year van Biljon and Hiemstra completed theses on the geology south-east of Steelpoort station.

Cameron and Abendroth (195~~1~~6) mention the possibility of considerable faulting along the "floor" contact of the Bushveld Complex on Grootboom 336 KT, east of the area.

Mafic rocks of the Bushveld Igneous Complex occupy the major portion of the area mapped. The structure of the Complex is complicated by folding and progressive thinning of the Pyroxenite and Central norite zones towards the "floor". Between Eerste Geluk 322 KT, just north of the Steelpoort-river and Tweefontein 360 KT the Merensky Reef appears to be missing, ~~expect of~~ except for doubtful outliers on Grootboom 336 KT east of the area and Annex Grootboom 335 KT.

Sediments of the Pretoria Series outcrop in the eastern part of the area and numerous inclusions

of/.....

of these rocks, but especially quartzite, are present in Maruleng norite and pyroxenite. From Tweefontein 360 KT in the South to Kennedy's Vale 361 KT in the north, a large mass of altered sediments constitute the so-called Dwars River Fragment. The solution of the structure of this body is of considerable importance in the study of the "floor" of the Bushveld Complex. Willemse (1959, p.lxviii) and Retief (1959 p.99) have already referred to this assemblage of rocks in the same connection.

Numerous pipe- and vein-like bodies consist of ultramafic pegmatoid (diallagite pegmatoid and hortonolite dunite). These bodies are intrusive into norite. Olivine-bearing ilmenite-magnetite diallagite, also related to the above assemblage, has been reported from several localities in the Bushveld (Wagner, 1929). The group-name ultramafic pegmatoid is now suggested for these rocks which were previously called pegmatite by other workers.

Vanadium-bearing titaniferous iron-ore in these bodies is of economic importance and will be described in some detail. A mineragraphic study of copper-nickel-iron sulphides in the magnetite deposit on Kennedy's Vale 361 KT is also included in this report.

The object of the investigation is thus in the first place a study of the mineragraphy of the Merensky Reef, the chromitite and the magnetite-bearing ultramafic pegmatoid in the area and in the second place an investigation of the structural relations of the Bushveld Igneous Complex and the upper part of the Pretoria Series, which forms the "floor"

of/.........

of the Complex.

As the optical properties of the constituent minerals of the Bushveld rocks in the Eastern Transvaal have been exhaustively dealt with by numerous authors, the latest of these being Retief (1959) in the adjoining area southeast of Dwars River bridge, the description of Bushveld rocks will be brief and the optical properties of minerals are given only where such information serves a specific purpose.

II. PHYSIOGRAPHY.

To the north, the Steelpoort River flows ~~west~~ east-wards along a broad valley, the altitude of which is between 2,600 and 3,000 feet above sea-level. The trend of the river is straight over long distances, suggesting that it follows a fault-zone. The valley of the river is deeply eroded and outcrops are rare.

Towards the east on Zwakwater 377 KT and Spitskop 333 KT quartzite ridges attain heights of over 4,000 feet above sea level, whereas the trigonometrical beacon on Zwakwater 377 KT has an altitude of 6,339 feet.

Extensive areas on Tweefontein 360 KT, Frischgewaagd 359 KT, Spitskop 333 KT and Kennedy's Vale 361 KT consist of plains with isolated outcrops of pyroxenite and norite.

The area is drained by the Steelpoort and Dwars rivers and numerous minor rivulets. Amongst the latter Sprinkaanspruit is the largest and drains the area south of Zwakwater 377 KT.

Where the Dwars River traverses the Fragment a series of meanders are developed. This phenomenon is very difficult to explain, but differential weathering of the rocks of the Complex and the Fragment was probably partially responsible for the erratic course of the river in this locality. No satisfactory explanation can, however, be submitted.

The annual rainfall averages 26 inches. The vegatation is of the typical Bushveld type; thorn trees and a low thorny shrub are the prevalent types in the flats, whereas euphorbia and various aloes favour the mountainous territory.

III. THE/.....

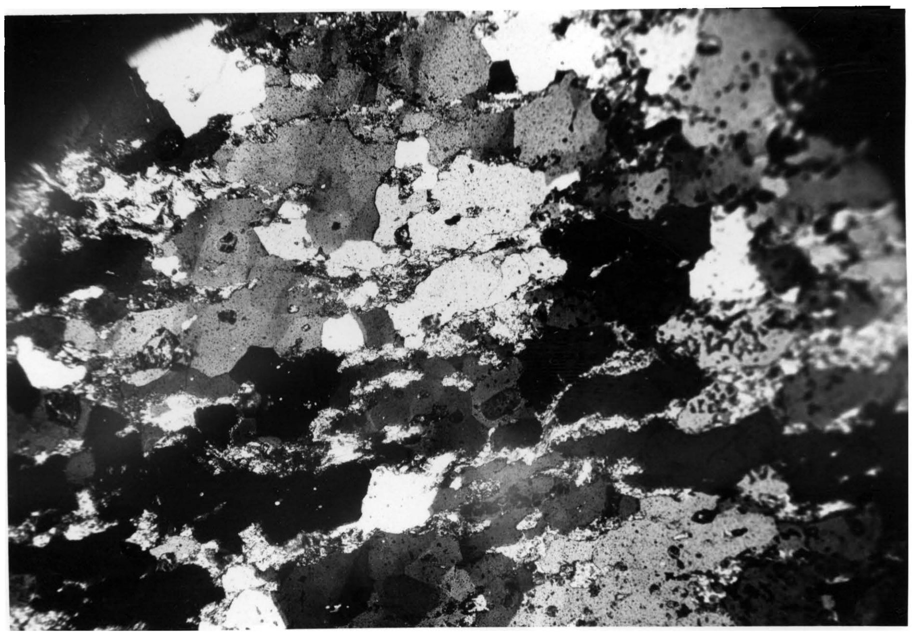


Photo 1:

Elongated quartz grains reveal lineation in quartzite Northern Part of Dwars River Fragment.

(W.v.R. 6) X 40.

III. THE DWARS RIVER FRAGMENT.

Because there are several quartzite - and three limestone bands in the Fragment, the metamorphosed rocks are described in the order of their relative abundance.

1. Quartzite:

Apart from the typical features of the quartzite recorded in table 1, there is little to add under this heading. There are, however, certain breccias intimately associated with and related to the quartzite which it is now proposed to consider in more detail.

In the bed of the Dwars River, north of the hornfels outcrop, fracturing and flowage of quartzite has taken place, resulting in the formation of a flow-breccia in which the matrix consists of impure quartzite and the fragments of hornfels. The rounded nature of the hornfels fragments suggests that mixing took place between quartzite and hornfels to a certain extent, resulting in the early stages in the formation of an impure quartzitic matrix.

Flakes of biotite partly chloritised constitute the impurities in the matrix of the quartz grains. (W.v.R. 168).

The random orientation of the hornfels fragments in this breccia suggests that the physical conditions were such that the quartzite was mobilized. Evidently an thin, original hornfels band in the quartzite, was crushed during the deformation. The fact that the fragments consist of hornfels,

and/.....

and not of quartzite, suggests that this band was deformed after the original shale had been transformed into hornfels by thermal metamorphism.

Granitization of the matrix took place at a late stage, as is indicated by the presence of feldspar. (W.v.R.168).

These observations do not confirm the transformation hypothesis suggested by van Biljon (1949) because the dynamo-thermal metamorphism resulted in a process of granitization and no evidence of noritization was obtained. The Lulu Mountain gabbro near the contact with the sediments of the Fragment does in fact show no signs of assimilation (W.v.R.60).

Further evidence of the mobilization of quartzite is provided by an outcrop further south on the eastern bank of the Dwars River, in the western part of the Fragment. Here the mobilized quartzite intruded a diabase sheet over a distance of more than 10 feet.

In the southern part of the Fragment, near the eastern contact with mafic rocks of the Complex, which are not exposed in that locality, the quartzite has also intruded the adjacent mafic sill. This outcrop is exposed in the bed of the Dwars River. Fragmentation of the mafic sill has taken place; fragments of the mafic rock of the sill, several inches in diameter being cemented together by the intrusive quartzite. This is obviously a rheomorphic phenomenon.

The temperature during this deformation was high enough to cause mobilization of the quartzite.

2. Hornfels/.....

Table 1.

Data on the Rocks of the Dwars River Fragment.

	Mineralogical Composition			Textural and Structural Features
	Predominant	Subordinate	Accessory	
1. Quartzite: Predominant Rock-type - forming several bands	Quartz (W.v.R.6)	a) Sericite) b) Muscovite) (W.v.R. c) Biotite) 6, 46) d) Chlorite)	In heavy mineral concentrate: zircon (idiomorphic predominant) rutile, magnetite. (W.v.R.46A)	Elongated quartz grains reveal pronounced lineation (W.v.R.6) (Photo 1). Brecciation of quartz grains only occasionally observed. Coarse-grained Doornpoort type to fine-grained in lower bands.
2. Hornfels: Band representing roughly about 15 per cent of the total thickness of the sedimentary succession.	a) Cordierite (W.v.R.57) considerably altered to pinite. b) Biotite - imparting a glittering surface to freshly broken fragments. c) Plagioclase (W.v.R.57)	Magnetite, chlorite, quartz.	Zircon in biotite produces pleochroic haloes. (W.v.R.57).	a) Bedding preserved. b) Drag-folding exposed in bed of Dwars River. c) Boudinage textures in highly deformed hornfels.
3. Metamorphosed impure Carbonate: a) Ophicalcite Three bands 5 - 20 feet thick.	a) Carbonate (W.v.R.11) b) Serpentine - two varieties - one free of magnetite, the other containing disseminated magnetite. (Photo 2).	Magnetite (W.v.R.52) chlorite garnet (W.v.R.74).		Bedding usually preserved.

Table 1 (continued)

	Mineralogical Composition			Textural and Structural Features
	Predominant	Subordinate	Accessory	
b) Diopsidefels thickness - about 5 feet.	Diopside - (W.v.R.174)	Plagioclase (W.v.R.174)		Bedding preserved.
c) Magnetite band in marble thickness - variable but less than 3 feet	Magnetite (Polished sections 44, 110) Diopside (W.v.R.42) Serpentine (W.v.R.44) Garnet (W.v.R.110)	Spinel - anhedral grains Olivine - (W.v.R.44)	Spinel exsolution blades parallel to (100) of magentite (Photo 5).	Slight brecciation as revealed by fragmental grains of magnetite along shear planes (W.v.R.110).
4. Mafic Rocks forming Sills: a) Lydenburg type	Tremolitic amphibole (W.v.R.75, 76, 78).	Quartz -(W.v.R.76) Sphene -(W.v.R.78) Plagioclase(W.v.R.76)	Magnetite (W.v.R.77)	Schistose texture - rock may be designated an amphibole schist.
b) Maruleng type	Orthopyroxene (W.v.R.49) Clinopyroxene (W.v.R.49) Plagioclase (W.v.R.54) Quartz (W.v.R.49) Olivine (W.v.R.54)	Biotite (W.v.R.49) Magnetite (W.v.R.54) Leucoxene	Zicron (W.v.R.49)	Porphyritic texture in basal portion of sill - olivine phenocrysts.

The localities of the samples are indicated on the Map.

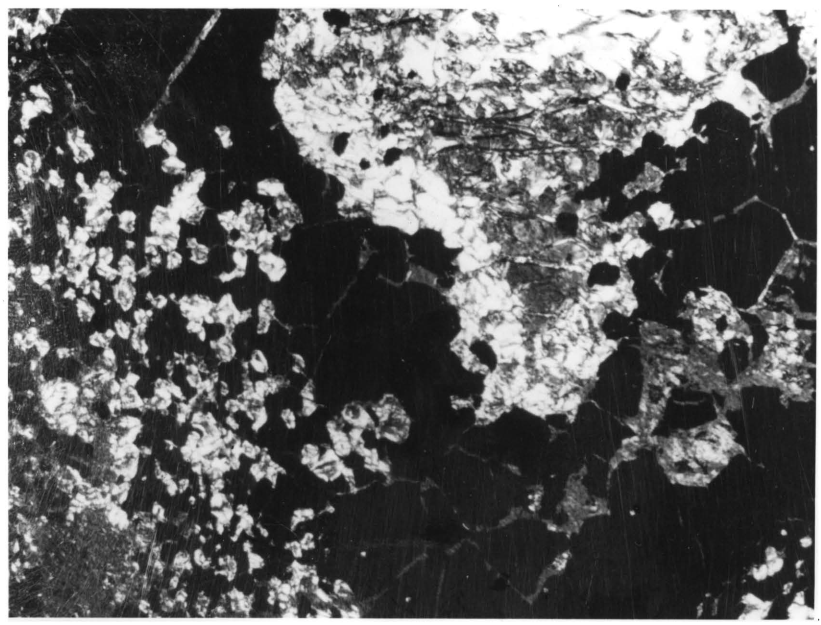


Photo 4: Coarse- and fine-grained magnetite (black) associated with serpentine (light-gray). Magnetite-rich band from northern part of Dwars River Fragment. (W.v.R. 44) X 80.

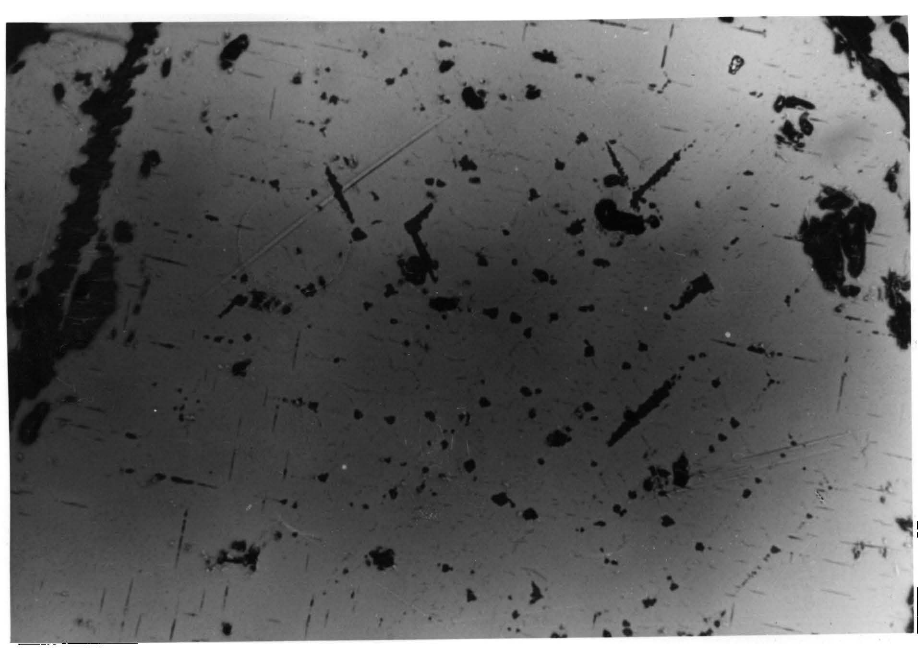


Photo 5: Spinel plates (black) in magnetite of magnetite-rich band from northern part of Tweefontein. (Polished section W.v.R. 111) X 200.

contains small quantities of Cr_2O_3. TiO_2 is much lower than in typical magnetite of magmatic origin from the Bushveld Complex (0.20% against at least 16%).

The mode of origin of the magnetite-rich rock from Tweefontein 360 KT is not quite clear. The laminated texture and low titanium content do point to a sedimentary origin, but the presence of garnet suggests a skarn, in which case the magnetite and garnet may represent a pneumatolitic product of the magma that produced the Lulu Mountain gabbro.

4. Mafic Rocks forming Sills:

There are two distinct types of mafic rocks forming sills in the Dwars River Fragment. The mineralogical composition of these two varieties is presented in table 1.

The one variety, rich in amphibole, is diabasic and is classified with the Lydenburg type. This variety belongs to the greenshist facies. The rocks forming the sills in the domed portion of the Fragment and those in the southern part belong to this type.

The rocks comprising the upper sills in the eastern portion of the Fragment, containing as they do orthopyroxene phenocrysts and fresh plagioclase (table 1) belong to the gabbro facies and are therefore grouped with the Maruleng type of mafic rocks, according to the classification of Willemse (1959, p. xliii).

The mafic sills are mainly concordant to the stratification of the sedimentary rocks in the fragment.

The/.....

The occurrence of sills possessing altogether different mineral assemblages and therefore belonging to different mineral facies so close together, warrants further discussion. It would appear that there were two periods of sill-formation. In that case the sills belonging to the Lydenburg type were probably intruded before the main body of mafic rocks reached its venue of emplacement. Subsequently the main body of mafic rocks of the Bushveld Complex was emplaced and more or less pari passu with this event the sills belonging to the Maruleng type were intruded into the "floor" of the Complex. During the intrusion of the main body of mafic rocks, the sills belonging to the Lydenburg type suffered thermal metamorphism, due to the increase in temperature caused by the intrusion of these mafic rocks. Stress operated in some cases so that these older sills now belong to either the amphibolite or greenshist facies.

5. Feldspathic Pyroxenite:

In table 3 information is provided on the composition of this rock-type. Structurally the occurrence forms an outlier in the Dwars River Fragment in the northern portion of Tweefontein 360 KT, west of the northern chrome workings on that farm.

The dip of the surrounding sediments is generally towards the outlier, which has thus been preserved in the trough of a syncline of sedimentary rocks. The strike of the axis of this syncline is north-south.

Table 3/.....

Table 3.

The Mineralogical Composition of Feldspathic Pyroxenite. W.v.R. 50.

	Mineral	Degree of Alteration	Mode of Occurrence
Main Components	Orthopyroxene ($2V\alpha = 78^{\circ}$)	Slightly altered to amphibole.	Subhedral to anhedral remnants and euhedral grains.
	Clinopyroxene ($\gamma\wedge C = 38^{\circ} - 42^{\circ}$)	Slightly altered to amphibole.	Large subhedral grains - inclusions in orthopyroxene.
	Plagioclase (An 68)	Slightly altered to saussurite.	Subhedral to anhedral grains twinning lamellae often bent.
Minor Constituents	Amphibole pleochroic colours very conspicuous.	Not altered.	Forms from pyroxene.
	Magnetite	Not studied.	Small grains in matrix.

B. Correlation of the Sediments of the Dwars River Fragment:

As the present investigation did not include a detailed study of the "floor" sediments, the correlation of the Dwars River Fragment is largely tentative. The resemblance between the sediments in the eastern portion of the Fragment and those of the "floor" on Zwakwater 377 KT, regarding lithology,

permits/.....

permits one to assume that the former are also chiefly of the Lakenvlei zone.

Willemse (1959, p. lvi and table vi) pointed out that cordierite hornfels is the typical metamorphosed equivalent of the argillites above the main quartzite of the Magaliesberg Stage. The hornfels of the Fragment is also rich in cordierite.

He also pointed out the abundance of spinel, diopside and ophicalcite in the carbonate rocks above the Magaliesberg quartzite on Groothoek 171. The same minerals are present in the upper calcareous zone of the Fragment (table 1).

Van Biljon (1951, p.14) records the presence of a serpentine-magnetite rock immediately below the Lakenvlei quartzite. In its mineralogical composition (diopside, forsterite, serpentine, spinel and magnetite) this magnetite rock strongly resembles the magnetite-serpentine rock in the upper calcareous zone of the Fragment.

The evidence thus available suggests that the original sedimentary rocks of the Fragment may possibly belong to the zones of the Pretoria Series ranging from shales immediately below the main quartzite of the Magaliesberg Stage up to and including the Lakenvlei quartzite.

IV. MAFIC AND ULTRAMAFIC PLUTONIC ROCKS OF THE BUSH-VELD COMPLEX.

A. Maruleng Norite:

The Maruleng norite or Marginal norite (Schwellnus, J.S.I., 1956, p.86) is the oldest of the plutonic rocks of the Bushveld Igneous Complex. The rocks are generally hybridized as a result of admixture of sedimentary material from the adjoining rocks of the Pretoria Series.

The Maruleng norite, like most of the rocks designated norite from the marginal areas of the Bushveld Complex, is actually a hyperite, in conformity with the usage of this term at Insizwa (Scholtz, 1936, p. 99), because it invariably contains both ortho- and clinopyroxene.

The mineralogical composition of Maruleng norite from the area mapped is presented in table 7.

An unusual variety of this rock-type is present on the eastern flank of the Dwars River Fragment in the northern portion of Tweefontein 360 KT (geological map). This rock contains about 10 per cent quartz and the mafic mineral is hornblende and not pyroxene (W.v.R.8). The rock may be designated a hornblende norite and is grouped with the Maruleng norite because of its occurrence at the base of the sequence of pseudo-stratified mafic rocks.

There is in certain localities no sharp line of demarcation between Maruleng norite and pyroxenite, for example on Annex Grootboom 335 KT. Here the Maruleng norite is not typical and in the southeastern portion of that farm the base of the complex is evidently represented by a chilled phase of the pyroxenite. This

chilled/.....

chilled pyroxenite is a fine-grained greyish rock containing occasional large phenocrysts of clinopyroxene in a matrix of predominantly orthopyroxene and in some cases subordinate plagioclase. Microsoopically it closely resembles the Maruleng norite.

During the emplacement of the Maruleng norite wedges of quartzite were prized off from the "floor". On Zwakwater 377 KT there are numerous such masses in the upper part of this norite zone. Further north, on Spitskop 333 KT and Annex Grootboom 335 KT a continuous band of quartzite in the norite has been folded into mild synclines and anticlines in conformity with the pseudostratification of the igneous rocks as displayed in the eastern portion of the profile ABCD (Map). This quartzite band wedges out away from the "floor".

Sheets of Maruleng norite have intruded the Magaliesberg quartzite on Zwakwater 377 KT where the norite is often concordant to the sediments. On Spitskop 333 KT and Annex Grootboom 335 KT it is noticeably discordant.

The feldspathic pyroxenite (table 3) which forms an outlier in the Dwars River Fragment in the northern portion of Tweefontein 360 KT, possibly also belongs to the Maruleng norite. This rock does, however, closely resemble the chilled pyroxenite on Annex Grootboom 335 KT and the author, therefore, regards this outcrop as another example where pyroxenite evidently chilled on the "floor" and where no true Maruleng norite was present.

B. The Pyroxenite Zone:

The rocks of this zone were evidently emplaced after the intrusion of Maruleng norite. In places the Maruleng norite was not present and the pyroxenite

chilled/.....

chilled directly on the "floor".

The zone consists of:-

1) Pyroxenite.
2) Chromitite.
3) Sheet norite.

1) Pyroxenite:

The mineralogical composition of the pyroxenite is provided in table 4.

In the southern portion of Tweefontein 360 KT, Frischgewaagd 359 KT and Zwakwater 377 KT there is a thickness of about 3,000 feet of pyroxenite. On Annex Grootboom 335 KT near the "floor" of the Complex, the total thickness of pyroxenite between the main chromitite horizon and the Maruleng norite is less than 200 feet. This phenomenon is attributed to progressive thinning of the pyroxenite zone in the direction of the "floor" (profile ABCD, Map).

Table 4.

Mineralogical Composition of Pyroxenite.*

Mineral	Mode of Occurrence	Relative Amounts
Orthopyroxene $2V\alpha = 80^{\circ}$	Idiomorphic to hypidiomorphic grains. Younger clinopyroxene in some cases interstitial to orthopyroxene.	70 - 80%
Clinopyroxene	Large phenocrysts in porphyritic pyroxenite (5 mm.). Small, irregular grains also present. (W.v.R.103).	2 - 8% - May be more in porphyritic pyroxenite.
Plagioclase (An 70)	Small rounded grains of plagioclase ophitically enclosed by bronzite. Also large grains not enclosed by bronzite. (W.v.R.103).	10 - 20% - In Feldspathic varieties may even reach 33%.
Biotite	Pleochroic flakes associated with magnetite.	0 - 3%
Magnetite	Minute grains.	less than 1%

* Optical/.....

* Optical constants and volumetric composition from Retief (1959, table 3).

W.v.R.94 - Below main chromitite band in the vicinity of the boundary Tweefontein - Kennedy's Vale.

W.v.R.102- Frischgewaagd, just east of northern beacon of Tweefontein 360 KT.

W.v.R.103- Southeastern part of Spitskop 333 KT.

The basal portion of the pyroxenite on Spitskop 333 KT, Frischgewaagd 359 KT and Zwakwater 377 KT has a porphyritic texture. Large phenocrysts of clinopyroxene, exceeding 5 mm. in diameter are present in an equigranular matrix consisting mainly of bronzite.

On the other hand, the upper portion of the pyroxenite on Tweefontein 360 KT and Frischgewaagd 359 KT has an equigranular texture. Above the main chromitite horizon on Tweefontein 360 KT the pyroxenite is noticeably chromiferous (W.v.R.2). On weathering of the chromiferous pyroxenite the chromite grains are liberated and no doubt contribute to the deposits of alluvial chromite in the beds of the rivulets.

2. Chromitite:

The main chromitite horizon is present near the top of the pyroxenite zone. The main chromitite band is about 4 feet thick and is separated from the overlying leader by about 3 feet of pyroxenite. Another group of chromitite seams occur in the basal portion of the Central norite zone. In some localities there are 4 seams in this latter group.

Individual bands have a fairly constant thickness but the different bands exhibit a variation in thickness from a fraction of an inch to more than 7 feet.

Several/.....

Several varieties of chromite could be distinguished:

a. The soft-friable variety:

This type consists of well-rounded chromite grains and interstitial silicate material. Chromite was the first mineral to crystallize and is in some cases replaced by silicates and sulphides.

Exsolution bodies of rutile parallel to (100) of the host (chromite) are often observed, for example in ore from the northern chrome-workings on Tweefontein 360 KT (Polished sections W.v.R. 1 & 2).

b. The hard-lumpy variety:

Bands of hard-lumpy chromitite outcrop in the plains near the eastern contact of the Dwars River Fragment and south of the northern chrome workings on Tweefontein 360 KT. These chromitite occurrences are at present being exploited by various concerns.

The chromitite grains are closely interlocking in this type. Interstitial rutile and ilmenite are present in this variety. Some chromite grains exhibit a zonal texture, for example in ore from south of the northern chrome-workings on Tweefontein 360 KT (Polished section W.v.R.38). In these zonal chromite grains, the rims are lighter in colour than the cores.

c. Magnetic chromitite:

Table 5/.....

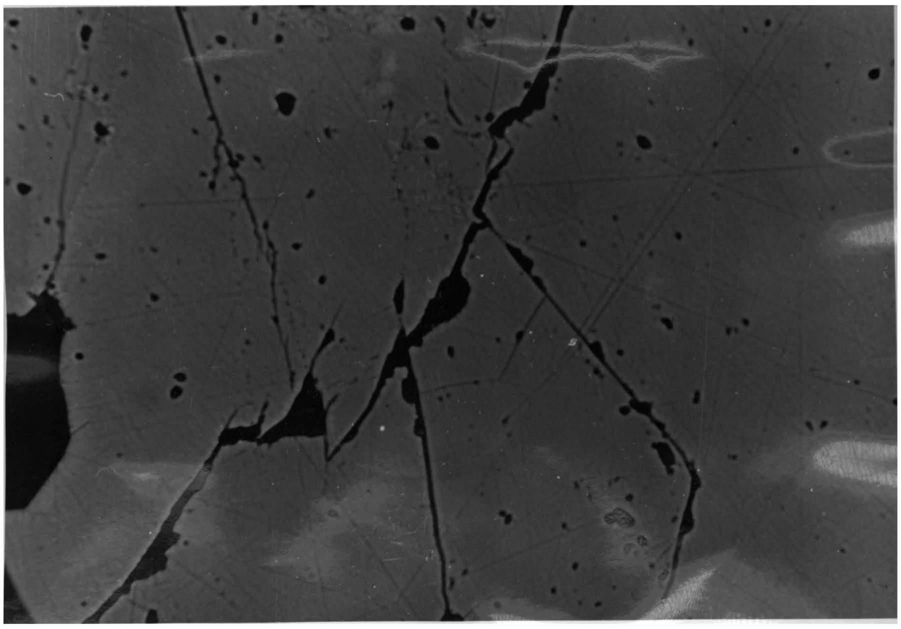


Photo 6:

Closely interlocking grains of chromite in magnetic chromite.
Eastern part of Annex Grootboom 335 KT.
(Polished section W.v.R.63) X 200.

Table 5.

Chemical Composition of Magnetic Chromitite.

Chemical Analysis		Norm		
SiO_2	0.44	Enstatite	$MgO.SiO_2$	0.74
Al_2O_3	8.06	Spinel	$MgO.Al_2O_3$	10.59
Fe_2O_3	21.20	Magnesioferrite	$MgO.Fe_2O_3$	4.52
FeO	27.48	Jacobsite	$MnO.Fe_2O_3$	0.94
MgO	4.49	Coulsonite	$FeO.V_2O_3$	3.33
CaO	0.00	Chromite	$FeO.Cr_2O_3$	41.70
Na_2O	0.03	Ilmenite	$FeO.TiO_2$	11.84
H_2O^+	0.05	Magnetite	$FeO.Fe_2O_3$	18.41
H_2O^-	0.08	Goethite	$Fe_2O_3.H_2O$	1.28
TiO_2	6.24	Maghemite	γ-Fe_2O_3	6.70
P_2O_5	0.02			
Cr_2O_3	28.12			
V_2O_5	2.25			
MnO	0.29			
Total	100.27		Total	100.15

Analyst -P. Fourie - Division of Chemical Service.

Locality - Eastern portion of Annex Grootboom 335 KT.

Polished Section - W.v.R.63.

A lustruous, strongly magnetic variety of chromitite has developed on Annex Grootboom 335 KT, where ultramafic pegmatoid is present in pyroxenite adjacent to the chrome seams.

The magnetic chromitite consists of closely interlocking grains of chromite (Photo 6), subordinate magnetite and sparsely distributed, round grains of ilmenite (W.v.R.63).

The Vickers hardness of the chromite in the magnetic chromitite is 1055, whereas that of normal chromite of the main seam on Tweefontein 360 KT (polished section W.v.R.38) is 1208.

The vanadium content of 2.25 per cent (table 5) suggests that this variety of chromitite should receive further attention as a possible source of that metal.

The chemical analysis in table 5 is that of a composite sample of the magnetic chromitite. The sample was not separated into magnetic and non-magnetic fractions because information was required on what influence the pegmatoid had on the chromitite.

The analysis indicates that iron, titanium and vanadium were probably partially introduced by the pegmatoidal magma.

3. <u>Sheet Norite</u>:

The name was suggested by Retief (1959, p.16) for leucocratic rocks, sheet-like or lenticular, of noritic composition, which are present in the pyroxenite zone.

These bodies may occupy any position in the pyroxenite zone from as low as the contact of

pyroxenite/.....

pyroxenite and Maruleng norite to as high as the contact of pyroxenite and Central norite. The sheets are concordant with the general pseudo-stratification of the Bushveld Complex and the dip varies between 5° and 16°. The discontinuous character of these bodies is clear from the geological map.

Microscopically there is very little difference between the norite of the sheets in the pyroxenite zone and the Central norite. The distinction is mainly based on the stratigraphical position in which the two varieties occur in relation to pyroxenite.

The mineralogical composition of the Sheet norite is compared with that of other gabbroic rocks in table 7. Although the main constituents of both the Central norite and the Sheet norite are plagioclase, orthopyroxene and clinopyroxene, Retief (1959, fig.3c) did establish that the Sheet norite is usually richer in orthopyroxene and poorer in clinopyroxene than the Central norite.

c. <u>Central Norite and Anorthosite</u>:

In order to avoid confusion with the Maruleng norite and the Lulu Mountain gabbro, the name "Central norite and anorthosite" was proposed for this group of gabbroidal rocks by Schwellnus, J.S.I. (1956, p.113).

An intrusive relationship of Central norite into pyroxenite was observed in an adit in the plain south of the northern chrome-workings on Tweefontein 360 KT, Retief (1959, p.93-94) also states that inclusions of pyroxenite and chromite are present in any position in the Central norite between the Merensky Reef and the top of the

pyroxenite/.....

pyroxenite zone. This evidence though not conclusive, leads one to surmise that the noritic and anorthositic rocks of this group represent an additional phase of intrusion. Anorthosite is mainly concentrated in the basal parts of this assemblage. There are all transitions from anorthosite to norite. Above the Merensky Reef, on the Koppie in the southwestern portion of Tweefontein 360 KT, the norite is markedly porphyritic.

On the eastern portion of Spitskop 333 KT an outcrop of Central norite contains anhedral crystals of titanite (W.v.R.128). The origin of this titanite is not clear but a similar occurrence is well-known near Bon Accord dam.

The mineralogical composition of the Central norite is compared with that of Maruleng norite, Sheet norite and Lulu Mountain gabbro in table 7.

d. The Merensky Reef:

The only exposure of the Merensky Reef in the area is on a koppie in the southwestern corner of Tweefontein 360 KT. This occurrence has received considerable attention from prospectors. The structure of the Reef at this locality is basin-like, but with an overall low inclination to the west, corresponding to the pseudostratification of the Bushveld Complex in the vicinity.

The Reef consists mainly of porphyritic pyroxenite, containing numerous inclusions of anorthosite, norite and pyroxenite. A thin

chromitite/.....

chromitite band ($\frac{1}{4}$" to $\frac{1}{2}$") is sporadically developed in the Reef. The thickness of porphyritic pyroxenite varies between 6 inches and 10 feet and it is generally concordant with the pseudostratification of the adjacent norite. In the inclined shaft on the southern side of the Koppie the Reef ramifies, forming two branches of porphyritic pyroxenite. There is a break in the development of the Reef between the most southerly exposure on Tweefontein 360 KT and the exposures in the northern portion of Dwarsrivier 372 KT, in the area mapped by Retief in 1959. This discontinuity he attributes to the effects of topography and slight folding (1959, p.30).

Table 6.

Mineralogical Composition of the Porphyritic Pyroxenite Comprising the Merensky Reef.

Orthopyroxene	Plagioclase	Biotite
$2V\alpha = 68^{\circ} - 75^{\circ}$ (Retief, 1959, table 8). Large bronzite crystals exhibit evidence of brecciation; contains inclusions of plagioclase, olivine and chromite (W.v.R.106e). Alters to amphibole and seldom to chlorite. (W.v.R.106b).	An 72°(Retief, 1959, table 8) interstitial to bronzite.	Small laths and irregular flakes (W.v.R.122)

The Merensky Reef also outcrops ~~in the northern part of the area~~ near the eastern beacon of Annex Grootboom, east of the area. At this occurrence the Reef is very poorly mineralized.

An occurrence of sulphide minerals in the magnetite deposit on Kennedy's Vale 361 KT could represent regenerated material of the Merensky

Reef/.....

Table 7.

Petrographical Data on Maruleng Norite, Sheet Norite, Central Norite and Lulu Mountain Gabbro.

	Maruleng Norite	Sheet Norite	Central Norite	Lulu Mountain Gabbro
Orthopyroxenite	$2V\alpha = 60^{\circ} - 70^{\circ}$ - Volume % = 20 - 40% Anhedral to subhedral grains (Retief 1959, p.9).	$2V\alpha = 60^{\circ} - 75^{\circ}$ - Volume % = 20 - 40% subhedral grains of bronzite (W.v.R.136).	$2V\alpha = 50 - 88^{\circ}$ - Volume % = 2 - 35% Subhedral grains of bronzite - Inclusions of plagioclase common (W.v.R.86) in ophitic intergrowth with orthopyroxene.	$2V\alpha = 60^{\circ} - 80^{\circ}$ - Volume % = 0 - 25% Orthopyroxene abundant in basal portion of this norite.
Clinopyroxene	$2V\gamma = 51^{\circ}$ Volume % = 3 - 17% Reaction Product of magma with orthopyroxene - hence interstitial (Retief 1959, p.10).	$2V\gamma = 40^{\circ} - 66^{\circ}$ $\gamma \wedge c = 25^{\circ} - 39^{\circ}$ Volume % = 0 - 10% Very little clinopyroxene in this variety - interstitial to orthopyroxene.	$2V\gamma = 40^{\circ} - 73^{\circ}$ $\gamma \wedge c = 28^{\circ} - 38^{\circ}$ Volume % = 0 - 38% Interstitial to orthopyroxene and irregular grains.	$2V\gamma = 53^{\circ}$ $\gamma \wedge c = 34^{\circ} - 38^{\circ}$ Volume % = 25 - 45%
Plagioclase	% An = 60 - 90% Volume % = 30 - 55% Grains subhedral also often zonal (Retief 1959, p.8).	% An = 60 - 90% Volume % = 60 - 70% Equigranular, subhedral grains.	% An = 66 - 88% Volume % = 50 - 95% Twinning lamellae often bent - more anorthite-rich lower down in succession.	% An = 60 - 80% Volume % = 55 - 80% More anorthite-rich lower down in succession - subhedral to anhedral grains (W.v.R.58).
Minor Constituents	Magnetite, biotite, very little quartz (Retief, 1959 table 2).	Irregular flukes of biotite (W.v.R.136). Interstitial grains of magnetite (W.v.R.136).	Small laths and irregular flukes of biotite (W.v.R.86) iron-ore (W.v.R.86) and titanite (W.v.R.128).	Iron-ore, biotite (W.v.R.60) and lencoxene. Close to sediments of Dwars River Fragment amphibole abundant. (W.v.R.60).

Table 7 (Continued)

Localities of Samples.

1. Maruleng norite:

a) W.v.R.145 - Eastern portion of Zwakwater 377 KT.

2. Sheet norite:

a) W.v.R.136 - Large sheet on southern part of boundary between Tweefontein 360 KT and Frischgewaagd 359 KT.

3. Central norite:

a) W.v.R. 86 - On western side of northern chrome-workings on Tweefontein 360 KT.

b) W.v.R. 35 - Southwestern part of Tweefontein 360 KT.

c) W.v.R.128 - Large Koppie on eastern part of Spitskop 333 KT.

4. Lulu Mountain norite:

a) W.v.R. 58 - A few yards from northern beacon of Tweefontein 360 KT.

b) W.v.R. 60 - One foot from western contact of sediments of the Dwars River Fragment on Kennedy's Vale 361 KT.

*Optical constants and volume percentages as determined by Retief (1959, tables 2, 4 and 5).

Reef. This possibility is discussed in chapted VI.

e. Lulu Mountain Norite and Gabbro:

The basal portion of the Lulu Mountain rocks on Tweefontein 360 KT is hyperitic in composition, (table 7) whereas the upper portion west of the area is gabbroic.

Outcrops of Lulu Mountain norite are present in the southern portion of Kennedy's Vale 361 KT and in the northern part of Tweefontein 360 KT. To the north and west on Spitskop 333 KT and Annex Grootboom 335 KT, the field relations between Lulu Mountain norite and Central norite are obscured by surface drift.

As the Central norite and the Lulu Mountain gabbro do not come into contact with each other in the area covered by the present investigation, no new information can be offered on their mutual relationship.

Macroscopically it is often difficult to distinguish between Central norite and the Lulu Mountain gabbro. Usually, however, the latter has a darker appearance than typical Central norite.

In the northern portion of Tweefontein 360 KT the rocks appear to be at a lower layered horizon than those on Kennedy's Vale 361 KT, in conformity with the easterly dip.

f. Ultramafic Pegmatoid:

The group-name ultramafic pegmatoid is suggested for rocks mutually associated and ranging in composition from hortonolite-dunite

to/.....

to diallagite. They evidently represent a pegmatoidal phase of the ultramafic rocks of the Bushveld Complex.

In the western part of the area, west of the Dwars River Fragment, 5 pipe-like bodies mainly of olivine-bearing diallagite outcrop. Irregular masses of hortonolite dunite are associated with the diallagite. Vein-like bodies of similar composition are present in the western part of Tweefontein 360 KT and the southern part of Kennedy's Vale 361 KT.

Titaniferous magnetite is disseminated throughout these rocks and is concentrated in the central parts of some of the pipe-like bodies. The largest of these is on Kennedy's Vale 361 KT. In this body sulphides are disseminated both in the central core of titaniferous iron-ore and in the diallagite. At the surface evidence of their presence is provided by opaline gossan which outcrop on the eastern slopes of the Kennedy's Vale mass.

Table 8.

Data on Silicate Minerals in Ultramafic Pegmatoid.

Olivine	Clinopyroxene	Plagioclase	Amphibole
Clear to clouded, subhedral to anhedral grains. Irregular extinction not uncommon. Sub-microscopic inclusions of magnetite. (W.v.R.108).	Distinct (100) parting permits designation as diallage (W.v. R.108). Rounded inclusions of diallage are present in magnetite grains.	Usually not present in ultramafic pegmatoid, but conspicuous in mass near western beacon of Tweefontein (W.v.R.104, photo 8).	Reaction of magma with diallage produced reaction rims of amphibole around magnetite grains. (Photo 7)

In the southern portion of Tweefontein 360 KT, west of the main road to Lydenburg, a pipe-like body of peridotitic pegmatoid cuts transgressively through Central norite. A large inclusion of hard-lumpy chromitite, 3 feet by 50 feet, in the pipe has been opened up by trenching. The occurrence of chromitite in this body is noteworthy, as all the other occurrences of ultramafic pegmatoid in the western part of the area contain titaniferous magnetite as a primary constituent and no chromitite.

In places this pegmatoid becomes noticeably feldspathic, a phenomenon which is attributed to the incorporation of norite from the adjacent country rock. A troctolitic character is imparted to the pegmatoid where the disintegration of norite inclusions has reached an advanced stage.

The pegmatoid bodies on Grootboom 336 KT, northeast of the area, and Annex Grootboom 335 KT are highly irregular in shape and their outcrops cap the mountains in that area.

No ultramafic pegmatoid masses were observed below the main chromitite band. This phenomenon is difficult to explain.

The olivine in the hortonolite-dunite pipe on the southeastern part of Tweefontein 360 KT has suffered little alteration to serpentine. Retief (1959, p.96) attributes the presence of diallage and amphibole in this rock to assimilation of pyroxenite by the dunite magma.

The/.....

The association of dunite and diallagite in most of the other pegmatoid masses does not support this view, particularly not in pegmatoid occurrences such as in the northwestern part of Kennedy's Vale 361 KT where dunite is subordinate to diallagite. Retief does mention that there may be a genetic relationship between these two rock-types because hortonolite-dunite and pegmatitic pyroxenite were emplaced shortly after each other and have the same mode of occurrence. Also according to Schwellnus (1956, p.146), types ranging from pyroxenitic through wehrlitic to dunitic rocks are encountered.

Wagner (1925, p.88) distinguishes two distinct types of hortonolite-dunite. In one the dunite forms parsnip- or pipe-shaped segregations or veins in olivine-dunite or serpentinite derived from it. In the other the dunite is associated with coarse-grained diallagite. The latter type includes the majority of the occurrences in the Lydenburg district. In the area investigated all the pegmatoid masses belong to the second type.

The process of emplacement of the pegmatoid masses is not quite clear. On Annex Grootboom 335 KT Cameron was able to follow undisturbed chromitite seams through pegmatoid bodies (Cameron, E.N., personal communication). A process of replacement of pyroxenite by ultramafic pegmatoid is envisaged. The adjacent chromitite seams were obviously more resistant to replacement than the pyroxenite.

Many/.....

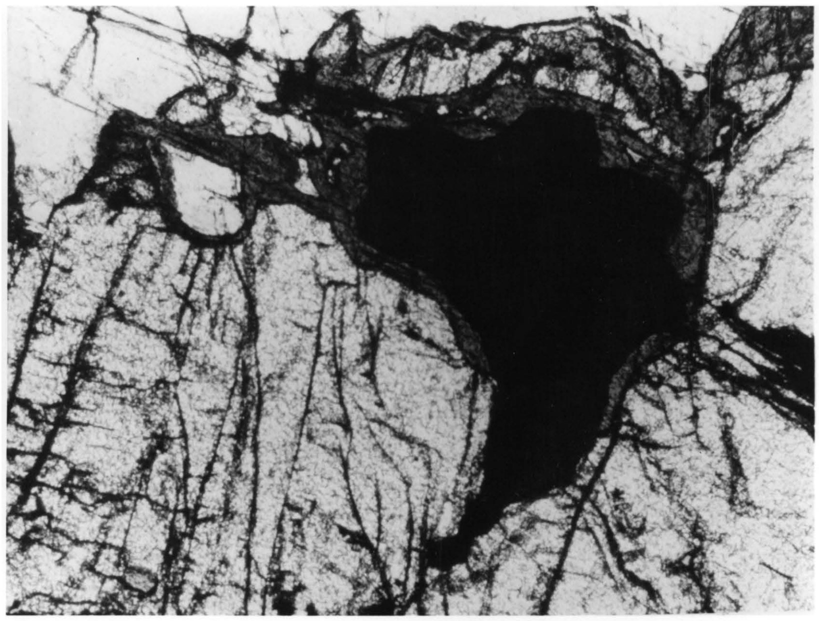


Photo 7:

Reaction rim of amphibole around magnetite
Kennedy's Vale 361 KT.
(W.v.R. 56) X 100.

Many theories have been advanced, regarding the origin of dunite, but none has been able to explain all the related phenomena, such as the presence of chromite and titaniferous magnetite in these rocks and their association with both noritic and pyroxenitic rocks. Ross, et al (1954, p.693 - 737), in a detailed study on the origin of dunite, reached the conclusion that they have been brought up from profound depth by orogenic processes.

The coarse grained texture of the ultramafic pegmatoid, ~~their~~ its variability in composition and ~~their~~ irregular outlines are all evidence of ~~their~~ pegmatoidal affinities.

V. STRUCTURAL RELATIONSHIPS.

A. Structural Relationships of the Dwars River Fragment.

The rocks of the Dwars River Fragment have been folded into a doubly plunging anticline, revealed by the argillaceous rocks in the Dwars river, and a syncline plunging south (Profile A-B).

The axial trace* of the anticline is convex to the east and that of the syncline strikes north-south. The axial plane of the anticline dips to the east, as can be seen from the steeper dips on the western flank of the anticline. There is a general correspondence in the attitude of the minor folds (dragfolds) in the crest of the anticline to that of the major folds.

Fracturing and plastic deformation of the sediments took place as indicated by the development of flow-breccia. The cause of the deformation could not be definitely established. The emplacement of the Lulu Mountain gabbro may have been partially responsible. The curved trend of the axial trace of the doubly plunging anticline suggests that the rocks were subjected to two periods of deformation.

According to Willemse (1959, p.lxviii) the western contact of the fragment is steep and tends to run straight for long distances, suggesting faulting. He further points out that there is a sulphurous spring on Tweefontein 360 KT along such a possible fault-zone, but that the abundance of

amphibole/.....

*The terminology is in accordance with that of Billings (1959).

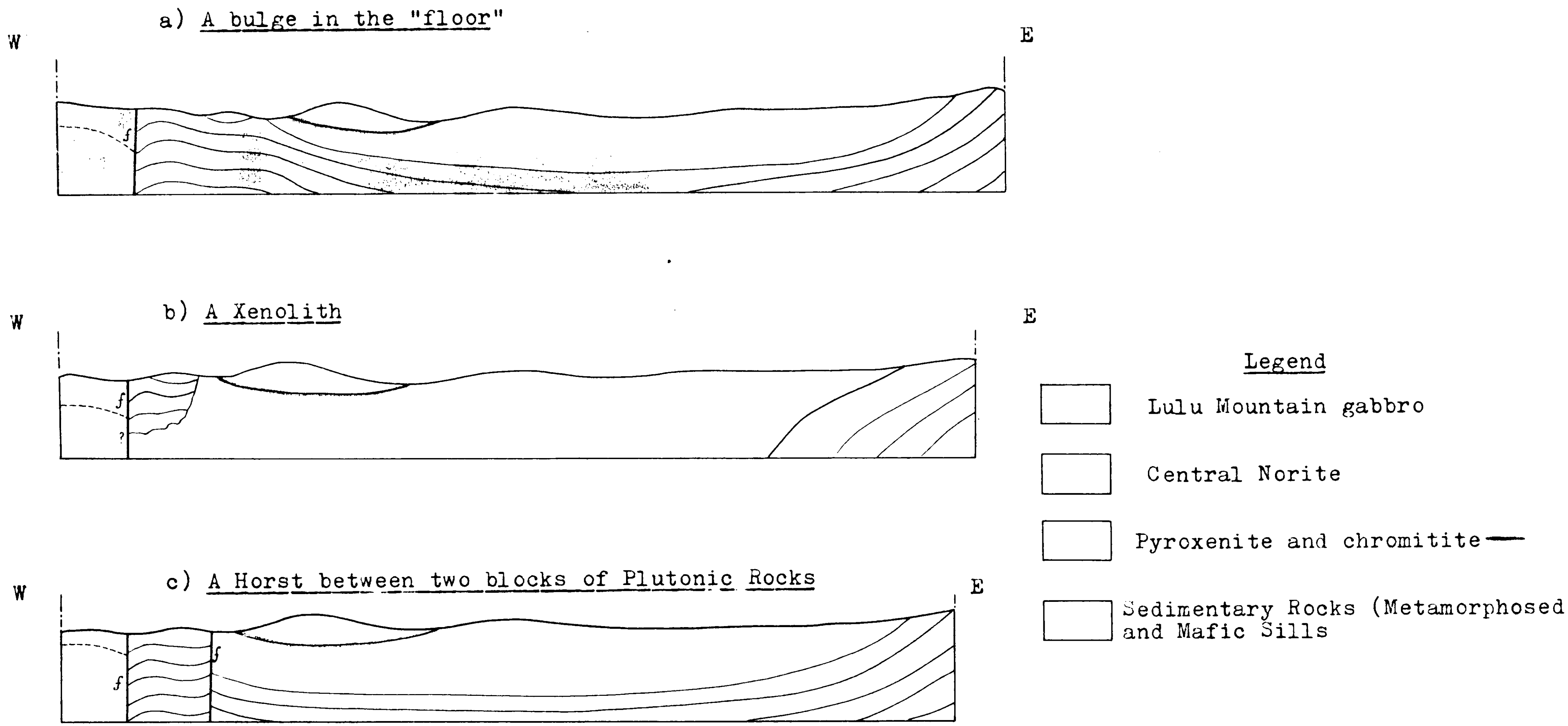
amphibole in the gabbro close to the contact with the sediments suggests an intrusive relationship. According to him a certain amount of down-faulting probably took place on the western side of the fragment shortly after or during the emplacement of the Lulu Mountain gabbro. On Kennedy's Vale 361 KT, where the contact is exposed, there is no sign of brecciation of the adjacent Lulu Mountain gabbro.

Trenches along the chromitite seams on the eastern side of the fragment in the southwestern portion of Tweefontein 360 KT reveal considerable brecciation. The chromitite seams have a steep dip to the east and are in places almost vertical. The brecciation of these chromitite seams can be explained by deformation during the updoming of the footwall of the Complex by the later surge of magma which produced the Lulu Mountain gabbro. It does, however, seem probable that a certain amount of down-faulting also took place on the eastern side of the fragment.

According to Willemse (1959, p.lxxv), the Dwars River Fragment is to be explained in one of two ways. It either represents the actual footwall of the Complex brought into that position by the surge of magma which produced the Lulu Mountain gabbro or it constitutes the hanging-wall portion of a fracture filled with magma. The question one has to answer is therefore: Does the fragment represent a "bulge" in the "floor" of the Complex or is it a xenolith.

Figure 1

Structural Interpretation of the Dwars River Fragment



In the light of the evidence presented above, a third possibility has to be considered, namely that the fragment represents a horst between two down-faulted blocks of plutonic rocks (figure 1 c). The latter is a variation of the bulge concept.

1. Evidence pointing to a "bulge" in the "floor".
   a) Near the base of the Complex the dip of the plutonic rocks is to the west, i.e. to the centre of the Complex. On the eastern flank of the fragment the normal westerly dip is reversed; the chrome seams evidently dip to the east.
   b) The Merensky Reef on the isolated koppie in the southwestern portion of Tweefontein 360 KT has a basin structure.
   c) On the western flank of the fragment the dip of the layering of the Lulu Mountain gabbro is to the east. Farther to the west the normal westerly dip is restored. An anticline representing a continuation in the folding of the "floor" is conceived.
   d) An outlier of feldspathic pyroxenite, which has been preserved in a basin in the northeastern part of the fragment, supports the view that the fragment represents a bulge in the "floor" sediments. Remnants of the basal portion of the mafic rocks of the Complex would quite conceivably be expected to adhere to the domed sediments.

2. Evidence/.....

2. Evidence pointing to a Xenolith.

a) Outcrops of chromitite are present on both the eastern and western sides of the fragment. These outcrops could belong to the same band, in which case the fragment would represent a xenolithic body. The outcrops of chromitite on the western side are, however, xenolithic and are present in gabbroidal rocks, whereas those on the eastern flank are associated with pyroxenite.

b) Both the eastern and western contacts of the fragment bear no relationship to the strike of the axes of the major folds.

3. Evidence pointing to a Horst.

a) There can be little doubt about the presence of a fault along the western contact of the fragment. The only evidence which does not support this view is the absence of brecciation in the fault-zone. This can be explained if the faulting took place during or shortly after the emplacement of the Lulu Mountain gabbro.

b) The fracturing of the chromitite on the eastern flank of the fragment, close to the contact with the sediments of the fragment and the presence of a sulphurous spring in the hypothetical fault-zone on the eastern side of the fragment, in the southern part of Tweefontein 360 KT (Map), point to the presence of a fault near the eastern contact of the fragment.

c) The steep easterly dip of the chromitite seams

on/.....

on the eastern side of the fragment, west of the outcrop of the Merensky Reef in the southern part of Tweefontein 360 KT, could be attributed to drag.

d) The eastern contact of the fragment in the Dwars River is partially covered with alluvium. Brecciation of quartzite, close to the contact, is evident and could be attributed to faulting and fragmentation of the quartzite by the mafic sills.

If all the available data is taken into consideration, the overwhelming evidence points to the structure of the Dwars River Fragment as representing a "bulge" in the floor of the Complex. Slight displacement took place along the eastern contact. On the western contact the displacement was much larger, bringing the Lulu Mountain gabbro in juxta-position with "floor" sediments.

A gravity or seismic survey of the area in the vicinity of the fragment could provide additional evidence concerning the relationship between the sediments of the fragment and the adjacent plutonic rocks.

B. <u>The Structure of the Bushveld Complex in the Vicinity of Kennedy's Vale and farther East</u>:

In discussing the structure of the Bushveld Complex in the area investigated, it is necessary to cast the net wider and include certain phenomena from the adjoining areas.

Although no evidence of faulting in the Steelpoort River valley could be obtained on

Kennedy's/.....

Kennedy's Vale 361 KT, Spitskop 333 KT or Annex Grootboom 335 KT, the Steelpoort river does follow a fault-zone on Apiesbomen 295 KT, close to Burgersfort, northeast of the area, according to Willemse (1959, p.lxxvii). Shearing is well displayed on the southern side of the river, about 3 miles upstream of the bridge leading to Magnet Heights. The remarkable straightness of the trend of the river also suggests a zone of weakness.

Mapping of the chrome-seams in the Steelpoort-Grootboom 336 KT area by Hiemstra and van Biljon (1959) and Cameron and Abendroth (unpublished map) has revealed a continuous succession on both sides of the river. North of the river a thickness of a few hundred feet of pyroxenite overlies the main chromitite band. South of the river the overlying pyroxenite is not more than 100 feet thick.

On Grootboom 336 KT east of the area and Annex Grootboom 335 KT the chromitite horizon is folded into mild synclines and anticlines. In the southern portion of Annex Grootboom 335 KT the main chromitite band can be followed to within a few hundred feet of the "floor". Cameron and Abendroth (1957, p.1065) consider this a faulted contact, but mapping further south (see Map) reveals no evidence of faulting along the "floor" contact of the Complex. Where the main chromitite band approaches the "floor" in the southern portion of Annex Grootboom 335 KT the whole pyroxenite zone has decreased to a thickness of less than

100 feet/.....

100 feet. This would suggest that progressive thinning, rather than faulting is responsible for the abnormal relationships.

The chromitite bands associated with the overlying Central anorthosite do bend up as if dragged near the "floor" in the eastern portion of Annex Grootboom 335 KT. A certain amount of sagging did take place along the contact of pyroxenite and Maruleng norite, probably while the rocks were still in a plastic state.

The emplacement of the Lulu Mountain gabbro provided additional load on the underlying rocks. With the increase of the load on these rocks and the decrease in the eruptive pressure of the magma, sagging probably took place and the equilibrium was so restored.

Away from the "floor" the sediments of the Pretoria Series above the main quartzite of the Magaliesberg Stage dip at an angle of 10 - 15° to the west. Close to the "floor" on Zwakwater 377 KT, Spitskop 333 KT and Annex Grootboom 335 KT the dip of the sediments increases to 40° - 55° to the west. The Maruleng norite appears to lie concordantly on the "floor" sediments, whereas the dip of the pyroxenite - and Central norite zones is 12° - 18° to the west.

A quartzite band in the Maruleng norite on Zwakwater 377 KT, Spitskop 333 KT and Annex Grootboom 335 KT evidently represents a slab wedged up from the "floor". In the southern portion of Annex Grootboom 335 KT this quartzite band is sharply folded close to the "floor", a phenomenon which

is/.....

is ascribed to the pressure of subsequent heaves of magma.

On Tweefontein 360 KT, Frischgewaagd 359 KT and Zwakwater 377 KT there is a subsidiary basin of Bushveld mafic rocks between the Dwars River Fragment in the west and the "floor" in the east.

VI. ORE-MINERALS OF THE MERENSKY REEF.

The ore-minerals of the Merensky Reef in the Lydenburg district have been described by various authors. Retief, (1959, p.57 - 69) included samples taken from the occurrence of the Reef on Tweefontein 360 KT in his investigation.

The porphyritic pyroxenite of the Merensky Reef is highly prone to weathering with the result that fresh samples of the mineralized rock are most readily obtained from ore dumps near prospecting adits.

The mineralization of the porphyritic pyroxenite of the Merensky Reef is sporadic, sulphides occurring as small blebs, somewhat larger grains and thin veinlets, whereas chromite is concentrated in a thin sporadic chromitite band and disseminated in the porphyritic pyroxenite.

A. Sulphide Minerals:

The sulphide minerals are described in the order of their deposition.

1. Pyrrhotite:

Pyrrhotite appears to be the oldest sulphide mineral and is replaced by other sulphides, such as chalcopyrite and in some cases pentlandite.

In sections exhibiting the pronounced basal cleavage, the mineral is slightly pleochroic (W. v.R. A.110).

Sulphide grains often consist of a core of pyrrhotite and a rim of pentlandite and chalcopyrite (Retief, 1959, p.57). Minute grains of pyrite are present in some grains of pyrrhotite. The pyrite may either represent a product of

early/.....

early crystallization or an alteration product of pyrrhotite (W.v.R. 106 b).

Scholtz (1936, p.151 - 156) observed that pyrrhotite of Insizwa consists of two varieties having almost identical properties. He called the darker type α -pyrrhotite and the lighter component β -pyrrhotite. According to my observations on pyrrhotite from several localities, the component which is the darkest in ordinary light is the lightest with crossed nicols and vice versa. In conformity with the definition of Scholtz of the two varieties, the darker component in ordinary light will be referred to as α-pyrrhotite and the lighter component (obviously also in ordinary light) as β -pyrrhotite.

In pyrrhotite of the Merensky Reef from Tweefontein 360 KT the exsolution lamellae are darker than the major component with ordinary illumination (W.v.R. A.110). The major portion of the pyrrhotite from Tweefontein 360 KT (more than 75%) therefore consists of β -pyrrhotite and the rest of α -pyrrhotite.

According to Ramdohr (1960, p.550) both modifications are known to form the major constituent of pyrrhotite in ore from different localities. A further complication is provided by the existence of a cubic, high-temperature γ -modification FeS.

In the ore of the Merensky Reef from Tweefontein 360 KT the darker (α) component exhibits a stronger reflecting pleochroism than the

-component/.....

β -component. In one position the two varieties are virtually indistinguishable (W.v.R.106 b), whereas on rotation the difference in colour increases gradually to a maximum.

Ramdohr (1960, p.551) ascribes the origin of the two modifications of pyrrhotite to exsolution of components differing in their Fe:S ratio.

Hawley and Haw (1957, p.132) proved experimentally that a nickel-bearing pyrrhotite, on being heated to 800°C, yields exsolution bodies of pentlandite. The process requires diffusion of iron, sulphur and nickel.

The exsolution of pyrrhotite into two different components may represent an early stage in the process described by Hawley and Haw.

Scholtz (1936, p.153) believes that there is a relationship between flames of pentlandite and his β -pyrrhotite, the flames of pentlandite almost invariably occurring in his β -component. In pyrrhotite of the Merensky Reef from Tweefontein, however, exsolution flames of pentlandite are observed in both varieties of the mineral (W.v.R. 106 b, d).

In inclusions (0.01 - 0.005 mm.) of pyrrhotite in pentlandite, the dark α -component often predominates (W.v.R. A.110). Pyrrhotite which has a defect structure invariably contains an excess of sulphur and thus has a higher sulphur content than pentlandite. The fact that the α -component predominates in inclusions of pyrrhotite in pentlandite, could possibly imply that the α -component contains more sulphur than

the/.....

Table 9.

X-Ray diffraction data of pyrrhotite of the Merensky Reef.

	Merensky Reef (A110) (Tweefontein) Rad. Co K		Morre Velho, Minas Gereas		Noranda, Quebec Harcourt (1942, p.94) Rad. λ = 1.78890	
No.	I/I.	d(A^{o})	I/I.	d(A^{o})	I/I.	d(A^{o})
1	30	2.958	.6	2.98	10	2.97
2	60	2.628	.8	2.64	50	2.63
3			.1H	2.45	5	2.45
4	5	2.271	.1H	2.26	5	2.26
5	100	2.0588	1.0	2.06	100	2.06
6			.1H	1.88	5	1.88
7	30	1.719	.7	1.72	40	1.72
8	5	1.606	.4	1.61	5	1.61
9			.2B	1.451		
10	10	1.434	.4	1.430	10	1.43
11			.6d	1.320	10	1.32
12			.2dB	1.288		
13			.2B	1.214		
14	5	1.180	.3	1.172	5	1.17
15	30	1.101	.8	1.106	40	1.10
16			.8B	1,094		
17			.1H	1.067	5	1.07
18			.7B	1.053	30	1.05
19	20	1.047	.8	1.045		
20	10	0.994	.5H	0.990	10	0.990
21	10	0.970	.5H	0.968	10	0.968
22	20	0.914	.7H	0.908	30	0.908

the β-variety. Scholtz, on the other hand, suggests that the intimate relation between his β-pyrrhotite and flames of pentlandite would imply that the difference in colour of the two components could be due to a variation in the nickel content in the case of the Insizwa ore.

X-ray diffraction data on pyrrhotite from Tweefontein reveals that it contains an atomic percentage of iron of 46.7, using the experimental data of Arnold (1956, figure 25) as a basis of reference.

2. Pentlandite:

Pentlandite is one of the most abundant sulphides of the Merensky Reef, though not as common as pyrrhotite. Small inclusions of chalcopyrite in pentlandite represent advance islands of replacement (W.v.R.106 b).

Contrary to Retief's observations (1959, p.60), clear patches of unaltered pentlandite were often observed, even in the vicinity of cracks where alteration to bravoite has taken place (W.v.R. A.110).

The alteration of pentlandite to bravoite progresses along cracks, along cleavage ~~plains~~ planes and from the grain boundaries.

X-Ray diffraction data on pentlandite from Tweefontein, does not reveal any abnormalities (table 10).

3. Chalcopyrite:

Chalcopyrite, which is the youngest mineral in the sulphide paragenesis, replaces all the other sulphides and in some cases even chromite, whereas the replacement of gangue material is a common phenomenon (W.v.R.106, a,b,d). Veins of chalcopyrite cut through pyrrhotite grains, exhibiting such evidence of replacement as "caries" textures in which the boundaries of chalcopyrite are convex towards the host (pyrrhotite) and rim replacement textures in which pyrrhotite is replaced by chalcopyrite along the grain boundaries.

Although/.....

Table 10.

X-Ray diffraction data of pentlandite of Merensky Reef and magnetic iron ore.

Co K α radiation

	Merensky Reef (A.110)		Magnetic iron ore (W.v.R. 107).	
No.	I/I.	d(A°)	I/I.	d(A°)
1	20	5.880	20	5.913
2			5	5.075
3	5	3.608	10	3.536
4	80	3.059	60	3.059
5	20	2.926		
6	5	2.530		
7	40	2.332	40	2.299
8				
9	50	1.940	60	1.938
10	100	1.786	100	1.773
11	20	1.711	30	1.719
12	20	1.529		
13			10	1.516
14	10	1.158	10	1.157
15	5	1.102	5	1.103
16	5	1.054		
17			10	1.048
18	20	1.026	30	1.024
19	5	1.012		
20	10	0.973	10	0.9696

Although not as abundant as pyrrhotite, chalcopyrite occurs not only in the porphyritic pyroxenite, but also as small blebs in the underlying norite.

4. Cubanite and valleriite:

Exsolution lamellae of cubanite and worm-like bodies of exsolved valleriite in chalcopyrite of the Merensky Reef from Tweefontein reveal that the chalcopyrite was originally oversaturated with iron.

Cubanite is not a major constituent of the ore. Large grains of chalcopyrite, completely devoid of any exsolution bodies, are common. The exsolution lamellae of cubanite are characterized by their long, regular contacts in chalcopyrite (W.v.R. A.110).

The worm-like bodies of exsolved valleriite are sparsely and irregularly distributed in the host (W.v.R. 106 b).

5. Bravoite:

Bravoite is a weathering product of pentlandite. The alteration of pentlandite to bravoite progresses rapidly along the pronounced (100) cleavage planes of the former (W.v.R. A.110).

The bravoite of the Merensky Reef from Tweefontein is noticeably anisotropic (W.v.R. A.110). According to Ramdohr (1960, p.748) bravoite formed by the weathering of pentlandite commonly exhibits this.phenomenon and the properties

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of the mineral vary with the chemical composition. He further points out that the polish of such bravoite is often weak due to the formation of minute marcasite grains by the same process. In bravoite from Tweefontein such marcasite could not be recognised. (W.v.R.A.110).

B. Oxide Minerals:

1. Chromite:

Grains of chromite are disseminated in the porphyritic pyroxenite of the Merensky Reef and are also concentrated in a thin chromitite band, sporadically present in the Reef.

Small exsolution needles of rutile parallel to (100) of chromite are present in some grains. Cracks in the chromite grains are in some cases filled with silicate material or chalcopyrite.

2. Magnetite and Ilmenite:

Very little magnetite and ilmenite was observed in the polished sections examined (W.v.R. 106 a, b, c, d, e). Both minerals are present as small, intergranular crystals in the chromitite band (W.v.R.106 e). No magnetite veins were observed in this chromitite band as described by Retief (1959, p.62).

C. Precious Metals:

No platinum or sperrylite was encountered. Minute inclusions of highly reflecting material (0.001 m.m) are present in chalcopyrite but they are too small to identify by means of either reflectivity, microhardness, or X-ray diffraction

methods/.....

methods.

D. Temperature of Ore-Formation:

It stands to reason and experimental work also indicates that there is a temperature gradient during the formation of most ore-bodies. Deposition of the ore-minerals does not take place at a constant temperature and the temperature at any time during the deposition may vary considerably in different parts of the ore-body.

The ore-minerals may give an indication of the temperature of ore-forming solutions, but only if no subsequent heating due to metamorphism took place.

Edwards (1954, p.) regards both pyrrhotite and magnetite as high-temperature minerals, forming above 500°C.

Experimental work by Arnold (1956, p.193) indicates that an inversion to a high-temperature γ-modification takes place in pyrrhotite at 670 $\pm$ 5°C. This high-temperature form is non-quenchable and inverts to the α-form on quenching. He is of the opinion that it is very likely that the pyrrhotite exsolution (forming α-and β -pyrrhotite) is related to the inversion that takes place at a temperature of about 670°C.

The use of the pyrrhotite-pyrite assemblage as a geological thermometer by determining the iron content of pyrrhotite is unfortunately not reliable in the case of the Merensky Reef for the following reasons:-

a)/.....

a) The pyrrhotite contains exsolution lamellae of α - and β - pyrrhotite and according to Arnold (1956, p.194) the d(102) spacing curve from which the temperature of formation is calculated, is pertinent only to homogeneous pyrrhotite.

b) The ore contains nickel which may occur to a certain extent as an impurity in pyrrhotite. As such it may have an influence on the d(102) spacing of non-stoichiometric pyrrhotite when present in excess of 0.4 per cent combined cobalt and nickel (Arnold, 1957, p.220).

c) It could not be established beyond any doubt that pyrrhotite and pyrite formed in equilibrium.

d) The abundance of pyrrhotite over pyrite suggests that there was a relative deficiency of sulphur during the formation of the sulphides. This would result in the crystallization of abnormally iron-rich pyrrhotite, corresponding to a lower temperature of formation on figure 2 than actually existed during the consolidation of pyrrhotite.

X-ray diffraction data on pyrrhotite from south Tweefontein (W.v.R.A.110) proves the case in point. The d(102) value of 2.059 A^{o} (table 9) indicates an iron content of 46.7 atomic per cent on Arnold's curve (Arnold, 1956, figure 25). This latter value corresponds to the following temperatures of formation (figure 2):

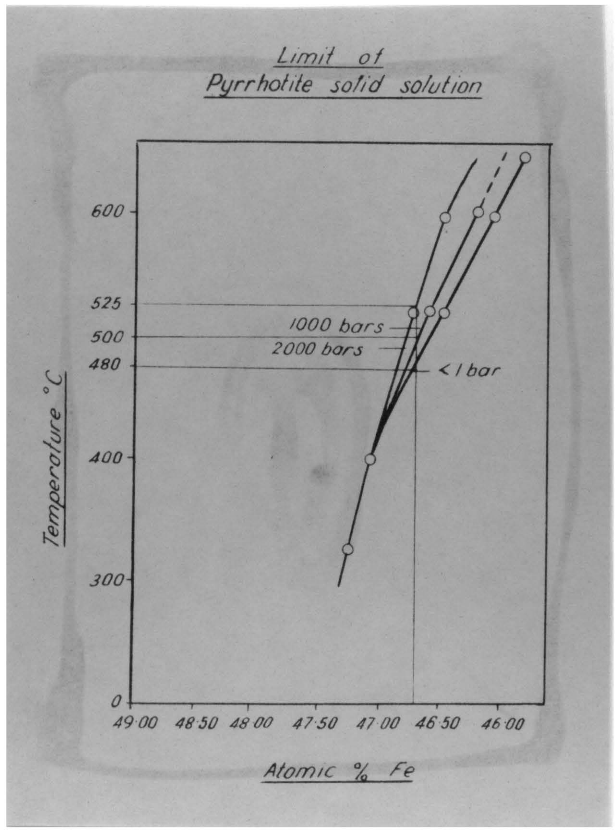

Figure 2:

The effect of pressure (< 1, 1000 and 2000 bars) on the composition of pyrrhotite that can coexist in equilibrium with pyrite. (Arnold, 1957, figure 26).

Pressure	Temperature
$<$ 1 bar	475°C
1000 bars	500°C
2000 bars	525°C

Under experimental conditions (Arnold, 1956, p.195) the lamellar phase (consisting of α - and β -pyrrhotite) was only identified in pyrrhotites quenched from above 670°C and initially more sulphur-rich than 45.6 atomic per cent Fe.

The fact that these lamellae are present in pyrrhotite of the Merensky Reef, would imply that the temperature of the mineralizing solutions was locally higher than 670°C, although the experimental data give a value of 525°C at a pressure of 2000 bars.

The presence of cubanite lamellae in chalcopyrite, indicates that the formation of chalcopyrite started above 250° - 300°C, the temperature of exsolution of cubanite from chalcopyrite.

From the experimental data, based on the work of Arnold, it would therefore appear that pyrrhotite formed to a certain extent above 670°C. The presence of cubanite lamellae in some grains of chalcopyrite indicates that such chalcopyrite formed above 250° - 300°C.

The temperature-range of formation of the Merensky Reef sulphides on Tweefontein 360 KT is therefore considered to have been from above 670°C. The lower limit is not known.

VII. MAGNETIC IRON-ORE IN THE VICINITY OF KENNEDY'S VALE.

A. Field Observations:

Several occurrences of magnetic iron-ore in the area were investigated. The ore is usually rich in titanium but differs from that of the normal magnetite bands of the Bushveld Complex in its mode of occurrence, stratigraphical position and association with ultramafic pegmatoid. These bodies of iron-ore are present in the lower part of the Lulu Mountain gabbro and even below the Merensky Reef horizon, whereas the normal bands are much higher up in the succession of mafic rocks. Moreover, the occurrences in the vicinity of Kennedy's Vale being irregularly pipe-like in form are transgressive to the layering in the gabbro and the other country rocks.

In the area covered by the geological map five pipe-like bodies of magnetite-bearing pegmatoid are present. They range in size from several yards in diameter to approximately 1200 feet by 150 feet in the case of the oval-shaped body on the central part of Kennedy's Vale 361 KT. Owing to the better exposure of this large occurrence, more information could be obtained about it than about the comparatively small bodies. The latter are invariably covered with rubble and eluvial ore.

In all cases the magnetite-bearing pegmatoid bodies are roughly circular or oval in cross-section at the surface and bear an intrusive relationship to the gabbro. The large body on Kennedy's Vale

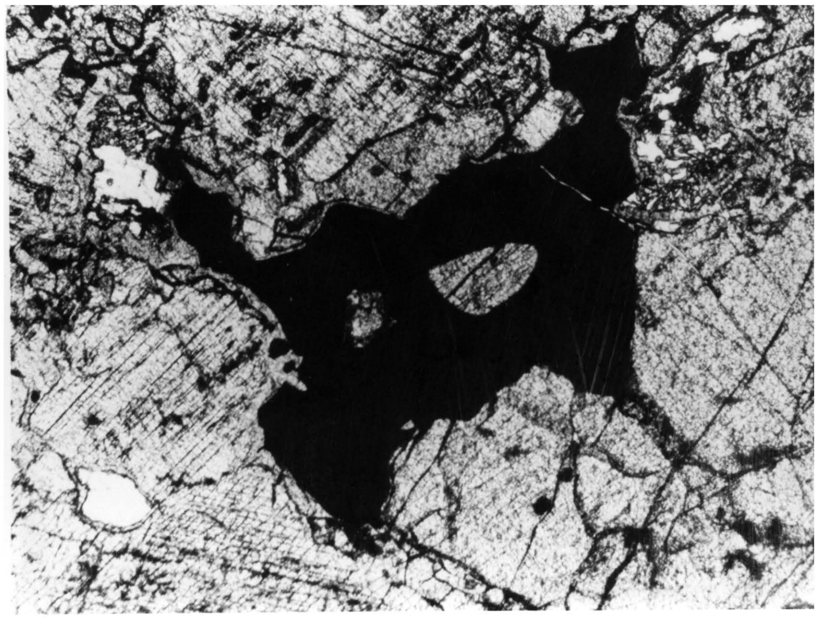

Photo 8:

Inclusions of diallage in Magnetite.
Kennedy's Vale 361 KT. (W.v.R.66) X 100

361 KT dips at an angle of 70° to the north. The designation "pipe-like" for these later intrusions appears to be justified, although the Kennedy's Vale occurrence may perhaps be better described as an inclined, transgressive, elongated fissure-filling.

Magnetic iron-ore is disseminated throughout these bodies and is concentrated in the central parts.

Associated with the pegmatoid bodies are appreciable reserves of eluvial titaniferous ore. Only such ore was being exploited during 1961. A comparison between weathered eluvial ore of the Kennedy's Vale pipe and fresh titaniferous iron-ore, from bore-hole cores of the same body, proved to be highly informative with regard to the effects of surface oxidation ~~on~~ of magnetic iron-ore.

Schwellnus (1956, p.142 - 145) and Steyn (1955, p.59 - 64) have both described similar occurrences of magnetite associated with olivine-bearing rocks in pipe-like bodies in the upper portion of the mafic rocks of the Bushveld Complex.

B. Microscopic Observations on Fresh Titaniferous Iron-ore:

Pinkish-brown magnetite is the main component of fresh titaniferous iron-ore. Inclusions of silicate minerals (olivine and clinopyroxene) in magnetite (Photo 8) and the interstitial mode of occurrence of magnetite, prove that the iron-ore minerals crystallized after the silicates. A reaction rim of amphibole is often present around magnetite (Photo 7).

Orientated/.....

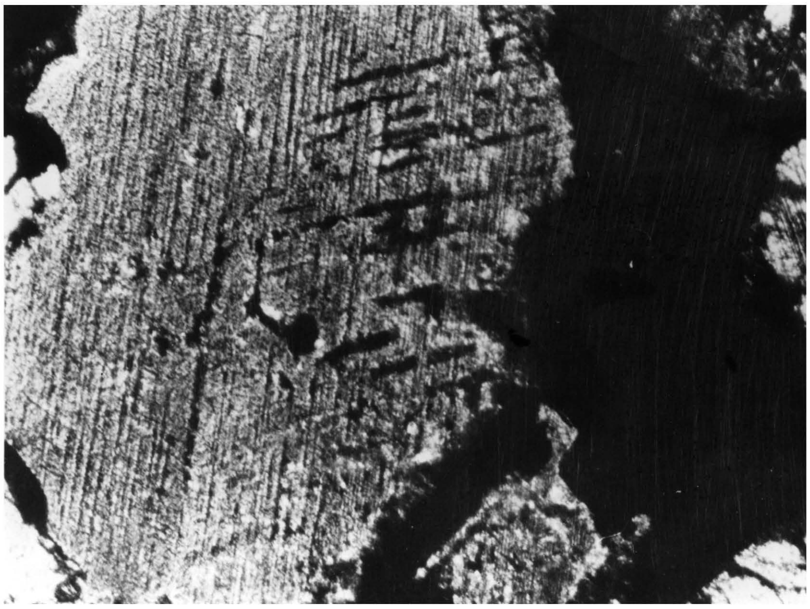

Photo 9:
Magnetite (black) and diallage (gray) in the magnetite-deposit on Kennedy's Vale 361 KT. (W.v.R.104) X 80.

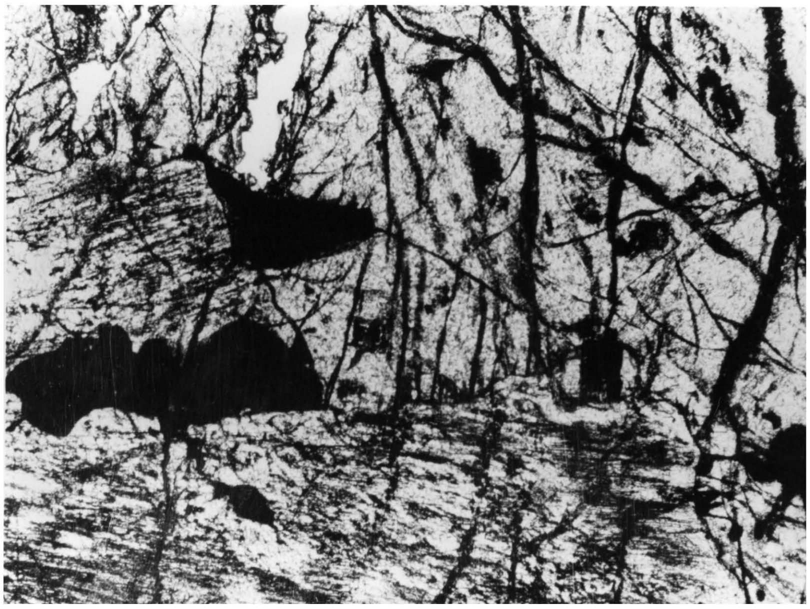

Photo 10:
Magnetite (black) possibly replacing diallage (gray) in ultramafic pegmatoid. Northwestern portion of Tweefontein 360 KT. (W.v.R.43) X 80.

Orientated spindles of spinel parallel to (100) of the host are concentrated in the central parts of the magnetite grains. Smaller "needles", representing a second generation of exsolved spinel, are in some cases associated with the larger spinel spindles. Tetrahedra, of possibly the same composition, are present either in association with needles of spinel, but more often where the latter are absent (W.v.R.K9). With very high magnification (X2200) the "needles" of spinel are observed to consist of minute, interlocking tetrahedra. Owing to the fine-grained nature of this mineral, the chemical composition could not be determined. Ramdohr (1953, p.681) refers to similar material from Magnet Heights as pleonaste.

Ulvite forms an exsolution "cloth texture" parallel to (100) of magnetite (W.v.R. K9 and 10). Lamellae of this mineral, smaller than 0.005 mm., prevent a successful physical separation of the magnetic iron-ore into a titanium-rich and titanium-free portion.

Ilmenite lamellae, elongated parallel to the (0001) directions are orientated in the (111) planes of magnetite and the mineral also forms irregular to rounded grains. A second generation of exsolved ilmenite is represented by an almost sub-microscopic "cloth texture" parallel to (111) of the host. This texture becomes more pronounced in weathered ore (W.v.R.17) or on heating to 400°C in air (heating experiments). According to Edwards (1954, p.77) the presence of ilmenite as interstitial grains indicates that the cooling

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was slow, as the ilmenite lamellae tend to diffuse to the margins of magnetite grains under such conditions and form discrete grains.

Small grains of homogeneous magnetite form islands in sulphide veinlets (A8). The reflectivity of these grains is higher than that of the major portion of the magnetite (table 11).

This highly reflecting homogeneous magnetite displays a sharp contact towards the magnetite containing exsolution bodies of spinel, ulvite and ilmenite. Its origin is dealt with in Chapter VIII.

At a depth of about 200 feet from the surface, the iron-ore suffered no alteration due to weathering effects. Evidence of maghemitization and martitization is lacking at this depth (W.v.R. 107, 108, K1 - 12, A1 - 12).

Table 11.

Reflectivity and Microhardness of Fresh Titaniferous Magnetite.

Variety	Reflectivity %	Vickers Hardness
Primary Magnetite (K9)	19.03	538
Magnetite forming islands in sulphide(A8)	20.52	545
Bowie and Taylor's values ~~ues~~ for magnetite	21.10	560

The chemical composition of fresh titaniferous iron-ore (samples 4 and 5, table 12) reveals that if all the TiO_2 is calculated as ilmenite, there is an excess of FeO, indicating that part of the TiO_2 in fresh titaniferous magnetite is present as ulvite (Fe_2 TiO_4).

C. Eluvial/.....

C. Eluvial and Weathered Magnetic Iron-ore:

Much work has been done on the microscopy of weathered Bushveld magnetic iron-ore. The mineral maghemite was identified by Wagner (1928, p.29). Subsequent work by Frankel and Grainger (1940, p.103), Schwellnus and Willemse (1943, p.29) and Strauss (1946, p.38) confirmed the identification. With the exception of Strauss, who was convinced that pinkish-brown magnetite replaces maghemite, all the above-mentioned authors regard maghemite as an oxidation product of magnetite. The fact that maghemite is not present in magnetic iron-ore of the Kennedy's Vale deposit below 200 feet, also supports this latter contention.

Many analyses of Bushveld maghemite show a considerable amount of TiO_2. Basta (1959, p.713) suggested that, as this excess TiO_2 is only normative and no rutile, anatase, brookite or other titanium mineral could be detected, it must be present in the maghemite structure, and that the homogeneous maghemite in this case be called titanomaghemite.

Two possibilities have been suggested to account for the presence of TiO_2 in homogeneous titanomaghemite in general. The first is the assumption that the excess titanium is trivalent and that the Ti_2O_3 may exist in a cubic γ -form isomorphous with γ -Fe_2O_3 (Basta, 1957, p.92). Recalculation of analyses that show a TiO_2 content much higher than that of FeO, cannot be explained in this way.

The second possibility for the interpretation

of/.....

of the composition of titanomaghemite is the existence of cubic γ -$FeTiO_3$ in solid solution with γ -Fe_2O_3. Basta (1959, p.715) suggested that gradual oxidation takes place according to the following scheme:

1) $Fe_3O_4 \cdot \gamma\text{-}FeTiO_3 \rightarrow \gamma\text{-}Fe_2O_x \cdot Fe_3O_4 \cdot \gamma\ FeTiO_3 \rightarrow$
$\gamma\ Fe_2O_3 \cdot \gamma\ FeTiO_3$

2) $\gamma\text{-}Fe_2O_3 \cdot \gamma\text{-}FeTiO_3 \rightarrow \gamma\text{-}Fe_2O_3 \cdot \gamma\ FeTiO_3 . Fe_2O_3 \cdot$
$TiO_2 \rightarrow \gamma\text{-}Fe_2O_3 \cdot TiO_2$

It was observed that the exsolution "cloth texture" of ulvöspinel parallel to (100) of magnetite gradually disappears as the oxidation of the magnetite host progresses or on heating of the magnetite (heating experiments). It is therefore suggested that, on oxidation, ulvöspinel is transformed into γ -$FeTiO_3$, which, being isomorphous with γ -Fe_2O_3, is fully miscible in maghemite.

Part of the original solid solution rich in titanium is oxidised and unmixes as lamellae of ilmenite parallel to (111) of the host. This (111) "cloth texture" of ilmenite is more prominent in weathered than in fresh magnetite (W.v.R.17).

During the present investigation of partly weathered magnetite it was noticed that at an early stage in the oxidation of ulvite, the exsolution lamellae assume a "zig-zag" pattern parallel to (100) of magnetite (photo 12). According to Ramdohr (1953, p.682) such a pattern of ilmenite lamellae parallel to (100) of magnetite denotes the oxidation of original ulvite to ilmenite.

Zonal textures and a moth-eaten pattern described by Strauss (1946, p.35) are not present

in/.....

Table 12.

Chemical Composition of Titaniferous Iron-Ore.

	1	2	3	4	5
SiO_2	0.68	0.82	0.00	1.60	0.28
Al_2O_3	2.09	2.22	4.28	5.45	5.52
Fe_2O_3	55.07	51.57	48.34	36.35	35.81
FeO	18.86	19.03	19.03	33.50	35.88
MgO	0.82	0.08	0.07	2.82	0.09
CaO	0.00	0.00	0.00	0.00	0.00
Na_2O	0.15	0.03	0.07	0.03	0.10
K_2O	0.01	0.00	0.00	0.00	0.00
H_2O^+	1.07	1.85	0.67	1.11	0.66
H_2O^-	0.10	0.16	0.13	0.13	0.09
TiO_2	18.24	18.88	24.80	16.40	17.80
P_2O_5	0.01	0.02	0.04	0.05	0.08
Cr_2O_3	0.25	0.41	0.43	0.19	0.20
V_2O_5	2.16	4.29	1.30	2.49	2.83
MnO	0.29	0.21	0.37	0.23	0.23
Total	99.80	99.57	99.53	100.40	99.54

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$MgO.SiO_2$	1.14	0.20		2.67	0.22	Enstatite
$FeO.SiO_2$		1.54			0.33	Ferrosilite
$MgO.Al_2O_3$	0.49		0.25	6.12		Spinel
$FeO.Al_2O_3$	2.97	3.76	6.99	1.81	9.41	Hercynite
$2FeO.TiO_2$				16.13	4.64	Ulvite
$MnO.Fe_2O_3$	0.94	0.68	1.20	0.75	0.75	Jacobsite
$FeO.V_2O_3$	3.20	6.35	1.92	3.68	4.19	Coulsonite
$FeO.Cr_2O_3$	0.41	0.60	0.63	0.28	0.29	Chromite
$FeO.TiO_2$	34.62	30.39	32.38	20.19	30.64	Ilmenite
$FeO.Fe_2O_3$	0.29			37.30	41.51	Magnetite
$Fe_2O_3.H_2O$	11.56	19.84	7.90	11.34	7.41	Goethite
γ-Fe_2O_3	43.80	33.21	40.41			Maghemite
TiO_2		2.87	7.74			TiO_2 in Titano-maghemite.
Total	99.42	99.44	99.42	100.27	99.39	

Table 12 (continued)

1. Titaniferous iron-ore, pipe-like body on north-western portion of Tweefontein 360 KT. (Surface sample).
   Polished Section W.v.R.34.
   Analyst:- P. Fourie, Division of Chemical Services.

2. Titaniferous iron-ore, Kennedy's Vale vanadium mine. (Surface sample).
   Polished section - W.v.R.99.
   Analyst:- P. Fourie, Division of Chemical Services.

3. Titaniferous iron-ore, pipe-like body in the southern part of Tweefontein 360 KT. (Surface sample).
   Polished section - W.v.R.95.
   Analyst:- P. Fourie, Division of Chemical Services.

4. and 5. Fresh Titaniferous iron-ore, bore-hole cores in the Kennedy's Vale vanadium mine. (Depth - more than 200 feet).
   Polished sections - K8 and 9.
   Analyst:- P. Fourie, Division of Chemical Services.

in fresh titaniferous iron-ore. These textures are, therefore, attributed to surface weathering effects. Quantitative measurement of reflectivity indicate that the zonal pattern is a rim oxidation texture, each successive zone from the core outwards representing a more advanced stage in the oxidation of magnetite to maghemite (or titanomaghemite).

Table 13.*

Reflectivity of Successive Zones of Oxidized Magnetite in a Single grain (W.v.R.17).

	Variety of Magnetite	Reflectivity %
1.	Core of pinkish-brown magnetite	20.25
2.	Inner zone of pink "magnetite"	22.41
3.	Central zone of white "magnetite"	23.72
4.	Outer zone of blueish-white "maghemite"	24.25

The contact between magnetite and maghemite is usually not sharp (W.v.R.17). On weathering the colour of magnetite changes from reddish-brown, to yellowish-brown, to greyish-white and finally to typical blueish-white maghemite, with all possible intermediate colours. The various magnetic iron-ore minerals described by Strauss are therefore merely stages in the oxidation of magnetite (W.v.R. 23, 30, 25). Experimental data show that the transformation of magnetite to maghemite is a

gradual/......

* Ulvite was present in the surfaces measured and interferes with the readings to some extent. As the ulvite occurs in all cases in comparable amounts, the effect is taken as a constant and negligible error.

gradual process (Twenhofel, L.H., 1927, p.180 - 188, and Hägg, 1935, p.22).

Transformation of magnetite to maghemite starts on the contact of spinel "needles". These "needles" evidently provide reactive open planes in magnetite along which oxidation can take place.

It was noticeable in the study of magnetites from various localities, that magnetite without exsolution lamellae of ilmenite, spinel or ulvite does not readily oxidise to maghemite, whereas the oxidation to martite is a common phenomenon. It would appear that titanium promotes the process of maghemitization.

Table 14.

Microhardness and Reflectivity of Magnetic Iron-Ore Minerals measured in different fields.

Magnetic Iron-ore Mineral	Reflectivity %	Vickers Hardness
1. Fresh magnetite - reddish-brown (Kennedy's Vale deposit - K9).	(18.94 - 19.12) 19.03	(521 - 554) 538
2. Pinkish-brown "magnetite" (Kennedy's Vale deposit - W.v.R.17)	(20.21 - 21.06) 20.63	(563 - 581) 571
3. Pink "magnetite" (Kennedy's Vale deposit - W.v.R.17, 99).	(22.31 - 23.25) 22.79	(565 - 687) 626
4. White "magnetite" (Kennedy's Vale deposit - W.v.R.17, 99).	(23.20 - 24.24) 23.72	(660 - 712) 686
5. Blueish-gray "maghemite" (Kennedy's Vale deposit - W.v.R.17, 99).	(24.05 - 26.51) 25.28	(846 - 893) 869

Coulsonite, which has been described as a vanado-maghemite by various authors, could not be positively identified in either fresh or weathered

magnetic/.....

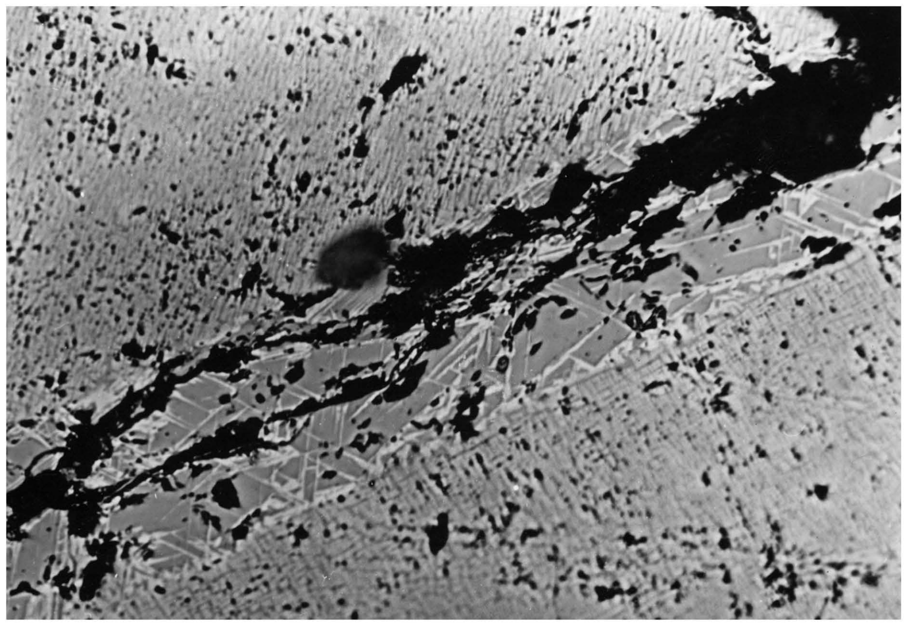


Photo 11: Various stages in the Fe_3O_4 - γ - Fe_2O_3 series, also unaltered magnetite containing martite parallel to (111), along crack. Magnetite-deposit on Kennedy's Vale - Eluvial magnetic iron-ore. Polished section W.v.R.17 - X 600 .

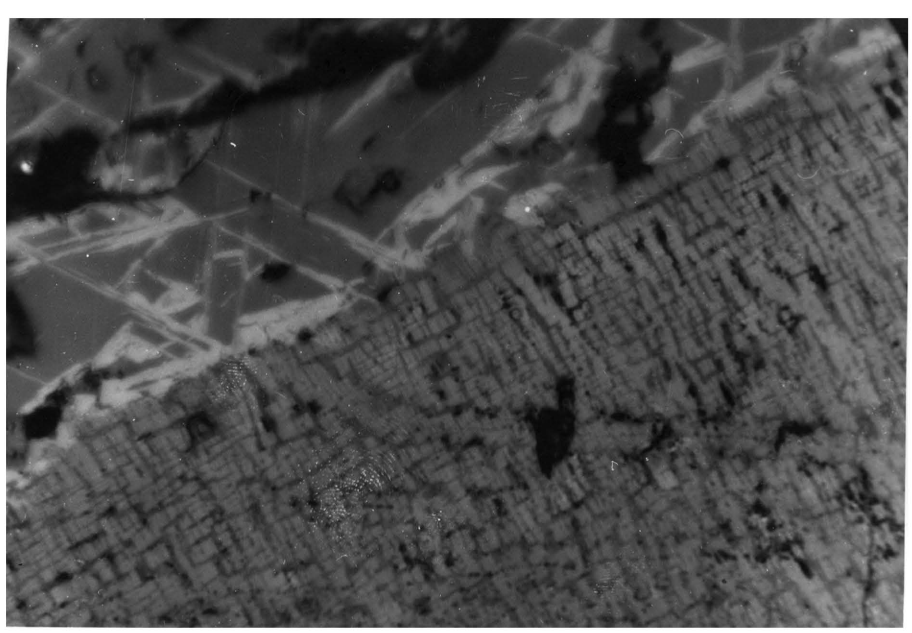


Photo 12: In bottom part of photo - "zig-zag" pattern in exsolution lamellae parallel to (100) of magnetite, representing original ulvite now oxidized to ilmenite. Top part of photo - martite lamellae (white) parallel to (111) of unaltered (gray) - Magnetite deposit on Kennedy's Vale, Oil immersion, Polished section W.v.R.17 - X 1800.

magnetic iron-ore.

Some magnetite grains have a narrow border completely free of exsolution bodies of ulvite, ilmenite or spinel. The same phenomenon was observed in titanomagnetite of the Skaergaard intrusion (Vincent, 1960, p.993, fig. 6).

Homogeneous pinkish-brown magnetite on the sides of cracks, form veinlike structures in the magnetic iron-ore. Martite lamellae are orientated parallel to the (111) planes of this magnetite (Photo 11). The early oxidation of magnetite to form martite along the reactive (111) planes of the host, evidently rendered this magnetite passive to further oxidation to "maghemite". No maghemite or any of the intermediate stages is present in the areas of martitized magnetite (W. v.R.17).

Basta (1959, p.710) suggests that oxidation of magnetite above 480°C will result in the formation of hematite and not maghemite, as the latter is unstable above this temperature. Experiments carried out during the present investigation indicate that maghemite can still form at 700°C, depending on the length of time during which oxidizing conditions existed.

The fact that martitized magnetite is present in the vicinity of cracks, the areas where any oxidation process would be expected to start, provides further evidence that martitization of magnetite takes place before maghemitization.

Unfortunately the author did not have all

the/.....

the bore-hole cores at his disposal so that it could not be definitely established at what depth martite and maghemite formed.

It is noticeable that titanium-rich magnetitic iron-ore which formed at fairly high temperatures (about 600°C) ~~and rich in titanium~~ is more prone to oxidation to maghemite than sedimentary magnetite. On cooling of high-temperature magnetite a certain amount of fracturing takes place. Along these fracture planes oxidation may readily take place. The reactive open planes provided by exsolution lamellae of ilmenite, spinel and ulvöspinel are also favoured by maghemitization.

Goethite is not uncommon in highly weathered magnetic iron-ore. Veins of this mineral, filling cracks in magnetite and even cutting through ilmenite grains, are fairly abundant in eluvial and alluvial titaniferous iron-ore (W.v. R.29).

D. Heating Experiments on Kennedy's Vale Magnetic Iron-ore:

Polished sections of fresh magnetite iron-ore of the Kennedy's Vale magnetite deposit were heated in air in a controlled differential thermal analysis unit for short periods, with the object of studying the oxidation processes that take place.

Similar experiments were carried out as early as 1927 when Newhouse and Callahan (1927, p.629) heated "blue magnetite" in an oxidising flame and produced "brown magnetite". At higher temperatures hematite was formed.

Present knowledge leads one to suspect

that/.....

that the original "blue magnetite" was already a partially oxidized product. Twenhofel (1927, p.180) proved that heating of magnetite below 500°C resulted in the gradual oxidation of magnetite, without any change in the crystal structure. Above this temperature oxidation of magnetite resulted in the formation of hematite.

Differential thermal analysis of natural magnetite was carried out by Schmidt and Vermaas (1955, p.422). Their thermal curves show two distinct exothermic peaks at 360° - 375°C and 580°C. The first of these peaks was most pronounced in fine-grained specimens and was attributed to surface oxidation of magnetite to hematite by them. No maghemite was detected by them at any stage.

1. Heating to 390°C.

A polished section (W.v.R.107a) of magnetic iron-ore of the Kennedy's Vale deposit (from a borehole core at a depth of more than 200 feet) was heated at a constant rate of 12°C per minute to 390°C, in the Geological Survey Laboratory, at which temperature the section was kept for 30 minutes, and then quenched in water.

The following changes were observed:

a) Ulvite exsolution lamellae parallel to (100) of magnetite underwent a change in volume. The zig-zag pattern of the individual lamellae after heating provides the necessary evidence of this increase in volume.

b) Comparison with fresh magnetite illustrates that the heated equivalent has become lighter

in/.....

in colour.

c) Irregular blueish-white areas near cracks in the magnetite evidently represent titano-maghemite.

The presence of products of the Fe_3O_4 - γ-Fe_2O_3 series in this heated magnetite is in accordance with the study by Lepp (1957, p.679) on the Mineville magnetite. Finely ground material was heated by him to 430°C and 500°C in a differential thermal analysis unit. X-ray powder photographs of the products showed strong magnetite patterns and a few of the strongest hematite lines. Chemical analyses, however, revealed a much higher Fe_2O_3 content than could be explained by the few weak hematite lines. He concluded that most of the oxidation below 500°C must have involved a change to maghemite, a conclusion that is supported by the broadening of magnetite lines at the high angle θ.

d) The ilmenite "cloth texture" parallel to (111) of magnetite is more pronounced in heated samples than in fresh magnetic iron-ore. Ulvite present in solid solution with magnetite (Vincent et al, 1957, p.1004) is probably oxidized to ilmenite.

2. <u>Heating to 510°C.</u>

The same section (W.v.R.107a) was then heated at a constant rate of 12°C per minute to 510°C, and maintained for 60 minutes at this temperature. Rapid quenching in water resulted in a hard surface layer of goethite being formed. This surface layer could not be removed by either alcohol, dilute hydrochloric acid or ammonium

hydroxide/.....

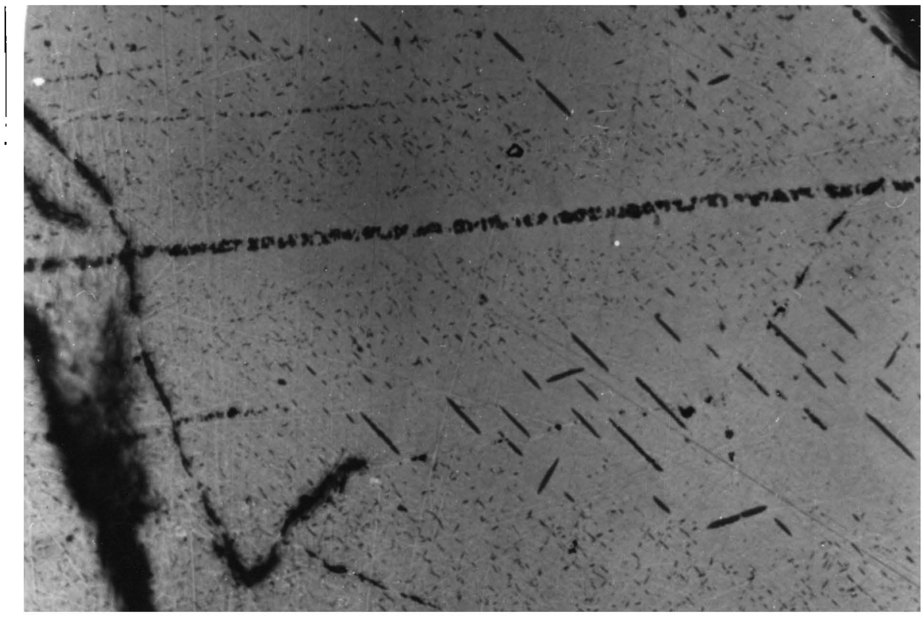


Photo 13: Partial solution of spinel into maghemite after heating to 510°C. Veinlet of spinel in central part of photo.
Polished section W.v.R.107a - X 600.

hydroxide. The section was then repolished, removing as little as possible of the surface.

a) Light pink and blueish areas in magnetite reveal that the oxidation of magnetite to maghemite is not homogeneous throughout the section. Exsolution bodies of spinel, ulvite and ilmenite, providing reactive open planes, apparently have an influence on the process.

b) Thin particles and minute, irregular blebs of hematite prove that this mineral may form below 580°C in very subordinate amounts.

c) The regular orientation of spinel needles parallel to (100) of magnetite was disturbed (see photo 13). Thin veinlets of spinel tetrahedra and irregularly distributed spinel spindles in the immediate vicinity of the spinel veinlets, are evident.

3. Heating to 700°C.

Section K3 of magnetic iron-ore of the Kennedy's Vale deposit (from a bore-hole core at a depth of more than 200 feet) was heated at a constant rate of 12°C per minute to 700°C. This temperature was maintained for 120 minutes. The section was not quenched as it was feared that magnetite would react with water or organic substances. The section was therefore allowed to cool in air.

The following phenomena were observed:

a) A surface layer of hematite destroyed the polish of the surface. The section was therefore carefully repolished.

b) Minute hematite spicules (1μ) are present in the (111) planes of greyish-white magnetite.

c) Large areas of possible maghemite are completely

free/.....

free of any exsolution lamellae of either ulvite, ilmenite or spinel. Ulvite and possibly ilmenite have probably dissolved in the defect structure of maghemite, their titanium contributing to the formation of titanomaghemite. The disappearance of spinel in these areas is very difficult to explain. Under crossed nicols in oil the maghemite exhibits a reddish internal reflection.

d) Irregular cracks are present throughout the section. Their origin is attributed to the rapid cooling of the heated specimen.

The experiments carried out in the present investigation indicate that the oxidation of titaniferous magnetite below 500°C results almost exclusively in the formation of titanomaghemite. The disappearance of spinel, ulvöspinel and ilmenite indicates that these constituents take part in the process of titanomaghemitization.

Contrary to the findings of previous investigators titanomaghemite was observed in sections heated to 700°C. Assuming that the repolished surface was in equilibrium with this temperature, it would therefore appear that when titanium is present the oxidation of magnetite, even at 700°, results in the formation of titanomaghemite rather than martite, and that during the oxidation of titaniferous magnetite martite forms only in subordinate amounts. The predominance of titanomaghemite over martite in naturally oxidized specimens of Bushveld magnetic iron-ore, would appear to substantiate this view.

VIII. SULPHIDES IN THE MAGNETITE-DEPOSIT ON KENNEDY'S VALE 361 KT.

Bore-hole cores in the magnetite-deposit on Kennedy's Vale reveal that sulphides are disseminated throughout the body. Single, large sulphide grains are associated with both pyroxene and olivine. The concentration of the sulphides is, however, higher in the central, magnetite-rich part of the body. It would therefore appear that the sulphides are genetically related to the titaniferous magnetite.

The sulphide mineral assemblage reveals a marked resemblance to that of the Merensky Reef. It is commonly accepted that the ultramafic pegmatoid is of later intrusion than the porphyritic pyroxenite of the Merensky Reef. Where these pegmatoid pipes broke through the Merensky Reef during their intrusion, sulphides could have been incorporated by the pegmatoid. Thus the Merensky Reef could have served as a source of copper and nickel sulphides for the pegmatoid.

No field-relationships were observed which could prove this possibility, although mapping has shown that down-faulting has taken place on the western flank of the Dwars River Fragment by which the Merensky Reef should have been brought to a position below the present outcrop of the ultramafic pegmatoid on Kennedy's Vale.

Droplets of sulphides enclosed in olivine grains, point to crystallization from a melt as the mode of origin of some of the sulphides.

A. Mineralogy:

The sulphide minerals are described in the

order/....

order of their deposition.

1. Pyrrhotite:

Both the α - and β -varieties of pyrrhotite are common. The difference between the optical properties of the two constituents is not as marked as in the case of pyrrhotite from the Merensky Reef. This phenomenon could be explained by differential weathering of the two varieties in the exposed samples collected of the Merensky Reef.

The d(102) value of 2.089A^{o} of pyrrhotite from Kennedy's Vale (table 15) corresponds to a composition of almost 50 atomic per cent Fe, whereas pyrrhotite of the Merensky Reef contains 46.7 atomic per cent Fe.

Small exsolution flames of pentlandite are often present in pyrrhotite grains (A9). These flames vary in size from almost submicroscopic to 20 μ in diameter.

Pyrrhotite is replaced by chalcopyrite (A2,10) and irregular cubanite (A10,12). Some pyrrhotite grains exhibit a pronounced basal cleavage (A4).

2. Pentlandite:

The colour of the pentlandite varies slightly from a light-yellow to purplish-yellow. Experimental work (Kullerud, 1957, p.174) indicates that the pentlandite cubic structure will tolerate considerable variation in the Fe : N. ratio and that this variation is responsible for the change in colour.

Exsolution flames of pentlandite are common in pyrrhotite. Such flames are also present in irregular cubanite (A12). Experiments at the Carnegie Institute, Washington (Kullernud, 1957, p.194) have shown that Fe_7S_8 and $Ni_{12}S_{13}$ form a

Table 15.

X-Ray diffraction data of pyrrhotite of the Merensky Reef and of the Magnetite Deposit on Kennedy's Vale.

Co K α Radiation.

Merensky Reef (A110)		Kennedy's Vale (A8)	
d (A^o)	I	d (A^o)	I
2.96	30	2.98	30
2.63	60	2.66	50
		2.52	10
2.27	5	2.31	20
<u>2.059</u>	100	<u>2.089</u>	100
		1.92	20
		1.77	10
1.72	30	1.72	30
1.61	5	1.64	20
		1.49	10
1.43	10	1.45	10
1.10	30	1.12	20
1.05	20	1.05	20
0.994	10	0.993	15
0.970	10	0.977	10
		0.930	5
0.914	20		

d(102) values are underlined.

X-Ray diffraction data of pentlandite in magnetic iron-ore.

	Kennedy's Vale 253 (W.v.R.107)		Sudbury		Ni-Pentlandite (Konvo, 0, 1959)		
No.	I/I	d(A°)	I/I	d(A°)	I/I	d(A°)	hkl
1	20	5.913			30	5.78	111
2.	5	5.075			5	5.01	002
3	10	3.536	.2	3.54	5	3.55	022
4	60	3.059	.9	3.03	80	3.03	113
5			.7	2.89	40	2.90	222
6			.1	2.51	5	2.51	004
7	40	2.299	.5	2.30	30	2.30	133
8					5	2.25	024
9			.1	2.13			
10	50	1.938	.8	1.95	50	1.931	115,333
11	100	1.773	1.C	1.77	100	1.775	044
12	30	1.719	.1	1.695	5	1.697	135
13			.2	1.525	10	1.530	335
14	10	1.516	.2	1.515	10	1.514	226
15			.5	1.305	20	1.307	355,731
16			.5	1.25	20	1.255	008
17			.2	1.235			
18	10	1.157	.1	1.155	5	1.160	157,555
19	5	1.103			5	1.105	119,357
20			.1	1.069	5a	1.052	139
21	10	1.049	.1	1.049			
22	30	1.024	.5	1.022	20a	1.025	448
23	10	.9696			5a	0.9704	159,377
24					5a	0.8878	088
25					5a	0.8068	579
26					10a	0.7941	0.4.12

complete solid solution series above 374°C. When heated for a minimum of 75 days, mixtures of FeS and NiS, in the region where NiS amounts to more than 20- and less than 70 mol per cent, will produce pyrrhotite-type $(Fe, Ni)_{1-x}S$ mix crystals as well as pentlandite.

Characteristic of pentlandite of the Kennedy's Vale magnetite deposit are numerous , orientated, irregular, feathery lamellae of valleriite. Although pentlandite is usually free of exsolvents, the occurrence of exsolution bodies of valleriite have been described by various authors (Ramdohr, 1960, p.465).

Small inclusions of pyrrhotite in pentlandite were also observed (A6, 8) and these are characteristic of pentlandite formed at very high temperatures, aoccrding to Ramdohr (1960, p.465).

3. Chalcopyrite:

Both pyrrhotite and pentlandite are replaced by chalcopyrite (A8). Exsolution lamellae of cubanite are common in the chalcopyrite. These lamellae are present as laths parallel to (111) of chalcopyrite.

Secondary magnetite is often associated with chalcopyrite and pyrrhotite. Such magnetite associated with pyrrhotite is usually regarded as an oxidation product of pyrrhotite, according to the following equation:

$$6\ FeS + 4O \rightarrow 3\ FeS_2 + Fe_3O_4$$

If this process were responsible for the formation of the secondary magnetite, pyrite would be expected to be present in the immediate vicinity of the magnetite. This is not the case in the

Kennedy's/.....

Kennedy's Vale ore and the mode of origin of this secondary magnetite is therefore in this respect exceptional.

The fact that veinlets of chalcopyrite invariably contain small grains of pentlandite and pyrrhotite reveals the intimate association between the copper-nickel-iron sulphides, although there is enough evidence to suggest that the crystallization of chalcopyrite took place after the consolidation of pentlandite and pyrrhotite.

4. Irregular cubanite:

Irregular areas of yellowish-brown cubanite (0.05 to 0.5 mm.) are present in the margins of chalcopyrite grains (A8). This cubanite is always associated with pyrrhotite, developing on the contact of pyrrhotite and chalcopyrite.

C.M. Schwellnus (1940, p.100) is convinced that irregular cubanite formed as a result of the reaction of chalcopyrite, still in the liquid state, with pyrrhotite,—hence at a very much higher temperature than the lamellar variety, which represents an exsolution product of chalcopyrite. The presence of flames of pentlandite, which are usually only present in pyrrhotite, in the irregular cubanite of the Kennedy's Vale deposit supports this view.

Scholtz (1936, p.174 - 176) distinguishes between lamellar cubanite and irregular cubanite in the Insizwa ore. He is unable to account for the excess of iron and sulphur in the irregular variety.

The Vickers hardness of irregular cubanite in the Kennedy's Vale magnetite deposit varies

between/.....

between 191 - 204. Bowie and Taylor (1958, p. 275) give a value of 199 - 228 for cubanite. X-ray diffraction data on cubanite from Kennedy's Vale reveals that the mineral closely resembles normal cubanite. (Table 17).

Table 17.

X-Ray diffraction Data on Irregular Cubanite.

Kennedy's Vale 361 KT (A8) Co K α Radiation		Waldo (Amer. Min., 20, p.585) Co K α Radiation	
I	d(A°)	I	d(A°)
W	4.15		
		VW	3.84
W	3.73		
W	3.47	W	3.48
M	3.22	M	3.21
S	3.08	S	3.07
VW	2.79	VW	2.78
VW	2.52	VW	2.52
		W	2.31
M	2.09	M	2.12
M	1.94	M	1.937
M	1.86	M	1.890

5. Lamellar cubanite:

Exsolution lamellae of cubanite parallel to (111) of chalcopyrite are common in the Kennedy's Vale magnetite deposit. The temperature of exsolution of cubanite from chalcopyrite is normally taken to be 250°C ~~and~~ 300°C (Ramdohr 1960, p.581).

~~The abundance of cubanite exsolution lamellae in chalcopyrite indicate that the latter was originally oversaturated with iron.~~

Where the lamellar and irregular varieties of cubanite are both present, there is usually a sharp contact between them (A6, 8).

6. Valleriite/.....

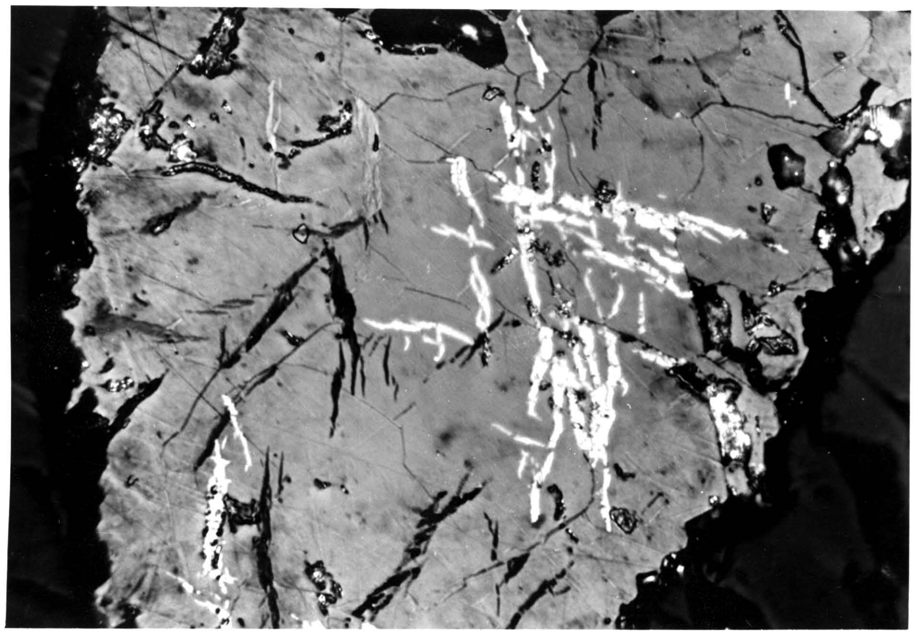


Photo 15: Exsolution lamellae of valleriite (white and black) in Pentlandite (grey) - Magnetite deposit on Kennedy's Vale.
Polished section K9 - Crossed nicols.
X 600.

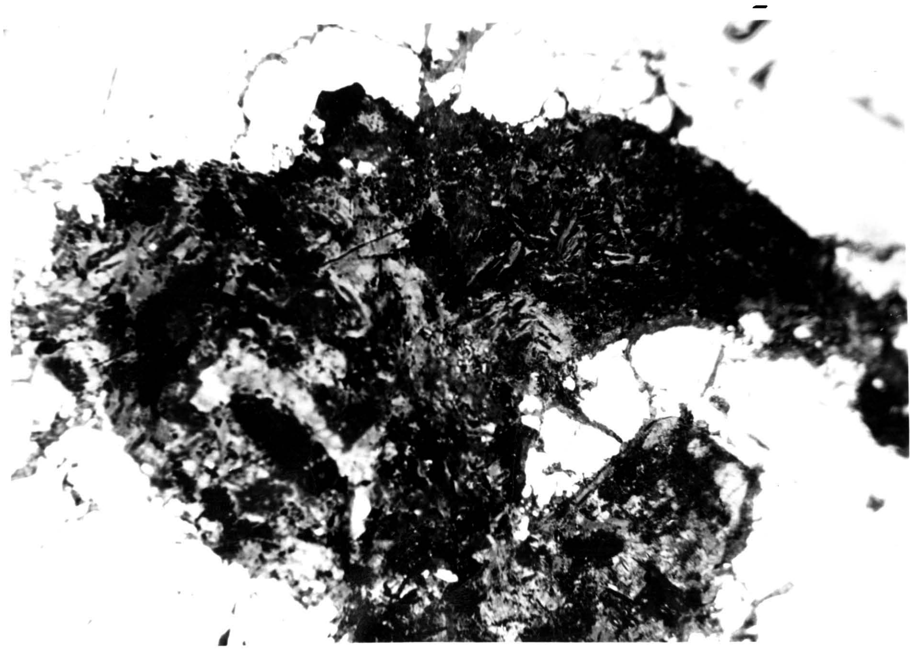


Photo 16: Valleriite (gray) associated with silicates (black) in magnetite (white). Magnetite deposit on Kennedy's Vale.
Polished Section A4. X 300.

6. Valleriite:

Very little valleriite is present in chalcopyrite but irregular, feathery lamellae of minute dimensions are very common in pentlandite (W.v.R. 107, K4, 5, A8, 9).

There is a difference of opinion in the literature regarding the origin of valleriite in pentlandite. According to Scholtz (1936, p. 164) "The microscopic study of the Insizwa and other ores clearly indicates that there is no evidence to support the contention that valleriite is to be regarded as an exsolution product of pentlandite", whereas Ramdohr (1960 P.405) points out that "Im Pentlandit von Insizwa und anderswo findet sich sehr schön und regelmässig Valleriit als Entmischungsprodukt".

The orientated nature of the inclusions in pentlandite points to exsolution from a complex Ni-Fe-Cu sulphide as the mode of origin of valleriite (Photo 15). At high temperatures (above 600°C, as valleriite lamellae in pentlandite have not been described in ore of hydrothermal origin) the existence of an unstable mineral, vallerio-pentlandite, is therefore postulated.

Individual grains and irregular veinlets of valleriite also occur (Photo 16) and are interstitial to magnetite. This latter variety of valleriite is considered to be of hydrothermal origin and was probably introduced later than the other sulphides; carbonate is also present in considerable quantities.

B. The Formation of the Kennedy's Vale Sulphides.

1. Introduction of Sulphur:

It is conceived that sulphur, presumably present in the ultramafic magma, reacted with magnetite to form pyrrhotite and possibly pyrite. at temperatures below 675°C. Experiments by Kullerud (1957, p.199) indicate that pyrite and pyrrhorite can coexist with magnetite at temperatures below 675°C.

According to him (1957, p.199), hematite, if present, may be transformed into pyrite and SO_2 gas by the introduction of sulphur. At about 675°C pyrite and magnetite react to form pyrrhotite and hematite. At 700°C pyrite and hematite react to form pyrrhotite and SO_2 gas. The experiments were carried out in evacuated, sealed silica tubes, so that the effect of pressure was negligible.

In Kullerud's experiments (1957, p.199) pyrite was no longer stable above 743°C, regardless of the amount of sulphur present. Hematite, magnetite and pyrrhotite remain a stable mineral assemblage. The iron-ore was poor in oxygen during the crystallization, as is ~~evidenced~~ indicated by the presence of ulvite ($Fe_2 TiO_4$), and therefore hematite would not be expected to have formed as a primary product of crystallization.

As the amount of sulphur was small in relation to iron, in the Kennedy's Vale magnetite deposit, very little pyrite would be expected to have formed even below 743°C.

2. Addition of Cu and Ni as Sulphides:

Reaction of NiS and CuS with pyrrhotite then

probably/.....

probably took place. At the elevated temperatures (above 670°C as both varieties of pyrrhotite are present) considerable solid solution is possible.

Above 374°C the low temperature modification of NiS, millerite, inverts to a high-temperature modification, isostructural with components of the pyrrhotite series. FeS could then have been taken into solid solution and as a result pentlandite formed (Arnold, 1957, p.197)

The presence of chalcopyrite exsolution bodies in pentlandite inclined Pauly (1958, p.2) to the view that a mineral chalcopentlandite exists at high temperatures. In the case of the Kennedy's Vale deposit, the excess iron caused the exsolution of valleriite ($Cu_3Fe_4S_7$) instead of chalcopyrite ($CuFeS_2$). In this case the high-temperature mineral was therefore valleriopentlandite.

In addition CuS reacted with FeS to form iron-copper sulphides of which chalcopyrite is the most stable. Near pyrrhotite grains the excess FeS resulted in the formation of irregular cubanite.

Small quantities of NiS were absorbed in solid solution with pyrrhotite and exsolved at a later stage as flames of pentlandite.

The fact that chalcopyrite replaces pyrrhotite and pentlandite is attributed to the possibility that the highly mobile CuS was still introduced after the crystallization of the pyrrhotite and pentlandite.

The sulphides in the magnetite deposit on

Kennedy's/.....

Kennedy's Vale should be classified with the pegmatitic ore-deposits, as defined by Niggli (1954, p.513) as far as their association with rocks of definite pegmatoidal origin is concerned. With regard to their temperature of formation, they do, however, resemble orthomagmatic deposits. The sulphide mineral assemblage, particularly the presence of irregular cubanite and valleriopentlandite, is also characteristic of ortho-magmatic deposits and in this respect the Kennedy's Vale ore shows a marked resemblance to deposits such as Insizwa and Vlakfontein, which are classified by Bateman (1951, p.71) as late magmatic.

It is therefore proposed that such an assemblage be referred to as pegmatoidal in character.

The pegmatoidal stage of ore-formation was concluded with the deposition of chalcopyrite and irregular cubanite (table 18). Evidence of slight hydrothermal action, such as the formation of biotite, the development of reaction rims of amphibole around magnetite grains and the occurrence of individual grains of valleriite associated with the silicates, indicate that as the temperature dropped to below about 550°C there was a gradual change-over from pegmatoidal to hypothermal conditions.

It is considered that in ultramafic magmas the pegmatoidal stage takes the place of the pegmatitic stage, and because of its exceptional characteristics warrants a separate classification.

Table 18/.....

Table 18.

Stages of Ore-Formation in the Kennedy's Vale Deposit.

Pegmatoidal Stage		Hydrothermal Stage
Residual Liquid Segregation	Immiscible Liquid Segregation	Hypothermal Stage
magnetite contain ing in solid solu- tion: ilmenite spinel ulvite	pyrrhotite valleriopentlandite chalcopyrite irregular cubanite	amphibole biotite valleriite

APPENDIX.

Quantitative Measurement of Microhardness and Reflectivity of Ore-Minerals.

A. Measurement of Micro-indentation Hardness:

As an additional means of identification and in order to study slight variations in the physical properties of irregular cubanite, microhardness tests were applied to the Kennedy's Vale sulphides. Variations in the physical properties of the magnetite-maghemite series were also studied by this method. A Reichert metallurgical micro-indentation hardness tester was used in these experiments.

The hardness value, which is a function of load over area, can be calculated from the reading on the screw-micrometer eyepiece by the use of the formula:

$$Hm = \frac{2PS \text{ in } \theta . 1000}{(d \cdot (68)^2}$$

P = load in grams
d = reading on Micrometer.

Previous work on the microhardness of ore-minerals was done by Bowie and Taylor (1958, p.271) using a load of 100 grams. In the present experiments loads of as little as 5 grams were used. By using smaller loads the hardness of exsolution bodies 0.01 mm. in diameter could be measured. Using a load of 100 grams the minimum grain diameter is 0.1 mm.

Unfortunately, however, the smaller the load, the greater is the margin of error, depending also on the hardness and resistance to shattering of the mineral tested. The object is therefore

to/.....

to select a load, for each specific mineral, that gives an indentation large enough to measure accurately.

In the study of the magnetite-maghemite series a load of 34 grams gave the most satisfactory results, whereas a load of 10 grams was sufficient in the case of chalcopyrite, cubanite, pentlandite and pyrrhotite.

The Reichert microscope to which the hardness tester was fitted, was not equipped with crossed polarizing prisms so that the orientation of mineral grains could not be readily determined. According to Bowie and Taylor (1958, p.274) some minerals show marked variation in hardness values in different crystallagraphic directions.

The hardness of fresh magnetite from Kennedy's Vale was determined for loads of 5, 10 and 34 grams. The results of this experiment are summarized in table 19:

Table 19.

Hardness of Fresh Magnetite from Kennedy's Vale at Different Loads.

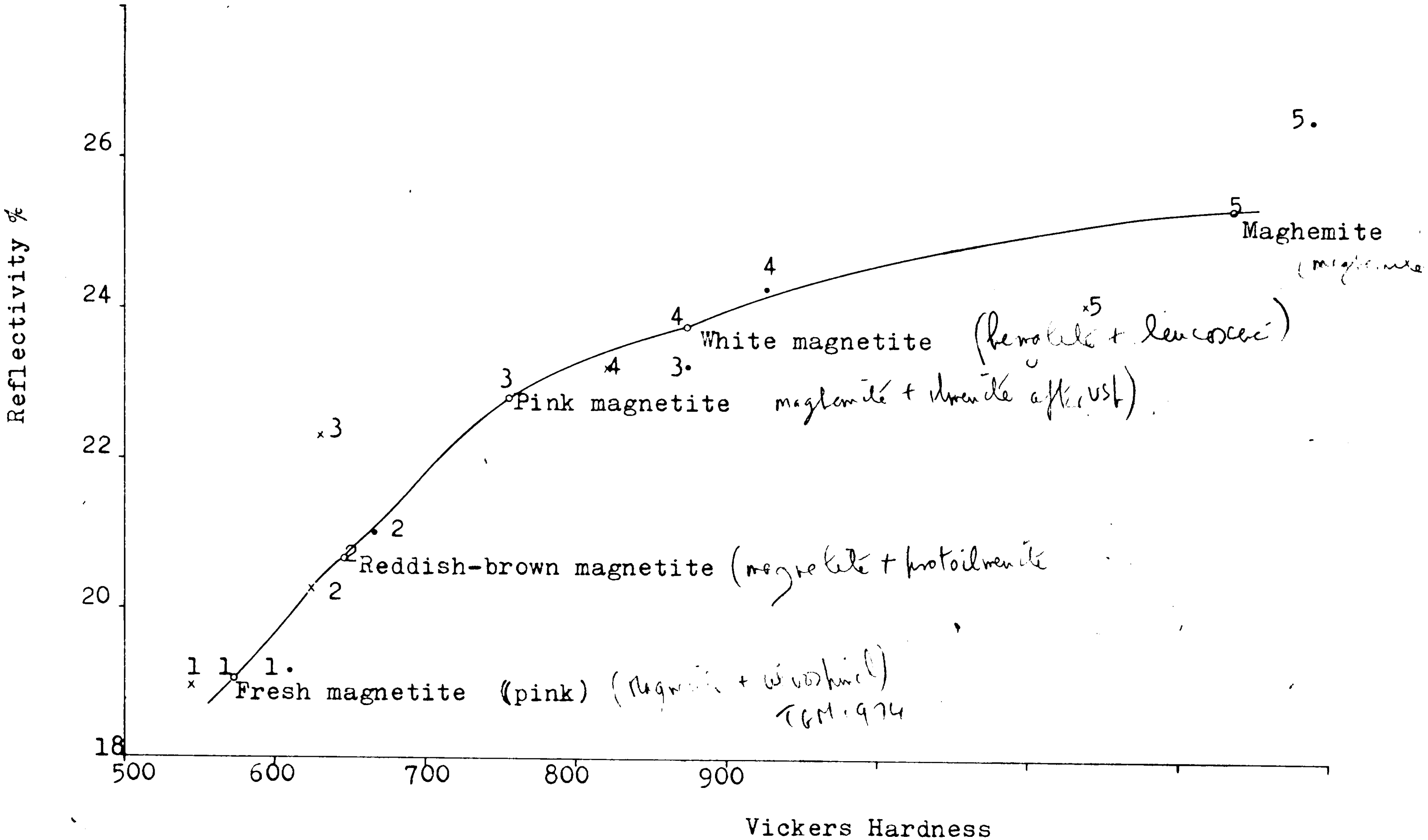
Reading	Load	Hardness
24	5 grams	570
34	10 grams	568
64.5	34 grams	536.6

To test the reproducibility of the hardness of a specific mineral at a constant load (34 grams), the hardness of magnetite was determined 10 times at different points in the same polished section (K9). An average value of 536.6 and an average deviation of 8.12 was obtained (Percentage deviation 1.51 per cent).

B. Measurement/.......

Micro-indentation hardness and Reflectivity of the Magnetic iron ore Minerals

Figure 3



∘ Mean value

× Minimum value

• Maximum value

1 Fresh Magnetite (pink)

2 Reddish-brown magnetite

3 Pink magnetite

4 White magnetite

5 Maghemite

B. Measurement of Reflectivity:

In order to study variations in the magnetite-maghemite series, the reflectivity of the intermediate stages were measured (figure 3).

The instrument used was built by Mr. P. Sterling of Iscor at the suggestion of Prof. J. Willemse and dr. C.P. Snyman.

The instrument consists of a light-sensitive cadmium-sulphide cell, the current of which is sent through a Wheatstone bridge. This current causes a deviation on a galvanometer, and the reading is restored to zero by means of a reostat. The reading on the reostat is inversely proportional to the reflectivity of the object. Immediately below the photo-cell a variable diaphragm is built in, allowing a very small part of the microscope-field to be cut out, so that the reflectivity of grains measuring less than 10 μ in diameter can be determined at a magnification of approximately 400 X. In order to eliminate the error produced by variations in the external electrical current, a constant voltage stabilizer (220 V, maximum output 2,000 W.) was used.

For very accurate work , it is necessary to switch on the instrument and leave it until it reaches a constant temperature, at which stage the reading remains constant. The time needed for this depends on the wave-length of the light used (the cell being most sensitive for red light), the intensity of the light source, the size of the diaphragm and the reflective power of the object. The time varies between 10 minutes and approximately 90 minutes (fig. 4).

Under/.....

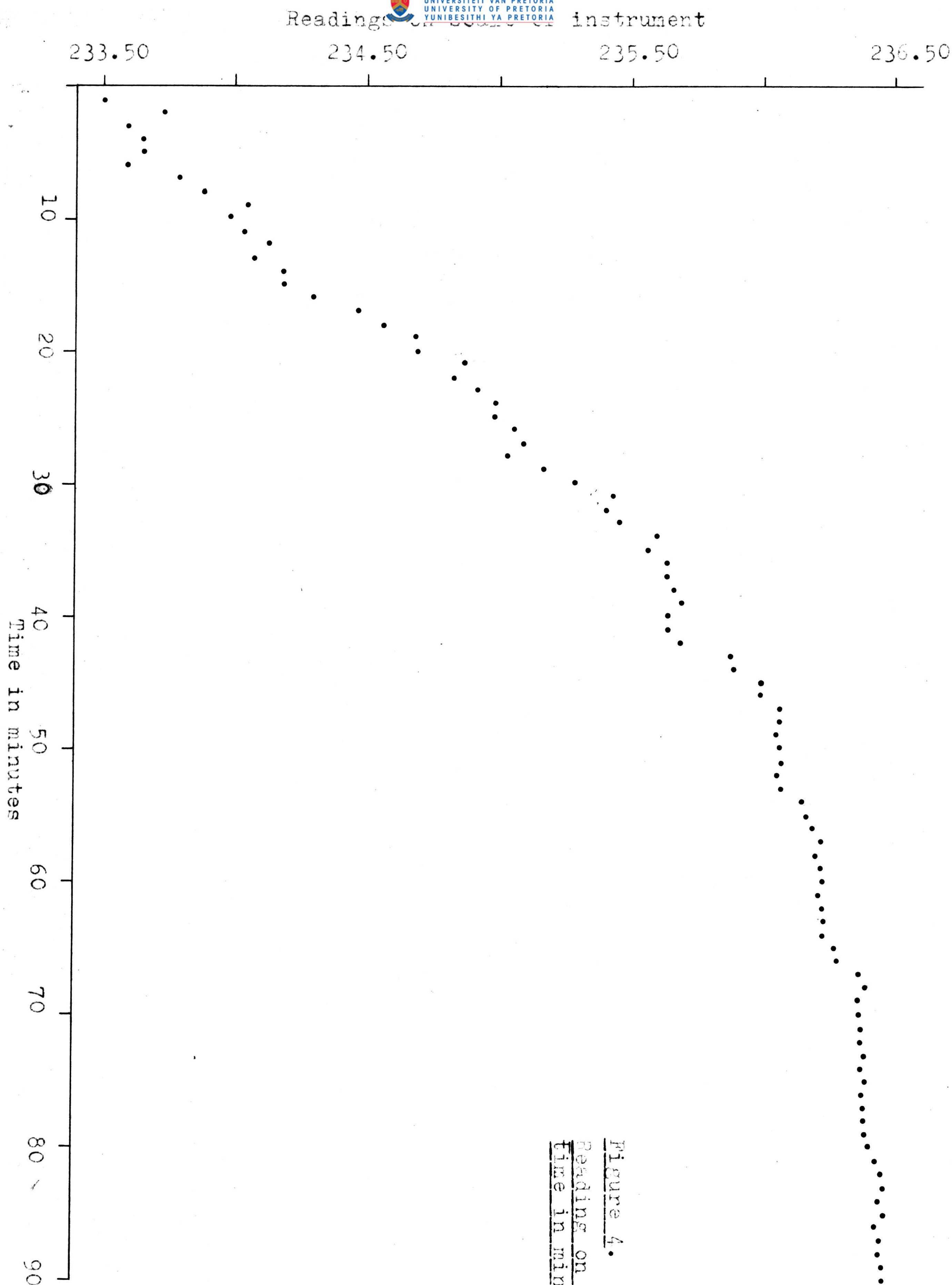


Figure 4.
Reading on scale plotted against time in minutes.

Under these conditions the average deviation of ten measurements in the case of pyrite (average reading on the instrument 234.467) was only 0.024 scale divisions.

For routine work, such as the rapid identification of ore-minerals, an alternative method was investigated. The photo-cell was covered up between readings. The best results were obtained when readings were taken exactly one minute after un-covering the photo-cell. A series of 10 readings were taken in this manner. The average deviation was 0.12 and the maximum deviation 0.52.

The choice of reflectivity standards has been a subject of discussion for many years, and none has been universally accepted. Minerals which are being used as standards should (1) have a minimum of isomorphic substitution, so that the reflectivity remains constant from specimen to specimen, (2) show little dispersion, (3) be isotropic, (4) be free from inclusions and flows, (5) polish well, (6) be fairly hard, and (7) should not tarnish.

For these reasons pyrite (reflectivity = 54.5 per cent) was provisionally chosen as one standard (Hallimond, 1957, p.487; Folinsbee, 1949, p.425; Bowie and Taylor, 1958, p.265), although it shows a slight dispersion towards the shorter wavelenghts (Gray and Millman, 1960), and allows quite extensive isomorphic substitution of iron by nickel (bravoite). A quartz crystal, cut perpendicular to the optic axis, as provided with the C.T.S. photometer, was used as a second standard (reflectivity = 4.58 per cent, reading on instrument 329.04). Quartz varies very little in composition,

and/.....

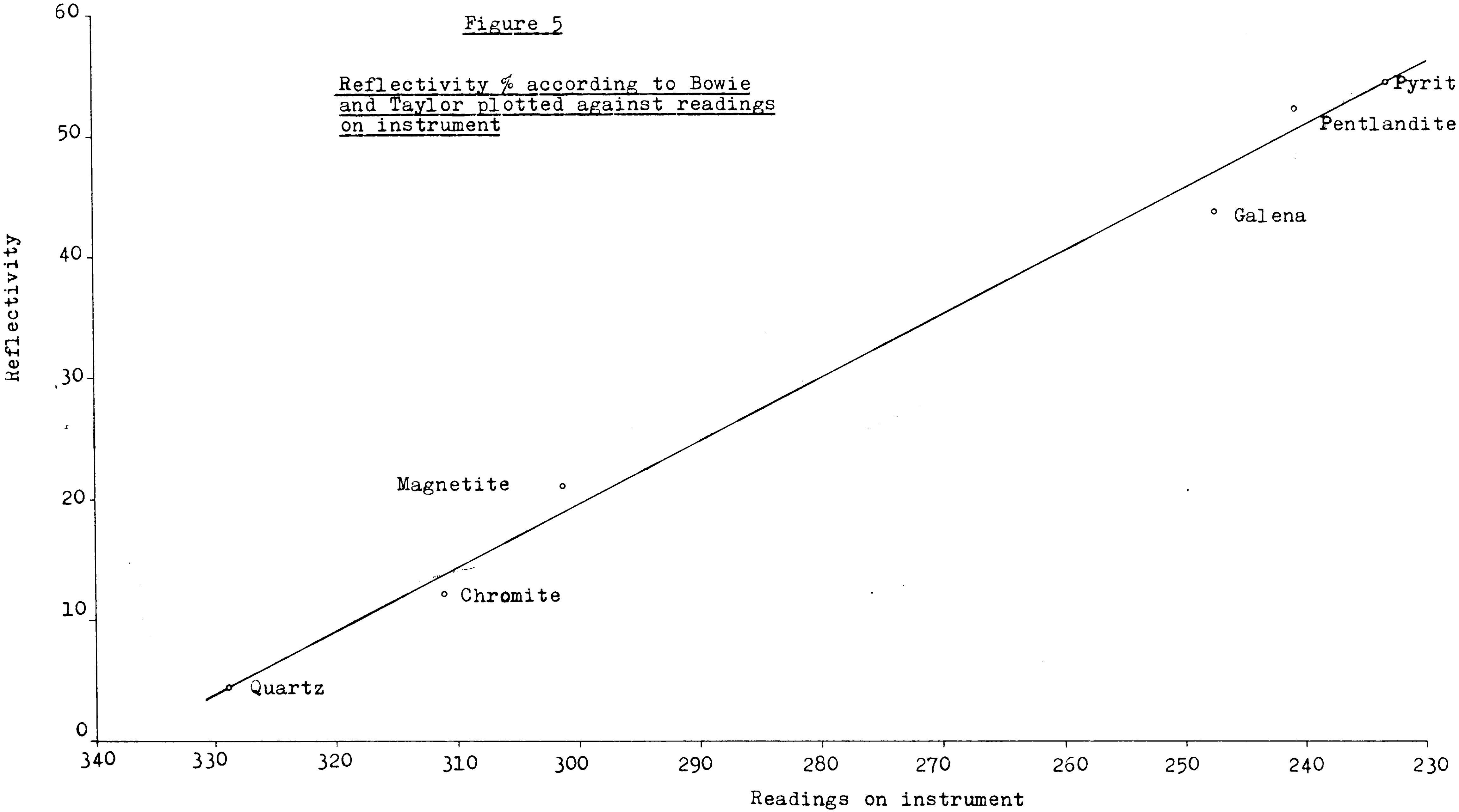


Figure 5
Reflectivity % according to Bowie and Taylor plotted against readings on instrument
Reflectivity
60
50
40
30
20
10
0
Pyrite
Pentlandite
Galena
Magnetite
Chromite
Quartz
340
330
320
310
300
290
280
270
260
250
240
230
Readings on instrument

and shows no appreciable dispersion (Gray and Millman, 1960). By using the reflectivity values of some of the minerals listed by Bowie and Taylor (1958), it was further established that the relationship between the reading on the instrument and the reflectivity value is a linear one (fig.5)*; so that it is possible to get the reflectivity of any ore-mineral from the calibration curve, once the reading on the instrument for the particular mineral is known.

The reflectivity of universal stage hemispheres can be calculated by means of Beer's formula:

$$R = \frac{(n_1 - n_2)^2 + (n_1 k)^2}{(n_1 + n_2)^2 + (n_1 k)^2} \times 100, \text{ where}$$

R = reflectivity of the object.

n_1 = refractive index of the object.

n_2 = refractive index of the medium in which the reflectivity is to be determined.

k = absorption index of the object.

In cases where the absorption index of the object is negligible, as in the case of glass, the formula becomes:

$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \times 100$$

Different glass hemispheres can therefore also be used as standards. However, in the case of such low values, the accuracy was only about 12 per cent of the reflectivity. It is quite probable that a xenon discharge lamp, which yields an intense light of continuous spectral composition, will overcome this difficulty, and will enhance the

accuracy/.....

*Later work by C.P. Snyman has shown that the relationship may not be a linear one.

accuracy of the instrument and probably extend its range of application.

The following example serves to explain the calculation of the reflectivity of a mineral (pentlandite) from the reading on the instrument:

Refl. pentlandite = Refl. pyrite - (Reading pentlandite - Reading pyrite) U.

Where : Reading = reading on instrument.

U = Unit value of instrument = 0.5225

= 54.5 - (240.97 - 233.55) 0.5225%

= 50.6%.

The reflectivity of magnetite from various localities was then determined. The results of this experiment are summarized in table 21 and indicate a considerable variation in the reflectivities of specimens from different localities.

Table 21.

No.	Locality	% Reflectivity
1	Magnetite crystal - Phalaborwa	18.91
2	Magnetite - Phalaborwa	18.73
3	Leeuwbosch - near Thabazimbi	18.98-18.76
4	Kennedy's Vale - District Lydenburg	19.12-18.94
5	Alnö - Sweden	21.11
6	Ekersund - Norway	20.00

C. Results and Conclusions:

Quantitative measurements of hardness and reflectivity of the Kennedy's Vale magnetite reveal that there are intermediate members between magnetite and maghemite.

The/.....

The reflectometer is a useful new instrument for the identification of ore-minerals. The combined use of reflectivity and hardness determination of ore-minerals may, after careful standardization, form the basis of a rapid method of identification of opaque minerals.

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THE GEOLOGY IN THE VICINITY OF KENNEDY'S VALE

SCALE 1:50.000

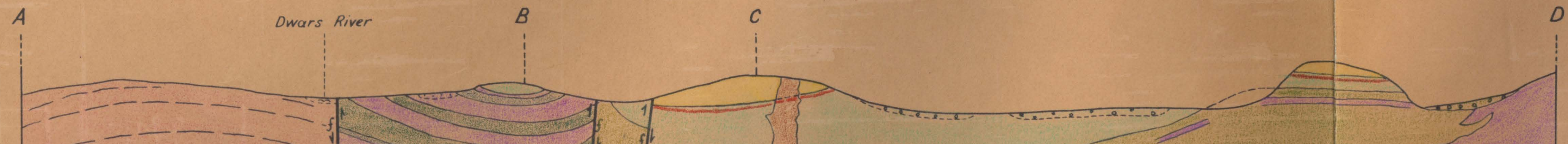
LEGEND

LATE TERTIARY TO RECENT (Symbols superimposed)
- Sandy soil
- Alluvium
- Terrace-gravel
- Scree

BUSHVELD IGNEOUS COMPLEX
- Karroo dolerite
- Ultramafic Pegmatoid including titaniferous Magnetite (m)
- Lulu Mountain Gabbro
- Central Norite and Anorthosite [Merensky Reef (mr —) Chromitite (— —)]
- Sheet Norite
- Pyroxenite (Chromitite — —)
- Maruleng Norite
- Mafic Rocks forming Sills

TRANSVAAL SYSTEM — PRETORIA SERIES
- Marble-magnetite band
- Quartzite
- Hornfels

- Quartz vein
- Fault
- Dip
- Fountain
- Perennial streams
- Non-perennial streams
- Main road
- Other roads
- Locality of speciman



Surveyed by W.C.J. van Rensburg
1960 - 1961