

A MINERALOGICAL AND PETROLOGICAL INVESTIGATION
OF THE PLATREEF ON DRENTHE 778 LR,
NORTHWEST OF POTGIETERSRUS

by

A.B. MOSTERT

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MATHEMATICAL AND NATURAL SCIENCE FACULTY,
UNIVERSITY OF PRETORIA.

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ABSTRACT

The Platreef on Drenthe 778 LR lies at the base of the Rustenburg Layered Suite of the Potgietersrus limb of the Bushveld Complex. Archaean granites form the floor rocks of this reef. It is 250 metre thick and consists of lower 50 metre thick feldspathic pyroxenite layer, overlain by 170 metre of norites. A 30 metre thick feldspathic pyroxenite layer overlies the norites and the top of the Platreef is taken to be where inverted pigeonite first appears in the sequence.

Orthopyroxene is a cumulus mineral throughout the Platreef and the most magnesian orthopyroxene has a composition of En_{75} . At the bottom of the Platreef is a sharp reverse trend in the composition of the orthopyroxene where it becomes more Mg-rich, from En_{60} to En_{70} . A sharp compositional change from En_{75} to En_{60} at the top of the Platreef, concomitant with the entry of inverted pigeonite, is taken to indicate that a new pulse of magma may have occurred at that level in the intrusion. However, plagioclase which has a composition of An_{70} in the Platreef, does not show such a change.

Metasedimentary inclusions of Transvaal Sequence dolomite abound in the Platreef on Drenthe. High temperature metamorphic minerals such as monticellite, forsterite and diopside occur in these xenoliths. The equilibrium temperature in the xenoliths is estimated to be in the order of 950°C at 3 and 4 Kbar. Many of the xenoliths have, however, been hydrated and their original metamorphic mineralogy has been obscured.

A large discontinuous zone of hydration, loosely termed a "serpentinite" zone, occurs near the top of the Platreef. This unit consists of hydrated igneous rocks, small hydrated xenoliths and totally altered rock, the origin of which is obscure. Serpentine, brucite, hydrogrossular and chlorite may be the major mineral in any part of this unit. This unit is considered to have formed due to the dissociation of a SiO_2 -poor dolomite. Major sulphide mineralization is associated with this "serpentinite" zone.

Platinum-group element bearing Ni-Cu sulphides make the Platreef of economic interest. The sulphides occur disseminated in the igneous

rocks and in the "serpentinite" zone. Ni:Cu ratios decrease with increasing height in the Platreef and two distinct sulphide assemblages occur: pyrite, pyrrhotite, pentlandite and chalcopyrite in the lower 150 metres and pyrrhotite (with or without troilite), pentlandite and chalcopyrite (with or without cubanite) in the upper 100 metres. Monoclinic pyrrhotite occurs mainly in the lower 150 metres and hexagonal and stoichiometric pyrrhotite in the upper 100 metres. This indicates that the sulphides are relatively enriched in metals in the upper part of the Platreef.

The sulphides of the "serpentinite" zone correspond to the sulphides in the fresh igneous rocks of equivalent stratigraphic position in the Platreef. Alteration features such as magnetite which replaces sulphides however, occur in the "serpentinite" zone.

The sulphides in the lower part of the Platreef are considered to have formed from an immiscible sulphide liquid which separated from the magma due to the lowering of the temperature in the magma because of the proximity of the country rocks. Contamination of the magma due to the dissociation of a SiO₂-poor dolomite changed critical physico-chemical parameters such as f_{O_2} in the magma which resulted in the formation of more immiscible sulphide liquid in the upper part of the Platreef, especially in the "serpentinite" zone.

Comparison of the Platreef on Drenthe with the Merensky Reef shows that, in mineral composition, the Platreef is slightly less basic than the Merensky Reef. The Platreef is also more leucocratic.

SAMEVATTING

Die Platrif op Drenthe 778 LR vorm die basis van die Gelaagde Suite Rustenburg in die Potgietersrus gedeelte van die Bosveldkompleks. Die vloergesteentes van die rif op Drenthe word gevorm deur Argeiese graniete. Die rif is 250 meter dik en bestaan uit 'n onderste veldspatiese laag wat 50 meter dik is en gevolg word deur 'n reeks noriete wat 170 meter dik is. Bo-op die noriete volg die boonste veldspatiese pirokseniet wat 30 meter dik is. Die top van die Platrif word geneem waar inversie pigeoniet sy eerste verskyning maak.

Ortopirokseen kom voor as 'n kumulusmineraal dwarsdeur die Platrif. Die samestelling van die mees magnesiumryke ortopirokseen is En_{75} . Aan die onderkant van die Platrif word die ortopirokseen meer magnesiumryk, van En_{60} tot En_{70} , en hierdie omgekeerde neiging is toegeskryf aan diskwilibrium toestande in die magma net na die intrusie van die magma op Drenthe (Jackson 1970). 'n Verandering in die samestelling van die ortopirokseen van En_{75} aan die top van die Platrif tot En_{60} in die oorliggende noriete gaan gepaard met die verskyning van inversie pigeoniet en mag toegeskryf word aan 'n nuwe inplasing van magma. In teenstelling hiermee toon die plagioklaas egter geen so 'n drastiese verandering in samestelling nie.

Metasedimentêre insluitels van dolomiete van die Opeenvolging Transvaal is volop in die Platrif. In hierdie xenoliete kom hoogtemperatuur metamorfe minerale voor, o.a. monticelliet, forsteriet en diopsied. Die ekwilibrium-temperatuur in die xenoliete is bereken en was vermoedelik in die orde van 950°C by druktoestande van 3 to 4 Kbar. Baie xenoliete is gehidreer, met die gevolg dat die oorspronklike hoogtemperatuur metamorfe minerale verander is.

'n Groot, nie-deurlopende sone waar retrogressiewe metamorfose plaasgevind het is aanwesig in die boonste gedeelte van die Platrif. Hierdie sone, wat gerieflikheidshalwe die „serpentiniet“-sone genoem is, bestaan uit gehidreerde stolrotse, klein gehidreerde xenoliete en rotse wat so verander is dat hul oorsprong nie afgelei kan word nie. Serpentyen, brusiet, hidrogrossulariet en chloriet is volop in die sone, en enige van die minerale kan as die hoofbestanddeel in 'n gedeelte van die sone

voorkom. Die sone word beskou as die produk van die dissosiasie van 'n SiO_2 -arme dolomiet. Belangrike sulfiedmineralisasie is geassosieer met die „serpentiniet“-sone.

Die Platrif is van ekonomiese belang as gevolg van die teenwoordigheid van Ni-en Cu-sulfiede. Die sulfiede is gedissemineer in die stolrotse en in die „serpentiniet“-sone. Die Ni:Cu verhouding verminder met toename in hoogte in die Platrif. Twee verskillende sulfiedmineraalassosiasies kom in die sulfiede van die Platrif voor. In die onderste 150 meter is piriet, pirrhotiet, pentlandiet en chalkopiriet teenwoordig en pirrhotiet (met of sonder troiliet), pentlandiet en chalkopiriet (met of sonder kubaniet) is aanwesig in die boonste 100 meter. Monokliene pirrhotiet kom meesal voor in die onderste 150 meter terwyl heksagonale en stoichiometriese pirrhotiet voorkom in die boonste 100 meter. Hieruit blyk dit dat die sulfiede relatief meer metaal-ryk is in die boonste gedeelte van die Platrif.

Die sulfiede in die „serpentiniet-sone“ stem ooreen met die in die stolrotse van ooreenstemmende stratigrafiese posisie in die Platrif. Verandering van die sulfiede soos byvoorbeeld vervanging deur magnetiet kom in hierdie sone voor.

Dit word gepostuleer dat die sulfiede in die onderste gedeelte van die Platrif gekristalliseer het van 'n sulfiedmengsel wat ontmeng het uit die magma nadat die temperatuur in die magma verlaag is, vanweë die effek van naby geleë vloergesteentes. Meer sulfied het in die boonste gedeelte van die Platrif ontmeng as gevolg van kontaminasie van die magma deur die dolomiet wat gedissosieër het. Die gevolg was dat belangrike fisiese en chemiese eienskappe soos f_{O_2} van die magma verander is, en die swaweldra vermoë van die magma verlaag het.

Die samestelling van die minerale in die Platrif blyk minder basies te wees as dié van die Merensky Rif. Die Platrif is ook meer leukokraties as die Merensky Rif.

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1. INTRODUCTION

1. GENERAL

During 1976 the Mining Corporation acquired the prospecting rights to the farm Drenthe 778 LR, a part of the Mapela tribal land in northern Lebowa. This farm is situated approximately forty kilometres north-west of Potgietersrus and is underlain by the Platreef which forms part of the Potgietersrus limb of the Bushveld Complex. An exploration programme, in which the author was involved, was initiated on the farm to evaluate the economic potential of the Platreef. The information and material which became available during that time form the source for this mineralogical and petrological study of the Platreef and this was used to assist in formulating further exploration.

Most of the investigations were carried out in the laboratory of the Geological Survey of South Africa in Pretoria with the aid of standard microscopy, X-ray diffraction, scanning electron microscope, microprobe and XRF techniques.

2. HISTORICAL BACKGROUND

Platinum and Ni-sulphide mineralization in so called Merensky Reef type rocks have been explored in the Potgietersrus limb of the Bushveld Complex since the early nineteen twenties. The mineralization and mining activities in the area near Potgietersrus were described in some detail by Wagner (1925, 1929) and evidence of this early exploration work is provided by old shafts and trenches on Drenthe. Wagner classified the mineralization which occurs at the base of the basic layered rocks of the Potgietersrus limb into strictly magmatic deposits, contact metasomatic deposits, and pegmatitic deposits.

Since Wagner's account very little additional information on the mineralization and associated rock types of this area has become available.

Van der Merwe (1976, 1978) was the first to give an account of the basic rocks of the Rustenburg Layered Suite in the Potgietersrus limb. He showed that the mineralization occurs in a layer, the so called Platreef, which may attain a thickness of up to 200 metres. The

Platreef occurs near the base of the Rustenburg Layered Suite and contains many xenoliths of metamorphosed dolomite of the Transvaal Sequence. Van der Merwe also divided the Platreef into a lower unit containing olivine, orthopyroxene and plagioclase cumulates and an upper unit consisting predominantly of orthopyroxene cumulates.

Brief mention of the Platreef and its mineralization was also made by Von Gruenewaldt (1977), who used information obtained from logs of boreholes drilled on Drenthe during 1969 by Chrome Corporation Limited. Intensive exploration on the Platreef to the south of Drenthe has been undertaken by Johannesburg Consolidated Investment Company Limited. Buchanan et al. (1981) have studied aspects relating to the genesis of the sulphide mineralization from material that was made available during this exploration programme. From sulphur isotope studies these authors concluded that the sulphides in the Platreef were derived from a sulphur-rich Merensky Reef type magma with additional sulphur being derived from the abundant dolomite xenoliths in the Platreef.

II GEOLOGY

1. REGIONAL GEOLOGY

The Rustenburg Layered Suite in the Potgietersrus limb constitutes a separate compartment of the Bushveld Complex (Van der Merwe, 1976). The limb covers an area of 2000 km² and extends in a northerly direction from just south of Potgietersrus for approximately 100 km (Fig.1). The limb attains its maximum width of approximately 12 km in the vicinity of Drenthe. It is truncated in the south by a fault which brings the Karoo Sequence into contact with the layered mafic rocks. In the north, the limb is overlain by Waterberg sediments. Bushveld granite and a variety of acid and metasedimentary rocks overlie the Rustenburg Layered Suite to the west. The floor-rocks are exposed to the east of the limb and consist of Archaean granites to the north and sedimentary rocks of the Transvaal Sequence to the south. The latter consist of dolomite overlain by banded ironstone, shales, hornfels and quartzites.

North of Potgietersrus the Transvaal Sequence forms a narrow wedge which closes approximately 10 km south of Drenthe. From this point northwards the basic rocks are in contact with Archaean granite.

Van der Merwe (1976) subdivided the Rustenburg Layered Suite into zones comparable with those of other areas of the Bushveld Complex: i.e. a lower zone, a critical zone, a main zone and an upper zone. The position of the feeder of the mafic rocks is situated 5 km to the south of Potgietersrus (Van der Merwe, 1976).

The bottommost zone, known as the lower zone, is best developed south of Potgietersrus where it consists of a 1600 m thick sequence of pyroxenites and peridotites (Hulbert, work in progress). North of Potgietersrus, the lower zone lithologies are present only as satellite bodies such as those at Uitloop, which consist of bronzitites and harzburgites and which may contain thin chromitite layers.

Lying above the lower zone is the critical zone which is poorly developed in this compartment of the Complex, and has its best development south of Potgietersrus. North of Potgietersrus, the critical zone is represented by the Platreef, which forms the base of the Rustenburg Layered Suite in this area. Local enrichments of Ni, Cu and platinum group elements in a 200 metre thick sequence of pyroxenites, melanorites

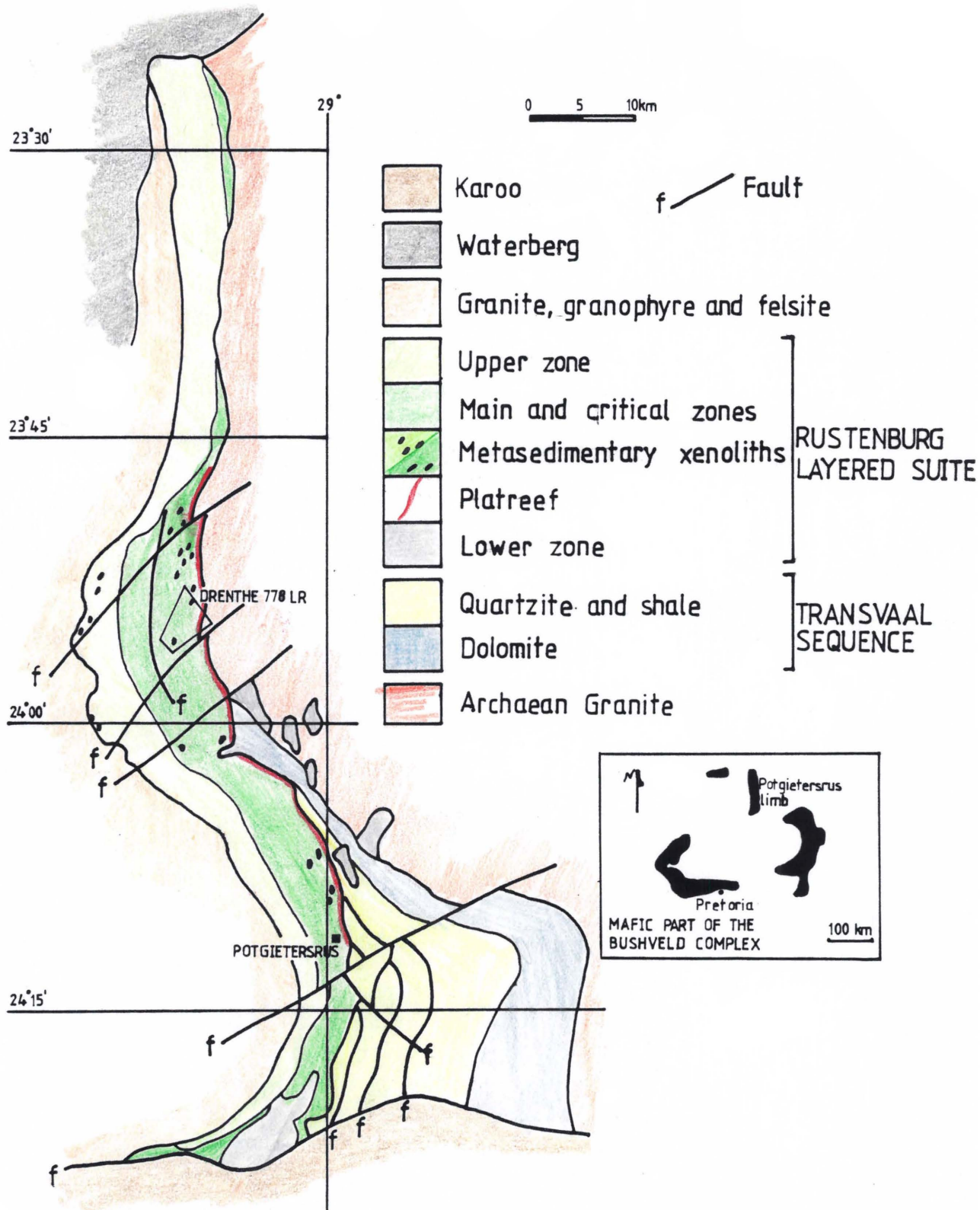


Fig 1. THE POTGIETERSRUS LIMB OF THE BUSHVELD COMPLEX

and norites make the Platreef economically significant. Many metasedimentary inclusions derived from the Transvaal Sequence rocks are also present in the Platreef.

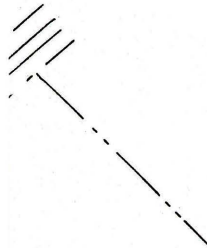
Overlying the Platreef is the main zone which consist of norite, gabbro, troctolite, pyroxenite and anorthosite layers which grade into the upper zone where cumulus magnetite first appears in the succession. Also present in the upper zone are magnetite and anorthosite layers. The uppermost rocks of the layered sequence are fayalite-bearing diorites which are either in contact with granitic roof rocks or with metasedimentary xenoliths of the Transvaal Sequence (Van der Merwe, 1976, 1978).

A characteristic feature of the layered sequence is its pronounced transgression of the Transvaal Sequence from a level above the Magaliesberg Quartzite Formation south of Potgietersrus, across the whole Pretoria Group, the banded ironstones and dolomites of the Chuniespoort Group onto rocks of the Basement Complex. This downward transgression into the floor rocks has been ascribed by Von Gruenewaldt (1979) to a structural upwarp in the area at the time of emplacement of the Complex. To the north of Drenthe, even upper zone lithologies transgress main zone rocks in a similar fashion.

2. THE GEOLOGY OF THE PLATREEF ON DRENTHE 778 LR

The Platreef is poorly exposed on Drenthe, being overlain in most places by one to two metres of turf and calcrete. The only outcrops consist of weathering resistant norites, and norite exposed in the Thwathwe River on the southern part of the farm. On the adjoining farm Witrivier to the north of Drenthe, outcrops occur more frequently, although the lower part of the Platreef is also covered by overburden. Most of the geological information shown in Figure 2 and the accompanying sections (Fig. 3) was obtained from diamond drill boreholes, percussion drilling and pitting. It is of interest to note that the geochemical soil sampling also broadly delineates the section of the Platreef on Drenthe (Fig.4) which is of economical interest.

The Platreef dips at 45° in a westerly direction and is approximately 250 metres thick. At the base, overlying the Archaean granite is a fine- to medium-grained feldspathic pyroxenite layer varying in thickness from 40-80 metres. Above this is a 170 metre thick sequence of norites intercalated near the top with thin (1 metre) pyroxenite layers. A few




GEOLOGICAL LEGEND.

○ BOREHOLE (VERTICAL)
466m FINAL DEPTH OF Bh


 DOLERITE DYKE

 SERPENTINITE

 NORITE

 PYROXENITE

 METASEDIMENTARY INCLUSION

 ARCHEAN GRANITE

A—B SECTION LINE


--- INFERRED CONTACT

== THWATHWE RIVER



GENERAL LEGEND.

 RIVER

 ROADS

--- FENCE

--- FARM BOUNDARY



FIG.2: GEOLOGY OF THE PLATREEF AS INFERRED FROM BOREHOLE DATA, PITTING AND MAPPING

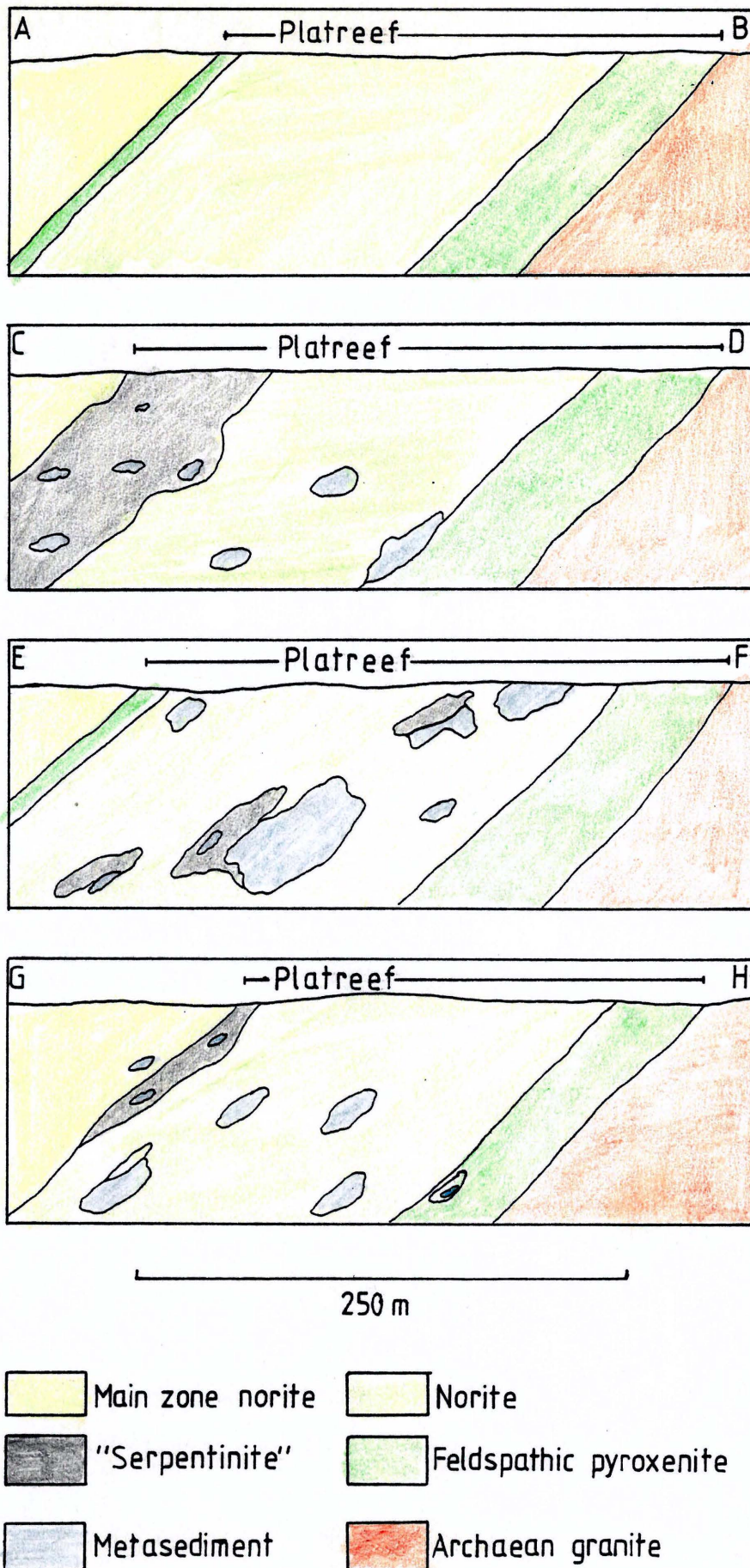
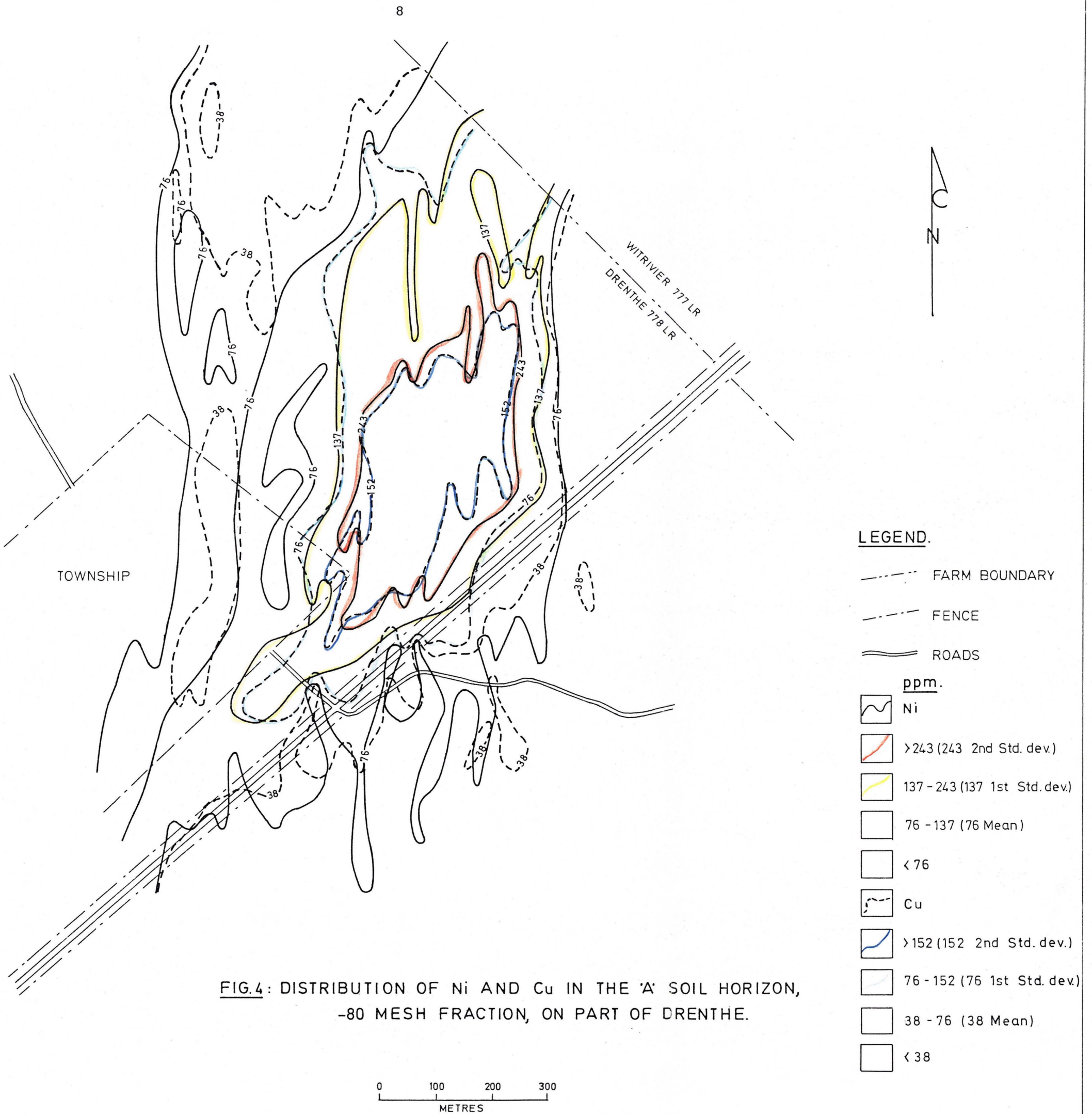


Fig 3. IDEALISED SECTIONS THROUGH THE PLATREEF
BASED ON BOREHOLE INTERSECTIONS



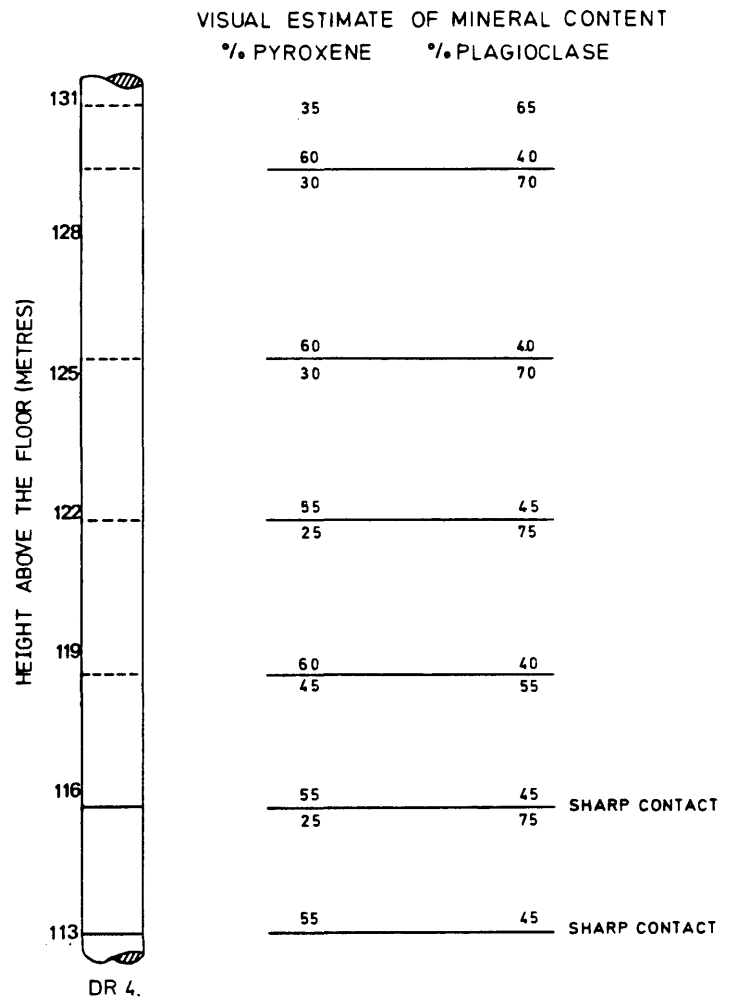
cyclic units are developed in the lower part of the norite sequence. These units are pyroxene-rich at the base becoming more leucocratic towards the top and range in thickness from 1 to 6 metres (Fig. 5). Above the norite sequence is a 10-20 metre thick feldspathic pyroxenite layer, which forms the top of the Platreef (See also Fig.6). The overlying norites contain inverted pigeonite and are thought to form part of the normal main zone rocks.

In the central and northern parts of Drenthe, metasedimentary inclusions are present with associated retrogressive alteration and possible contamination of the igneous rocks. These inclusions vary greatly in size, from less than one metre to more than 50 metres in diameter. Large inclusions were also mapped on Witrivier and a large xenolith was intersected by borehole DR 3 on Drenthe (Fig.3, section E-F). The xenoliths are not confined to the Platreef. Prominent inclusions have also been mapped in the overlying norites and anorthosites on both Drenthe and Witrivier by the author and by Van der Merwe (1978).

As a result of retrogressive alteration of both the sedimentary and igneous rocks, the contacts between the inclusions and the igneous rocks are rarely sharp. Where contacts between between igneous and meta-sedimentary rocks are clearly defined, pegmatoidal gabbro is developed along the contact. The xenoliths vary in appearance due to differences in composition and grade of retrogressive alteration. Banding has been preserved in many places but has no preferred spatial orientation.

In Figure 3 section C-D, a wide zone of retrogressive metamorphism is indicated. Although this zone is loosely termed a "serpentinite" zone, serpentine is not always the most important mineral, and chlorite, brucite and hydrogrossular may dominate in many rocks of this unit. Igneous rocks, displaying all stages of alteration, small (0,5 m) metasedimentary inclusions and totally altered rocks occur together in this zone. The rapidly alternating rock types (1 cm - 1 metre) with their different appearances give this "serpentinite" zone a complex appearance in the borehole core.

Dykes of granitic composition intrude the Platreef. These usually strike in an east-west direction except for one prominent granite dyke, which strikes roughly parallel to the Platreef, cutting across the Reef at a small angle on Witrivier.



**FIG. 5: CYCLIC VARIATION IN MINERAL CONTENT
IN PART OF THE NORITE SEQUENCE,
BOREHOLE DR 4.**

Several dolerite dykes also outcrop on Drenthe, the most prominent of which strikes east-west and is followed by the Thwathwe River.

III MINERALOGY OF THE IGNEOUS ROCKS

1. GENERAL

For the investigation of the igneous minerals borehole DR 3 was used as a reference hole as it exhibited most of the features collectively observed in the other boreholes. Gaps in the profile of DR 3 caused by xenoliths or zones of alteration were "filled in" from boreholes DR 4 and DR 5.

The main igneous minerals in the Platreef on Drenthe are orthopyroxene, plagioclase and clinopyroxene. No igneous olivines were found on Drenthe in contrast to the observations of Van der Merwe (1978, p.29) who described an olivine-plagioclase-orthopyroxene cumulate layer in the lower part of the Platreef on Zwartfontein 814 LR.

2. VARIATION OF THE IGNEOUS MINERAL CONTENT OF THE PLATREEF

A Swift automatic point counter was used for determining the modal per centages of the minerals. About 1500 points were counted over an area of approximately 350 mm^2 per thin section. The degree of accuracy of each count was calculated from the I.C. number (i.e. the number of identity changes over a 40 mm traverse) and the curves given by Chayes (1956, p.77). Although the I.C. numbers vary, most of the values are above 50 and the estimated average analytical error is mostly below 3 per cent and never above 6,5 per cent. This is considered sufficiently low for the purpose of this investigation.

Orthopyroxene, clinopyroxene and plagioclase were counted as separate minerals and all the other minerals were grouped together. Variations of the mineral content in the Reef are shown in Figure 6.

The orthopyroxene content of the lower feldspathic pyroxenite layer is relatively constant, constituting between 50 and 70 modal per cent of the rock. Above this layer, the orthopyroxene content generally decreases with considerable variations between 5 and 60 per cent. These variations are due to the presence of cyclic units which have been shown to be pyroxene-rich at the bottom and feldspar-rich at the top (Fig. 5). In the norite above the feldspathic pyroxenite layer plagioclase generally becomes the most abundant mineral, constituting between 20 and 80 per cent of the mode. In the upper part of the norite sequence

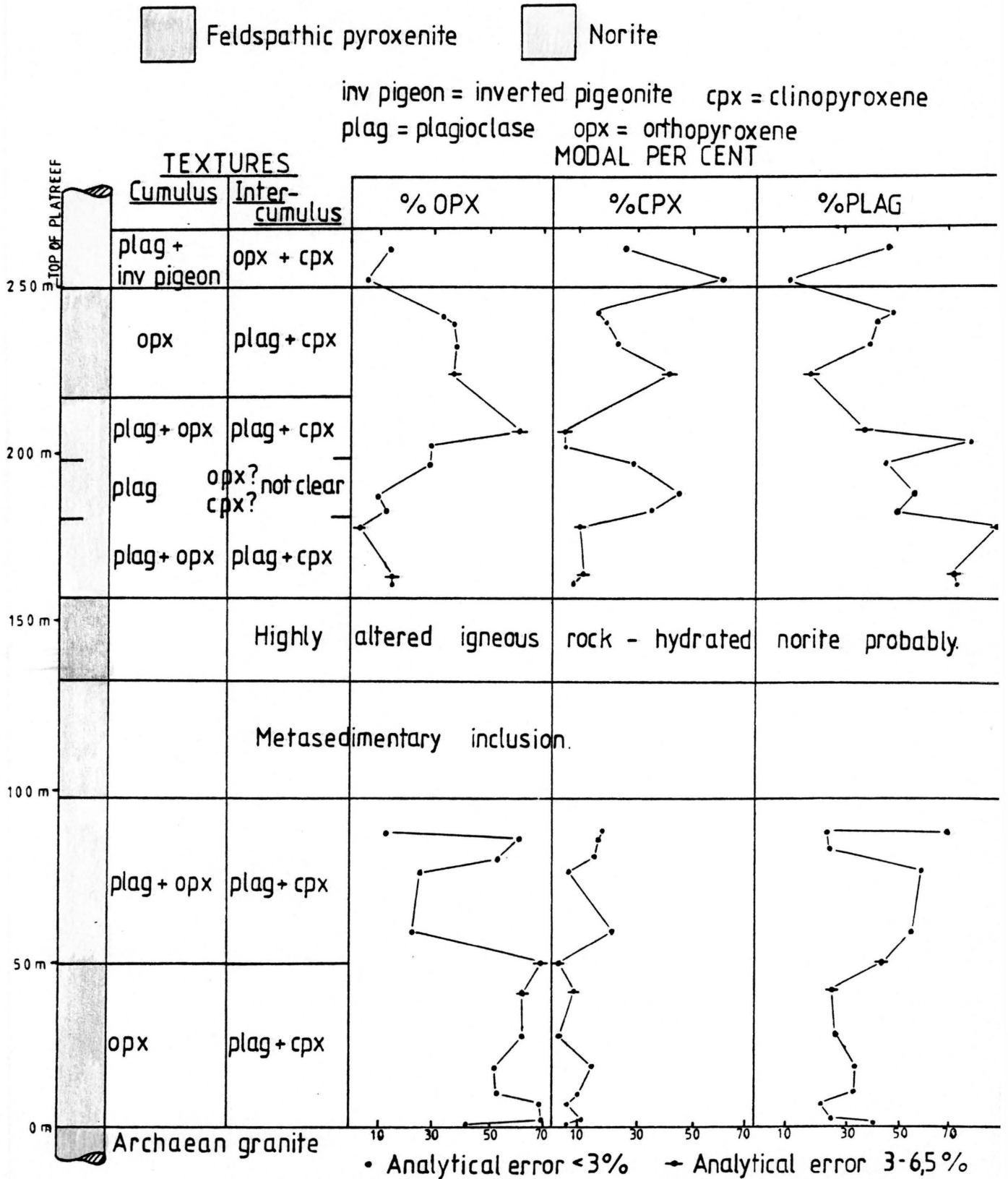


Fig 6. MINERALOGICAL PROFILE OF, AND VARIATION OF THE MINERAL CONTENT IN THE IGNEOUS ROCKS OF THE PLATREEF IN BOREHOLE DR 3.

clinopyroxene becomes prominent for approximately 15 metres, forming up to 50 per cent of the rock. Generally the clinopyroxene forms less than 25 per cent of the rock in the lower part of the Platreef. At the top of the Platreef the rock is again more pyroxenitic with orthopyroxene constituting approximately 45 per cent of the rock, and clinopyroxene varying between 20 and 50 per cent. This has been called a feldspathic pyroxenite layer but it clearly has a tendency to gradually become more noritic towards the top. Above the Platreef, where inverted pigeonite first makes its appearance, there is a drastic change in the feldspar content to approximately 15 modal per cent, although this increases rapidly to nearly 50 modal per cent higher up in the main zone norite.

3. ORTHOPYROXENE

Orthopyroxene is the most abundant femic mineral of the Platreef and occurs as a cumulus mineral throughout the sequence (Figs. 6 and 7). The cumulus nature of the mineral is easily recognized throughout, except for a 20 metre thick layer 180 metres above the base. Here the orthopyroxene occurs together with clinopyroxene in a relationship which is not clear. Embayments of both minerals are found in each other which suggests that crystallization of both pyroxenes took place simultaneously. The orthopyroxene also encloses plagioclase poikilitically. Above this layer the mineral again displays a clear cumulus texture up to approximately 250 metres above the basement rocks. This position is taken as the top of the Platreef, and above this point the orthopyroxene again becomes poikilitic, while inverted pigeonite enters as a co-existing Ca-poor pyroxene (Figs. 6 and 8). The inverted pigeonite is found as small, irregular grains containing thick lamellae of exsolved augite, parallel to the (001) plane of the orthopyroxene. The inverted pigeonite is usually also surrounded or partly surrounded by augite. Embayments of augite in the inverted pigeonite imply partial replacement (resorption) of the latter by the former. This augite has the same optical orientation as the lamellae in the inverted pigeonite.

In Figure 9 the average diameter of basal sections of orthopyroxene is plotted against height above the floor for borehole DR 3. Correlation was attempted in the other boreholes and the broad trends, especially in the lower pyroxenitic layer, were confirmed.

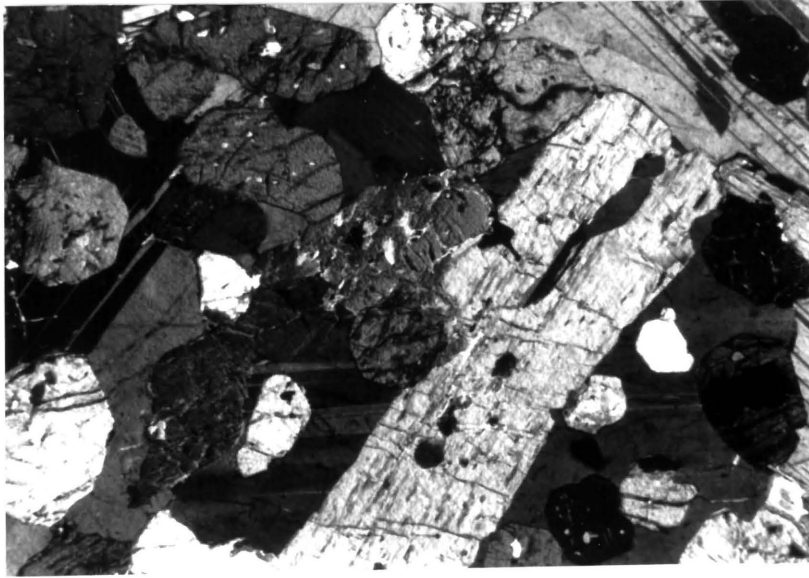


FIG. 7. CUMULUS ORTHOPYROXENE TOGETHER WITH INTERCUMULUS PLAGIOCLASE FROM THE LOWER FELDSPATHIC PYROXENITE LAYER. DR 3/63. TRANSMITTED LIGHT, CROSSED NICOLS, X 90.

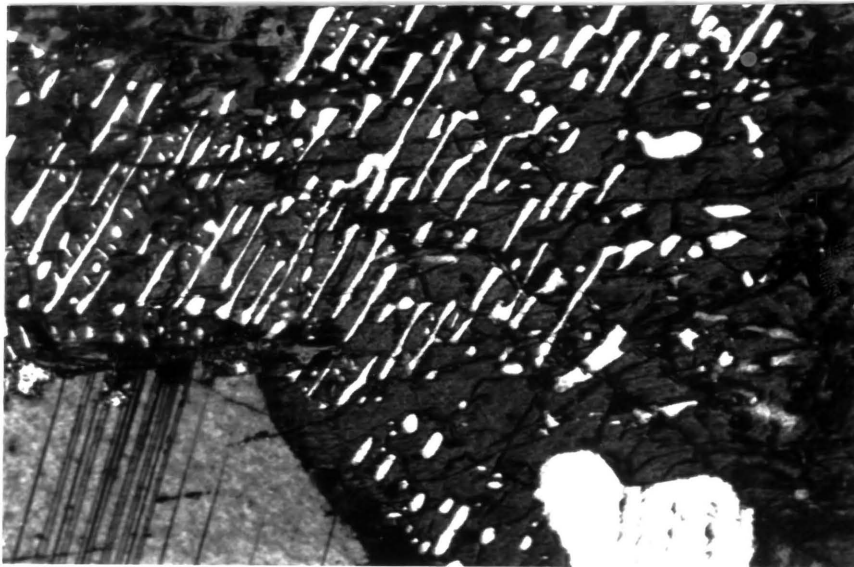
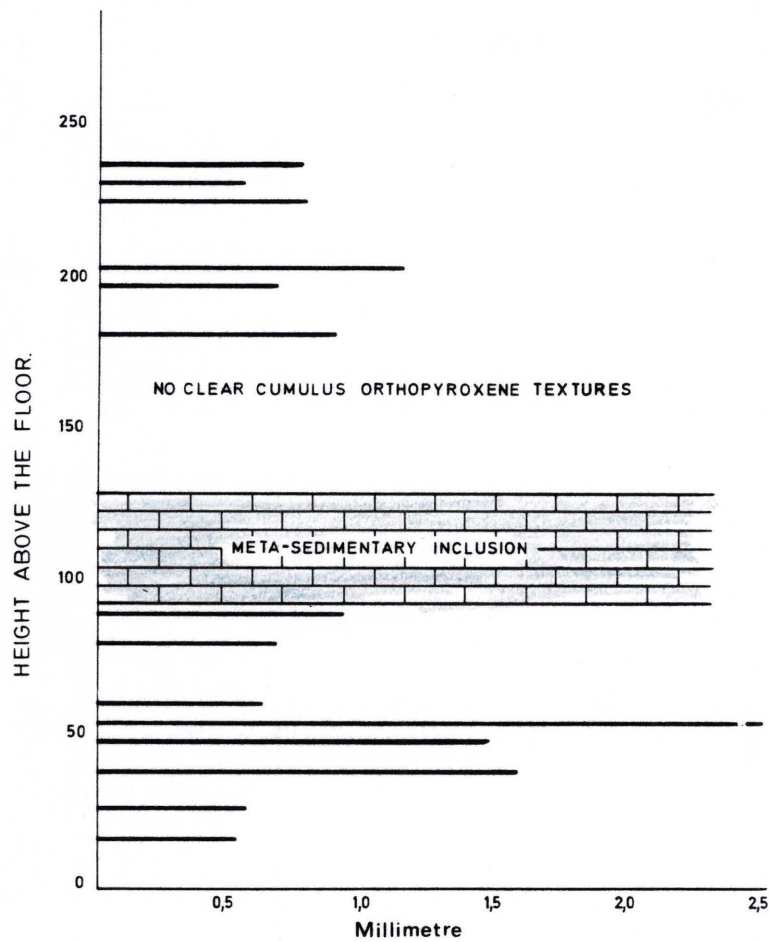


FIG. 8. EXSOLUTION LAMELLAE IN Ca-POOR PYROXENE WHICH IS CHARACTERISTIC OF INVERTED PIGEONITE. MAIN ZONE NORITE. DR 3/2. TRANSMITTED LIGHT, CROSSED NICOLS, X 180.



**FIG. 9 : VARIATION IN DIAMETER OF BASAL SECTIONS
OF CUMULUS ORTHOPYROXENE GRAINS
IN BOREHOLE DR3.**

The grain size of the orthopyroxene grains was determined by measuring the diameter of those grains orientated with their C-axis perpendicular to the plane of the thin section. Elongated grains were avoided. Except where grains were too large, at least 15 grains per thin section were measured. No measurements were taken where grains showed signs of post-cumulus overgrowths.

The grains just above the floor rocks are smaller than those in the upper part of the feldspathic pyroxenite layer. This is probably due to the supercooling of the magma close to the floor rocks during the intrusion. The top of the lower pyroxenite layer is marked by the largest grains in the sequence (+2,2 mm) where conditions for crystallizing orthopyroxene were probably at an optimum. In the norite sequence the grain size is variable, as is the mineral content of the rocks.

4. PLAGIOCLASE

Plagioclase occurs as a cumulus and as an intercumulus mineral in the Platreef on Drenthe. The first cumulus plagioclase is found just above the lower feldspathic pyroxenite layer and it continues to occur as a cumulus mineral throughout the rest of the Platreef sequence except for the uppermost 30 metres, where only intercumulus plagioclase is present. Cumulus plagioclase is also an abundant constituent in the rocks overlaying the Platreef.

The cumulate grains are usually subhedral to euhedral and vary considerably in size (0,2 mm - 4 mm). Laths of plagioclase are often enclosed poikilitically by clinopyroxene, in which case they often have slightly irregular outlines indicating that some reaction may have taken place between the two minerals (Fig. 10).

In hand specimen, the feldspar often has a greenish tinge due to its alteration to saussurite. The latter is commonly taken to consist of a mixture of albite (or oligoclase) and zoisite or epidote, together with variable amounts of calcite, sericite, prehnite and calcium-aluminium silicates other than those belonging to the epidote group (Gary et al., 1973). Where this type of alteration is not advanced, the plagioclase displays an uneven extinction in thin section. Scanning electron microscope images of these areas reveal a texture consisting of two components (Fig. 11) different from the host. Energy dispersive spectra

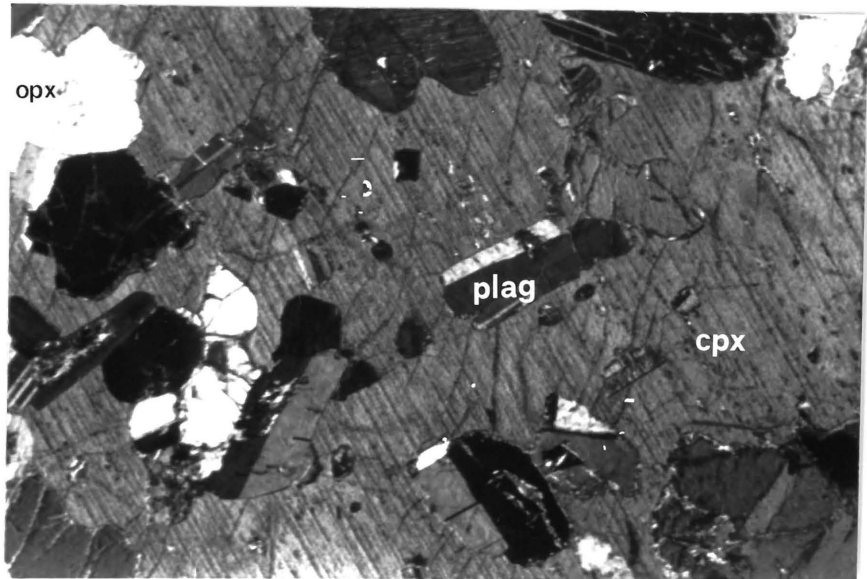


FIG. 10. PLAGIOCLASE (PLAG) AND ORTHOPYROXENE (OPX) IN OPHITIC CLINOPYROXENE (CPX). DR 3/21. TRANSMITTED LIGHT, CROSSED NICOLS, X 90.

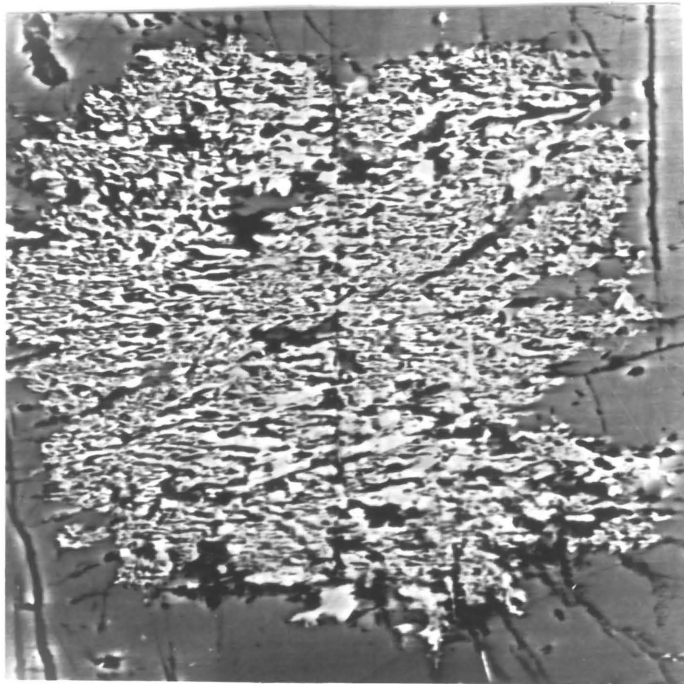


FIG. 11. SCANNING ELECTRON MICROPHOTOGRAPH OF AN INTERGROWTH WHICH IS THE RESULT OF ALTERATION IN PLAGIOCLASE. THE INTERGROWTH PROBABLY CONSISTS OF HYDROGROSSULAR (WHITE) AND OLIGIOCLASE (BLACK) IN PLAGIOCLASE (GREY). MAGNIFICATION X 250 AT 39 k.V.

of the host plagioclase and the two phases (Fig. 12) showed that while the host contains Na, Al, Si and Ca, one phase consists only of Al, Si and Ca and the other contains Si, relatively more Na and less Al and Ca than the host. On the basis of this information this feature was initially confused with the Huttenlocher-type intergrowths in which one component consists of anorthite and the other of labradorite-bytownite ($An_{62} - An_{75}$). However the observed feature does not conform to the published descriptions (Smith, 1974, Vol. 2, p. 541) of the Huttenlocher-type texture and further investigation under high magnification in transmitted light indicated one of the components to be isotropic.

This, in addition to the fact that this component consists essentially of Ca, Al and Si, gives reason to assume that the isotropic phase is hydrogrossular. The Na-bearing phase is most probably oligoclase and, together, these phases seem to form the first step in the saussurization of the plagioclase. The uneven extinction that plagioclase displays could be caused by the presence of the isotropic alteration product.

The uneven extinction described above cannot be confused with the zoning in the plagioclase, because the zoning is mostly confined to the outer margins of both cumulus and intercumulus grains. Normal zoning and oscillatory zoning were observed but reversed zoning which is present in other areas of the Bushveld Complex seems to be absent.

5. CLINOPYROXENE

The clinopyroxene of the Platreef occurs as an intercumulus mineral throughout the sequence, except in the previously mentioned 20 metre thick gabbroic layer 180 metre above the base. Here, the pyroxene textures are not clear. The Ca-pyroxene in this layer is more Mg-rich than the normal intercumulus Ca-pyroxenes (note 3/14 in Table 1) and on this ground it may be considered to be a cumulus phase at this position in the reef.

Exsolution lamellae parallel to the (100) direction are present in the clinopyroxene throughout the sequence. A second set of exsolution lamellae parallel to the (001) direction is also present in the clinopyroxene of the gabbroic layer. These lamellae are shorter and thicker than the (100) lamellae and do not traverse the whole grain as the (100) lamellae do (Figure 13).

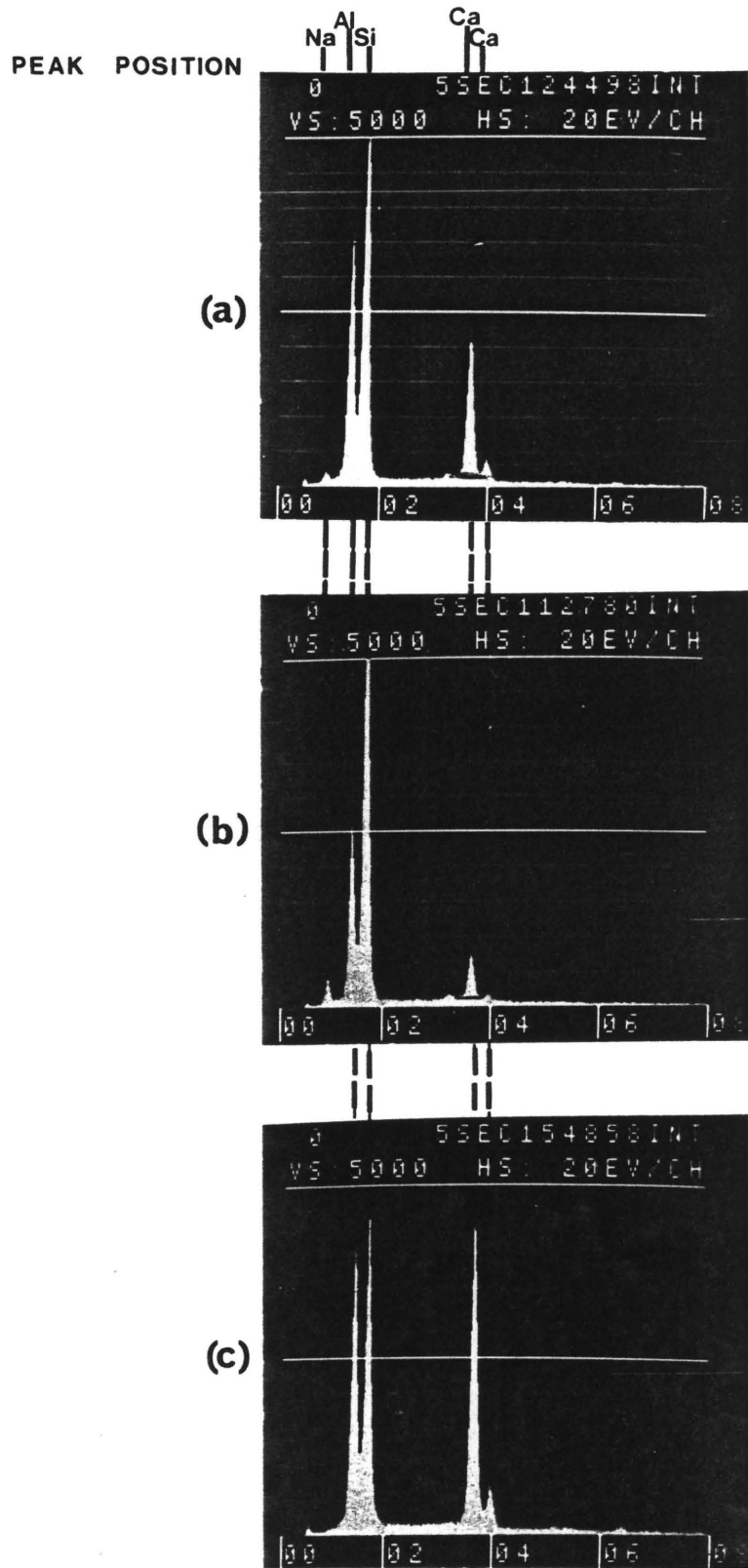


FIG. 12 SPECTRA SHOWING THE COMPOSITIONAL RELATIONSHIPS BETWEEN UNALTERED PLAGIOCLASE, (a), AND THE TWO ALTERATION COMPONENTS OLIGOCLASE, (b), AND HYDROGROSSULAR (?), (c). DETERMINED BY ENERGY DISPERSIVE X-RAY ANALYSIS.

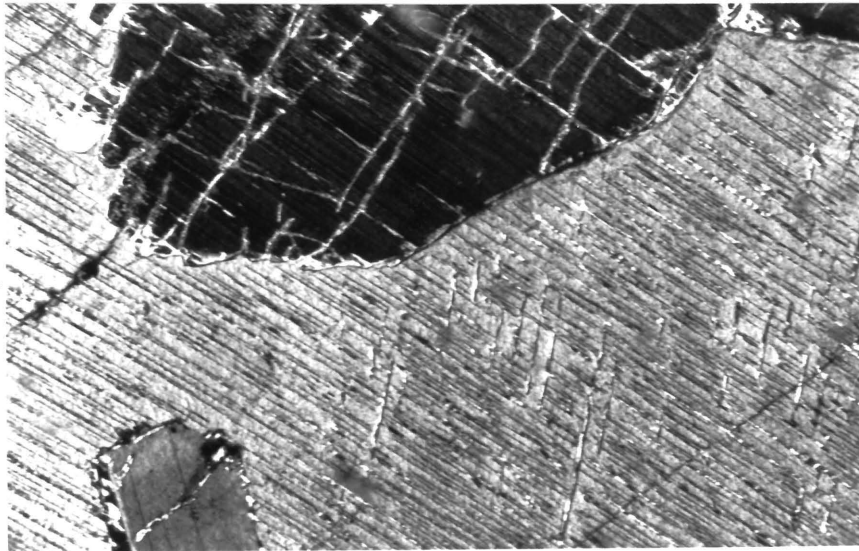


FIG. 13. EXSOLUTION TEXTURES IN CLINOPYROXENE IN THE GABBROIC LAYER IN THE UPPER PART OF THE PLATREEF. THE (100) LAMELLAE TRAVERSE THE WHOLE GRAIN BUT THE (001) LAMELLAE ARE SHORTER AND THICKER. DR 3/17. TRANSMITTED LIGHT, CROSSED NICOLS, X 180.

A monoclinic pyroxene always exsolves an orthopyroxene parallel to (100) and another monoclinic pyroxene parallel to (001) (Cox et al., 1979, p.297). The presence of the latter lamellae therefore implies that the Ca-rich pyroxene crystallized above the pigeonite-orthopyroxene inversion temperature in this layer. As no inverted pigeonite is present it would also imply that the Ca-poor pyroxene crystallized subsequent to the inversion. This provides further evidence that the clinopyroxene probably crystallized as a cumulus phase at this position in the Reef.

Above the Platreef, where inverted pigeonite is present, the clinopyroxene occurs as a typical interstitial mineral and is also seen to replace the inverted pigeonite.

6. OTHER SILICATES

The most important accessory minerals present are biotite and quartz. Quartz is especially noticeable close to the contact with the Archaean granite and points to ^{local} contamination of the magma.

Hornblende is present as a replacement product of pyroxene in weathered rocks.

7. COMPOSITIONAL VARIATIONS

The composition of individual mineral grains were determined with the aid of a Jeol JXA 50A microanalyser at the Geological Survey, Pretoria. An accelerating voltage of 15kV, a specimen current of 0,2 mA and a beam diameter of 2 μm were applied to polished thin sections coated with a 200 Å thick carbon layer. Data thus obtained were corrected by using the Bence data reduction method (Bence and Albee, 1968).

In Figure 14 the compositions of cumulus orthopyroxene and cumulus plagioclase from boreholes DR 3, DR 4, and DR 5 are plotted against height above the floor. Analyses of orthopyroxene grains are of the host material only and do not include the exsolved augite. (The compositions of a clinopyroxene and orthopyroxene are also plotted on the pyroxene tri-angle in Figure 37, p. 67).

Plagioclase analyses represent the composition of the core of the grains (Table 1). Relatively few good analyses of plagioclase were obtained because of extensive alteration. This, together with the fact that cumulus plagioclase does not occur throughout the the sequence, resulted in insufficient information being available to reconstruct their fractionation trend. The few points plotted do however, suggest a slight enrichment of Na with increasing height. Intercumulus plagioclase generally contains 7-10 mol per cent less anorthite than cumulus plagioclase.

The most sodic plagioclase present in the Platreef is intercumulus plagioclase from close to the contact with the floor rocks (Table 1, analysis 4/1, intercum. plag.).

Three features are noted in the compositional variations of orthopyroxene in the Platreef. In the lower 30 metres of the sequence, the Mg content increases sharply, from 60 mol per cent En near the base to 70 mol per cent En approximately 20 metres above the floor. Above this, the Mg content increases slightly to 74 mol per cent En at about 100 metres above the floor. From here to the top of the Platreef the composition remains more or less constant. The top of the Platreef is characterized by a pronounced change in the composition of the orthopyroxene, from En_{75} at the top of the Platreef to En_{60} at the base of the overlying norites. Simultaneously the Ca-poor pyroxene changes from primary bronzitite to inverted pigeonite.

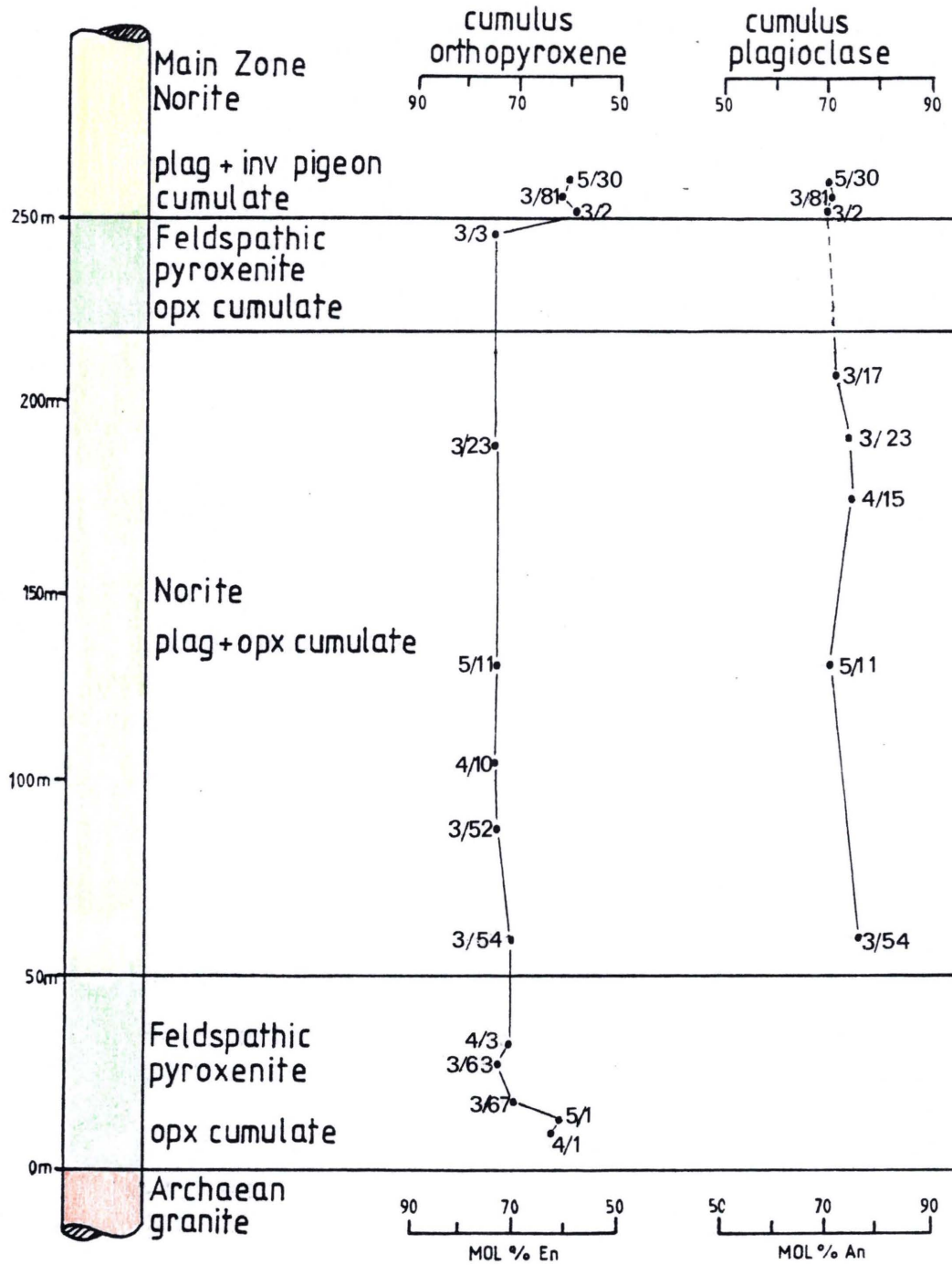


Fig 14. Compositional variations of cumulus orthopyroxene and plagioclase in the Platreef. Based on data from boreholes DR3, DR4 and DR5.

TABLE 1: MICROPROBE ANALYSES OF ORTHOPYROXENE, PLAGIOCLASE AND CLINOPYROXENE

DESCRIPTION	OPX	INV PIG	INV PIG	OPX	INV PIG	OPX	OPX	OPX	OPX(OPHITIC)	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX
SAMPLE NO.	3/2	3/2	3/81	3/81	5/30	5/30	3/3	3/5	3/23	3/52	4/3	4/1	3/54	3/63	3/67	5/11	5/1	4/10
SiO ₂	51,72	51,99	52,43	52,88	51,77	51,84	52,48	52,28	53,25	52,38	52,30	52,08	53,85	53,11	53,22	53,71	49,04	52,86
Al ₂ O ₃	0,81	0,72	0,99	1,06	0,89	1,31	1,78	2,06	1,36	1,71	1,80	0,58	1,08	1,08	1,19	1,29	2,60	1,24
TiO ₂	0,25	0,24	0,28	0,24	0,30	0,43	0,18	0,32	0,24	0,27	0,38	0,22	0,30	0,27	0,28	0,28	0,21	0,38
MgO	21,01	20,59	21,56	23,18	22,39	22,89	28,29	28,44	27,56	27,16	25,95	22,33	25,56	26,92	25,65	26,66	21,73	27,47
Fe ^o	24,59	24,83	22,25	20,90	21,71	21,25	13,36	14,13	14,11	16,50	17,24	23,57	15,83	14,19	16,55	14,88	23,03	14,66
MnO	0,06	0,47	0,50	0,34	0,30	0,23	0,46	0,40	0,35	0,43	0,44	0,76	0,39	0,42	0,44	0,27	0,60	0,52
NiO	0,16	0,17	0,16	0,28	0,33	0,25	0,29	0,19	0,26	0,21	0,27	0,15	0,23	0,25	0,21	0,22	0,21	0,27
CaO	1,00	0,82	0,17	0,80	1,44	1,44	2,26	2,31	2,18	0,65	1,28	0,68	2,51	2,45	1,41	1,60	0,73	1,70
Na ₂ O	0,07	0,05	0,08	0,07	0,09	0,09	0,08	0,08	0,08	0,09	0,05	0,04	0,06	0,08	0,09	0,04	0,06	0,07
K ₂ O	0,05	0,05	0,08	0,07	0,06	0,07	0,06	0,05	0,05	0,04	0,05	0,05	0,05	0,06	0,05	0,04	0,05	0,04
Cr ₂ O ₃	0,09	0,06	0,10	0,14	0,13	0,20	0,42	0,30	0,27	0,11	0,20	0,08	0,26	0,26	0,37	0,32	0,11	0,42
TOTAL	99,81	99,89	98,60	99,96	99,41	100,00	99,66	100,56	99,71	99,55	99,96	100,54	100,12	99,09	99,46	99,31	99,17	99,63

STRUCTURAL FORMULA BASED ON N OXYGEN IONS

N=	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Si	1,953	1,968	1,982	1,963	1,948	1,934	1,905	1,886	1,931	1,917	1,917	1,950	1,951	1,942	1,951	1,955	1,874	1,925
Al	0,036	0,032	0,044	0,096	0,039	0,058	0,076	0,087	0,058	0,074	0,078	0,026	0,046	0,047	0,051	0,055	0,117	0,053
Ti	0,007	0,069	0,008	0,007	0,008	0,012	0,005	0,009	0,007	0,007	0,010	0,006	0,008	0,007	0,007	0,007	0,006	0,010
Mg	1,179	1,162	1,215	1,282	1,256	1,273	1,530	1,529	1,400	1,482	1,418	1,247	1,385	1,467	1,401	1,446	1,238	1,491
Fe	0,776	0,786	0,703	0,649	0,683	0,663	0,406	0,426	0,428	0,505	0,528	0,738	0,481	0,434	0,507	0,453	0,762	0,447
Mn	0,019	0,015	0,016	0,011	0,010	0,007	0,012	0,012	0,010	0,013	0,014	0,024	0,012	0,013	0,014	0,008	0,019	0,008
Ni	0,005	0,005	0,003	0,008	0,010	0,007	0,008	0,006	0,008	0,006	0,008	0,004	0,007	0,007	0,006	0,006	0,006	0,008
Ca	0,040	0,029	0,005	0,032	0,058	0,057	0,088	0,089	0,085	0,025	0,050	0,027	0,098	0,096	0,055	0,062	0,030	0,066
Na	0,005	0,003	0,007	0,005	0,007	0,006	0,005	0,005	0,006	0,006	0,003	0,003	0,004	0,006	0,006	0,003	0,005	0,005
K	0,002	0,003	0,004	0,003	0,003	0,003	0,003	0,002	0,002	0,002	0,002	0,003	0,002	0,003	0,002	0,002	0,002	0,002
Cr	0,003	0,002	0,003	0,004	0,004	0,006	0,012	0,009	0,008	0,003	0,006	0,002	0,007	0,008	0,001	0,004	0,003	0,012
Z	1,989	2,000	2,026	2,078	1,987	1,992	1,981	1,973	1,989	1,991	1,995	1,976	1,997	1,989	2,002	2,002	1,991	1,978
X	2,036	2,074	1,964	2,001	2,039	2,034	2,069	2,087	1,954	2,049	2,039	2,054	2,004	2,041	1,999	1,991	2,071	2,057
En	59,10	58,78	63,18	65,31	62,89	63,87	75,59	74,80	73,18	73,66	71,04	61,98	70,52	73,46	71,37	73,74	60,99	74,40
Fs	38,90	39,76	36,56	33,06	34,20	33,27	20,06	20,84	22,37	25,10	26,45	36,68	24,49	21,73	25,83	23,10	37,54	22,31
Wo	2,01	1,47	0,26	1,63	2,90	2,86	4,35	4,35	4,44	1,24	2,51	1,34	4,99	4,81	2,80	3,16	1,48	3,29

FeO as total iron.

DESCRIPTION	CUMULUS PLAG	CUMULUS PLAG	CUMULUS PLAG	CUMULUS PLAG	CUMULUS PLAG	CUMULUS PLAG	CUMULUS PLAG	CUMULUS PLAG	CUMULUS PLAG	INTERCUM PLAG	INTERCUM PLAG	INTERCUM PLAG	INTERCUM PLAG	INTERCUM PLAG	INTERCUM PLAG	INTERCUM PLAG
SAMPLE NO.	3/2	3/81	5/30	3/5	3/17	3/23	3/54	5/11	4/15	4/1	4/10	5/1	5/30	4/3	3/67	3/52
SiO ₂	50,16	50,79	51,49	51,85	50,85	49,99	48,75	50,50	49,44	59,76	53,50	50,83	51,48	51,64	53,47	51,79
Al ₂ O ₃	30,81	30,27	30,02	31,13	30,14	31,51	30,74	30,81	31,16	24,61	28,79	31,12	30,14	31,45	29,00	29,89
TiO ₂																
MgO																
FeO	0,10	0,24	0,25	0,20	0,43	0,45	0,41	0,21	0,46	0,20	0,33	0,34	0,34	0,32	0,27	0,36
MnO																
NiO																
CaO	14,64	14,15	1,464	15,07	15,64	14,77	16,40	14,17	15,05	6,25	11,78	14,14	12,96	12,52	11,87	13,50
Na ₂ O	3,18	3,60	3,13	2,97	3,12	2,52	2,17	2,96	2,50	8,06	4,26	2,74	4,35	3,81	4,01	3,49
K ₂ O	0,19	0,18	0,19	0,22	0,23	0,25	0,09	0,21	0,07	0,66	0,34	0,16	0,25	0,27	0,35	0,32
Cr ₂ O ₃																
TOTAL	99,08	99,23	99,72	101,44	100,44	99,49	98,56	98,86	98,68	99,54	99,00	99,33	99,52	100,01	98,97	99,35

STRUCTURAL FORMULA BASED ON N OXYGEN IONS

N=	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
Si	9,288	9,337	9,409	9,317	9,283	9,167	9,073	9,296	9,147	10,735	9,774	9,301	9,424	9,365	9,773	9,481
Al	6,607	6,559	6,467	6,594	6,486	6,811	6,744	6,685	6,796	5,211	6,200	6,712	6,504	6,724	6,248	6,451
Ti																
Mg																
Fe	0,015	0,037	0,038	0,030	0,066	0,069	0,064	0,032	0,071	0,030	0,050	0,052	0,052	0,049	0,041	0,055
Mn																
Ni																
Ca	2,905	2,787	2,867	2,902	3,059	2,902	3,271	2,795	2,984	1,203	2,306	2,772	2,524	2,433	2,325	2,648
Na	1,142	1,288	1,109	1,035	1,104	0,896	0,783	1,056	0,897	2,807	1,509	0,972	1,544	1,340	1,350	1,239
K	0,045	0,042	0,044	0,050	0,055	0,058	0,021	0,050	0,017	0,151	0,079	0,037	0,058	0,063	0,082	0,075
Cr																
Z	15,895	15,896	15,876	15,911	15,769	15,978	15,817	15,981	15,943	15,946	15,974	16,013	15,926	16,089	16,021	15,932
X	4,107	4,154	4,058	4,017	4,284	3,925	4,139	3,933	3,969	4,191	3,944	3,833	4,178	3,885	3,798	4,017
An	71,0	67,9	71,3	72,8	72,6	75,3	80,3	71,7	76,6	28,9	59,3	73,3	61,4	63,5	60,8	66,9
Ab	27,8	31,1	27,6	25,9	26,2	23,2	19,2	27,1	23,0	67,4	38,7	25,7	37,2	34,9	37,1	31,2
Or	1,2	1,0	1,1	1,3	1,2	1,5	0,5	1,2	0,4	3,7	2,0	1,0	1,4	1,6	2,1	1,9

- 25 -

DESCRIPTION	INTERCUM CPX	CUMULUS(?) CPX	INTERCUM CPX	INTERCUM CPX	INTERCUM CPX	INTERCUM CPX
SAMPLE NO.	3/2	3/14	3/23	4/22	5/1	5/11
SiO ₂	51,02	51,20	51,96	54,33	52,29	51,33
Al ₂ O ₃	2,10	2,92	2,23	0,41	0,89	2,07
TiO ₂	0,40	0,26	0,25	0,13	0,26	0,40
MgO	12,33	23,31	16,26	14,48	13,29	15,54
FeO	10,00	9,45	7,69	5,28	9,07	5,76
MnO	0,32	0,44	2,64	0,31	0,37	0,25
NiO	0,25	0,18	0,18	0,24	0,16	0,14
CaO	22,30	11,90	19,84	24,72	22,31	23,38
Na ₂ O	0,34	0,21	0,34	0,08	0,27	0,31
K ₂ O	0,05	0,08	0,06	0,04	0,05	0,05
Cr ₂ O ₃	0,10	0,44	0,44	0,09	0,06	0,23
TOTAL	99,41	100,39	101,89	100,11	99,02	99,46

STRUCTURAL FORMULA BASED ON N OXYGEN IONS

N=	6	6	6	6	6	6
Si	1,935	1,865	1,931	2,003	1,978	1,914
Al	0,094	0,125	0,098	0,017	0,039	0,091
Ti	0,017	0,007	0,007	0,003	0,007	0,011
Mg	0,697	1,266	0,901	0,796	0,749	0,864
Fe	0,317	0,288	0,239	0,163	0,289	0,180
Mn	0,010	0,014	0,008	0,009	0,012	0,008
Ni	0,008	0,005	0,005	0,007	0,005	0,004
Ca	0,906	0,465	0,790	0,977	0,904	0,934
Na	0,025	0,014	0,025	0,006	0,020	0,022
K	0,003	0,004	0,003	0,002	0,002	0,002
Z	2,029	1,990	2,029	2,020	2,017	2,005
X	1,986	2,076	1,990	1,966	1,989	2,032
En	36,11	62,27	46,49	40,93	38,33	43,50
Fs	16,94	14,85	12,75	8,84	15,40	9,47
Wo	46,95	22,88	40,76	50,23	46,27	47,03

Reverse trends similar to that found in the lower part of the Platreef on Drenthe have been observed in the critical zone of the eastern lobe of the Bushveld Complex (Cameron, 1980) as well as in other layered intrusions. Jackson (1970) explained this phenomenon as possibly being an indication that the magma did not achieve equilibrium conditions until a considerable thickness of the intrusion had crystallized. Osborne (1980) has shown that a reverse fractionation trend is possible in a solid solution system if the pressure decreases. Although the change in composition were thought to be related to a change in pressure as suggested by Osborne, recent calculations by Hatton (1982) have shown that changes in pressure in the order of tens of Kbar are necessary to cause the observed changes in composition in the bottom part of the Platreef. Consequently Jackson's hypothesis may be regarded as a more feasible explanation.

The dramatic compositional change of the Ca-poor pyroxene (En_{75} to En_{60}) together with the entry of inverted pigeonite is another important feature of the compositional variations of orthopyroxene on Drenthe. This change may be due to a new influx of magma which, after mixing with the remaining liquid of the initial magma, produced Ca-poor pyroxenes of a lower MgO:FeO ratio than previously, but did not apparently change the composition of the plagioclase markedly. It is of interest to note that Van der Merwe (1978, p.120) proposes that a new influx of magma occurred 300 metres above the Platreef. However, neither this explanation nor those cited in the previous paragraph are considered to explain this abrupt change satisfactorily.

IV THE METASEDIMENTARY INCLUSIONS

1. GENERAL

All the sedimentary inclusions have, as can be expected, undergone high grade metamorphism. The high temperature metamorphic mineral assemblages are usually only preserved in the larger xenoliths as the smaller ones have been subjected to extensive retrograde effects which caused the formation of hydrated minerals. These high temperature mineral assemblages have been investigated in order to determine the conditions of metamorphism which must necessarily reflect the conditions during crystallization of the magma.

The most important high grade metamorphic minerals found in the xenoliths are forsterite, diopside, monticellite, and less commonly, spinel (hercynite). The xenoliths that were mapped on surface or intersected by boreholes did not display any zonation with regard to metamorphic mineral assemblages as described, for example by Willemse and Ben^Sch (1964) for calcareous xenoliths in the eastern Bushveld.

Minerals were identified by means of transmitted light microscopy, X-ray diffraction or with the aid of an energy dispersive X-ray analytical system coupled to a scanning electron microscope.

2. DIOPSIDE (FASSAITE)

The clinopyroxenes in the xenoliths are all rich in aluminium (Table 2). Fassaite is the name generally used to denote Ca and Al-rich pyroxenes which are commonly found in metamorphosed dolomite and limestones. However, it is not clear where the compositional boundary between fassaite and diopside lies, as Deer, Howie and Zussman (1962, Vol. 2, p. 47 and 164) show both diopside and fassaite from skarns to contain 6 per cent Al_2O_3 . Recently, Shedlock and Essene (1979) arbitrarily defined fassaite as those pyroxenes containing more than 10 per cent aluminium in the tetrahedral site. Accordingly two of the analysed grains from Drenthe would qualify as fassaite as defined by Shedlock and Essene (1979). Pyroxenes containing between 8,63 and 15,43 per cent Al_2O_3 were described by Willemse and Ben^Sch (1964). Only two of the analysed metamorphic clinopyroxenes from Drenthe contain an Al_2O_3 content close to this range. To avoid confusion the clinopyroxenes of the xenoliths will hereafter be referred to as diopside.

TABLE 2: MICROPROBE ANALYSES OF SOME DIOPSIDES FROM METAMORPHOSED XENOLITHS IN THE PLATREEF

SAMPLE NO.	3/39.1	3/39.2	3/39.3	3/41.1*	3/41.2
SiO ₂	49,30	49,73	48,92	45,84	45,03
Al ₂ O ₃	4,18	3,82	5,19	7,91	8,76
TiO ₂	0,48	0,59	0,19	1,86	2,24
MgO	15,61	15,66	15,42	13,83	13,62
FeO**	2,66	2,98	2,51	3,68	2,83
MnO	0,19	0,29	0,25	0,29	0,12
NiO	0,16	0,15	0,15	0,15	0,14
CaO	26,31	25,81	26,38	26,27	25,92
Na ₂ O	0,15	0,13	0,06	0,08	0,13
K ₂ O	0,08	0,05	0,06	0,05	0,06
Cr ₂ O ₃	0,07	0,11	0,07	0,08	0,08
TOTAL	99,19	99,32	99,20	100,04	98,93

STRUCTURAL FORMULA BASED ON 6 OXYGEN ATOMS

Si	1,838	1,850	1,821	1,710	1,690
Al	0,162	0,150	0,179	0,290	0,310
Al	0,022	0,017	0,049	0,058	0,077
Ti	0,013	0,017	0,005	0,053	0,063
Mg	0,867	0,868	0,856	0,767	0,762
Fe	0,083	0,093	0,078	0,115	0,089
Mn	0,006	0,009	0,009	0,009	0,004
Ni	0,005	0,004	0,005	0,004	0,004
Ca	1,051	1,029	1,052	1,050	1,043
Na	0,011	0,009	0,004	0,006	0,010
K	0,004	0,003	0,003	0,002	0,003
Cr	0,002	0,003	0,002	0,002	0,002
Z	2,000	2,000	2,000	2,000	2,000
Y	0,998	1,011	1,003	1,008	1,001
Z	1,066	1,041	1,059	1,058	1,056
En	42,73	43,01	42,63	39,23	39,75
Fs	4,73	5,40	4,63	6,55	5,16
Wo	52,54	51,59	52,74	54,12	55,09

* Analysis of diopside grain adjacent to forsterite. Analysis point close to diopside rim. Used for calculating equilibrium temperature.

** Total iron as FeO

Diopside is found in nearly all the metasedimentary rocks; as the major constituent in granular, light green diopside fels; in monticellite-diopside-forsterite felses where it is usually intergrown with monticellite and forsterite; and as a secondary mineral. In the diopside felses the mineral occurs as rounded, subhedral grains which display marked zoning due to the variation of the Al-content in the grains (Figs. 15 and 16). Figure 15(a) is a trace showing the variation of Al, Fe and Mg across a diopside grain. The substitution of Fe for Al in Al-poor zones is clearly displayed. Figure 15 (b-d) shows that the Al-content varies considerably across grains whereas the Ca-content remains reasonably constant. It is evident that no pattern exists in the zoning; neither the rims nor the cores are preferentially enriched in Al. In some cases one side of a grain is enriched in Al compared with the other side. Tracy et al. (1978) described similar, irregular zoning in diopside from the Adirondack Mountains and attributed the compositional variations to the fact that the diopside formed in a continuous reaction where the reactants and the products of the reaction systematically changed composition as the reaction progressed.

Associated minerals in the diopside felses are interstitial calcite, spinel (hercynite) and rounded grains of partly serpentinized forsterite which occur as inclusions in the diopside grains.

The diopside of the monticellite-diopside-forsterite association is complexly intergrown with monticellite and forsterite. Cleavage is well developed but zoning is absent.

Secondary diopside is developed as rims between altered grains of monticellite and serpentinized forsterite (Fig.17). De Waal (1969) described narrow zones of augite between altered feldspar and chromite and between chromite and serpentinized olivine in serpentinite from the Tugela Rand intrusion, Natal. Similar rims of augite around bronzite enclosed by plagioclase were described by Wells (1952) from norites in the Bushveld Complex. Both authors considered that the formation of the augite was due to the reaction between the phases separated by the augite. De Waal (1969) also described augite rims which occur between two different serpentine pseudomorphs. This augite is also ascribed to have formed due to the reaction between original feldspar and chromite or olivine.

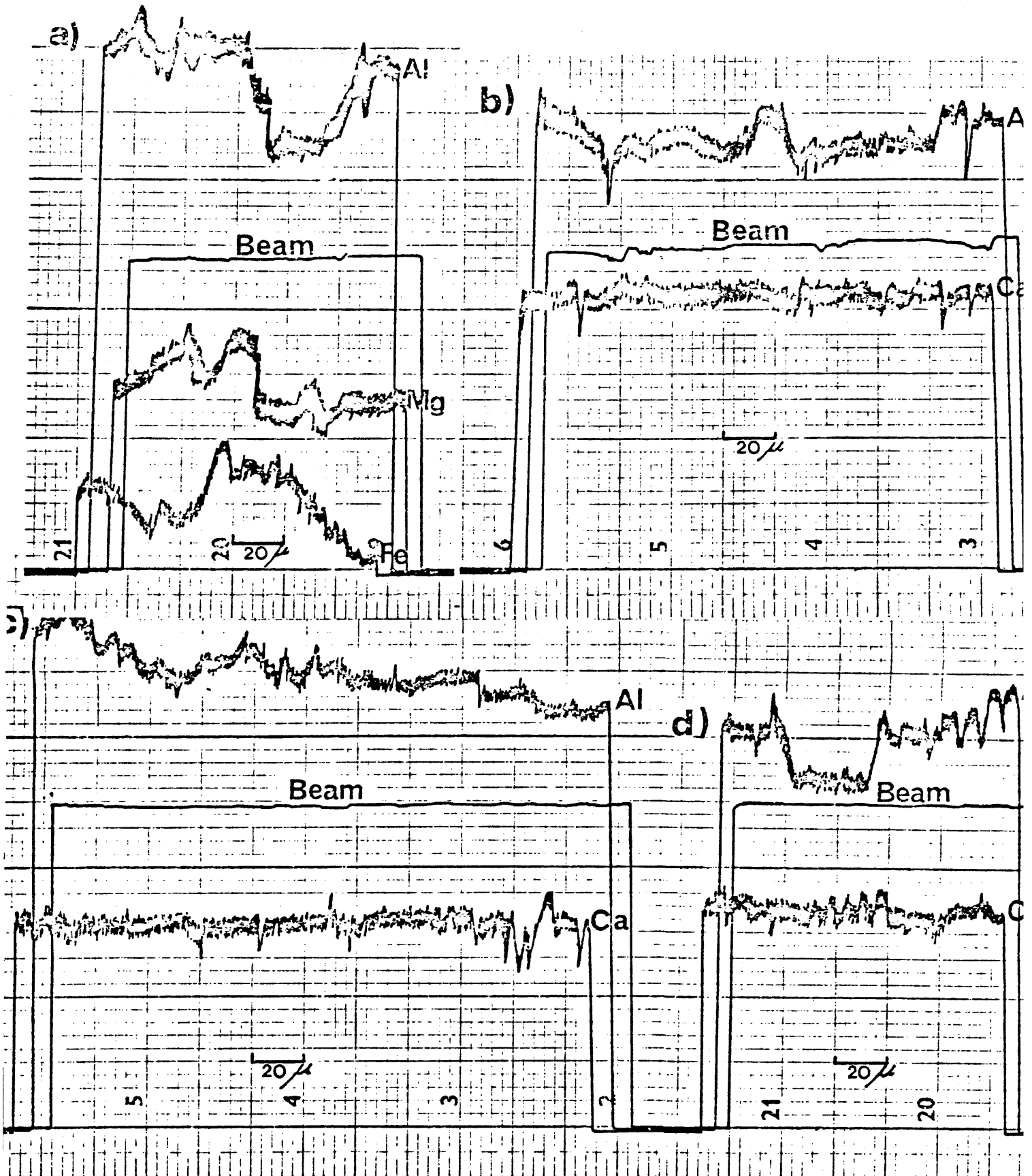


FIG. 15. VARIATION OF ELEMENTS IN DIOPSIDE. SCANNING TRACES FROM ELECTRON MICROPROBE.

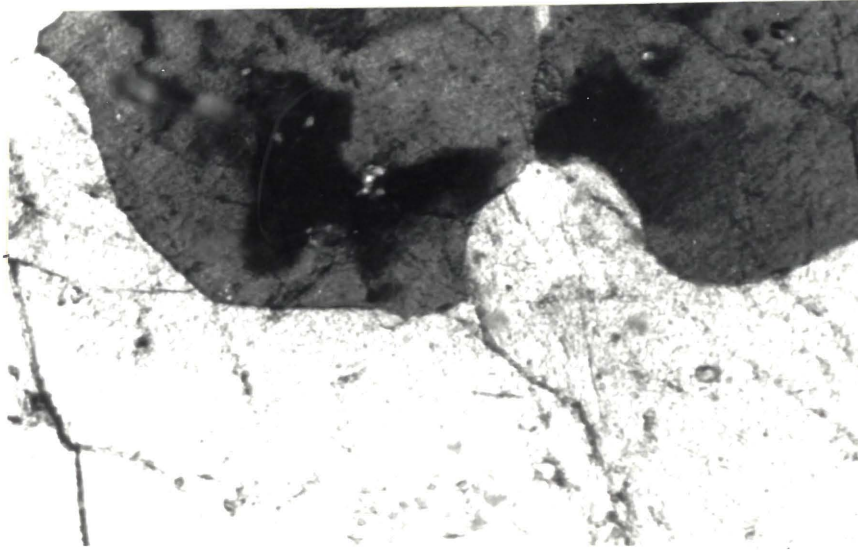


FIG. 16. ZONING IN DIOPSIDE IN A GRANULAR DIOPSIDE FELS. DR 3/40. TRANSMITTED LIGHT, CROSSED NICOLS, X180.

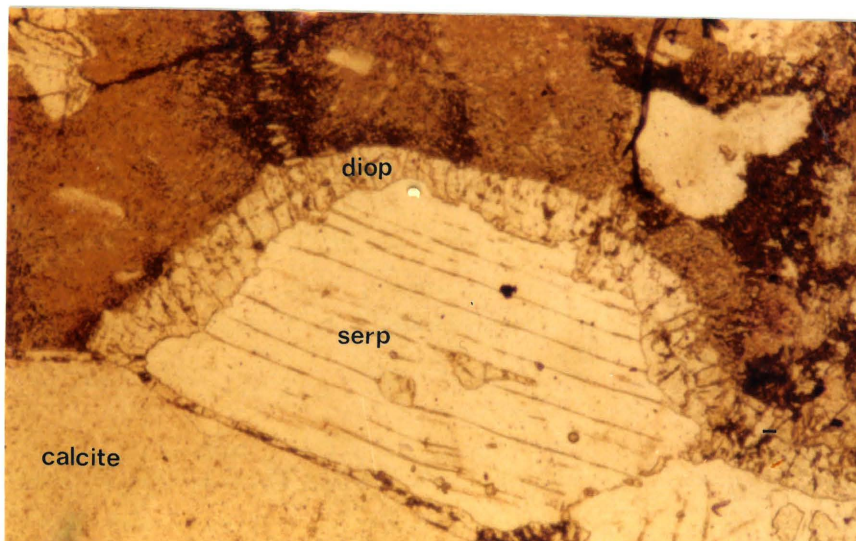
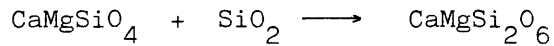


FIG. 17. SECONDARY DIOPSIDE VEIN BETWEEN SERPENTINE AFTER OLIVINE (WHITE) AND ALTERED MONTICELLITE (BROWN). A THIN RIM IS ALSO PRESENT BETWEEN THE SERPENTINE AND CALCITE (GREY-WHITE). DR 3/8. TRANSMITTED LIGHT, NICOLS NOT CROSSED, X 200.

Thus, the development of the diopside rims in the xenoliths may be considered to be due to the reaction of olivine with monticellite. However, no such reaction rims were observed between fresh monticellite and forsterite. It may be considered that serpentinization at constant volume causes removal of MgO and SiO₂ from the olivine and addition of H₂O. Some of the SiO₂ may then react with monticellite to form diopside:



3. FORSTERITE

Forsterite is the second most common mineral in the xenoliths, occurring as rounded grains which show typical serpentine veining. The olivine is found as inclusions in, or as complex intergrowths with monticellite and diopside.

An uncommon exsolution feature in the forsterite of the monticellite felsites is Ca-olivine exsolved along the (010) direction in the forsterite. Forsterite in turn is found to be exsolved from monticellite in these rocks. These exsolution features will be described in more detail in the following section.

Microprobe analyses have shown the olivine to be very Mg-rich (Fo₈₉ - Fo₉₆) and to contain considerable amounts of Mn (Table 3).

4. MONTICELLITE

Monticellite is less common than forsterite or diopside and occurs intergrown with them and also as individual grains in monticellite felsites where the monticellite can constitute up to 80 percent of the rock.

In the monticellite felsites the individual monticellite grains are large (+0,5 mm) and slightly elongated parallel to the (010) direction. The mineral is greyish white with a faint pearly lustre in hand specimen and is colourless in thin section. The (010) cleavage is particularly well developed.

In the monticellite felsites, the monticellite grains may include rounded grains of forsterite. Diopside however, is developed between individual monticellite grains. Calcite is always present as small anhedral grains disseminated throughout the rock and vesuvianite was noted as a rare interstitial constituent.

TABLE 3: MICROPROBE ANALYSES OF MONTICELLITE, FORSTERITE AND SPINEL

MINERAL SAMPLE NO.	MONTICELLITE		FORSTERITE		SPINEL	
	3/45.1	3/45.2	3/45	3/41.1*	3/41.2	3/41
SiO ₂	36,09	36,41	39,37	39,12	39,86	0,51
Al ₂ O ₃	0,13	0,16	0,12	0,17	0,16	63,05
TiO ₂	0,13	0,15	0,11	0,12	0,12	0,15
MgO	23,63	23,78	53,83	47,82	48,35	21,79
FeO ^{***}	3,69	3,10	3,98	10,23	10,43	13,25
MnO	1,03	1,12	1,18	1,09	1,09	0,55
NiO	0,16	0,17	0,12	0,13	0,15	0,19
CaO	34,79	35,27	0,51	0,53	0,39	0,06
Na ₂ O	0,07	0,06	0,04	0,04	0,05	0,05
K ₂ O	0,05	0,06	0,04	0,05	0,05	0,05
Cr ₂ O ₃	0,05	0,05	0,08	0,05	0,07	0,07
TOTAL	99,82	100,33	99,38	99,35	100,72	99,72

STRUCTURAL FORMULA BASED ON N OXYGEN IONS

N=	4	4	4	4	4	32
Si	0,967	0,968	0,957	0,976	0,981	0,104
Al	0,004	0,005	0,004	0,004	0,005	15,134
Ti	0,003	0,003	0,002	0,002	0,002	0,023
Mg	0,943	0,943	1,951	1,779	1,773	6,615
Fe	0,083	0,069	0,081	0,213	0,214	2,257
Mn	0,023	0,025	0,024	0,023	0,023	0,095
Ni	0,003	0,004	0,002	0,003	0,003	0,032
Ca	0,998	1,005	0,013	0,014	0,010	0,013
Na	0,004	0,003	0,002	0,002	0,002	0,020
K	0,002	0,002	0,001	0,002	0,002	0,012
Cr	0,001	0,001	0,002	0,001	0,001	0,011
Z	0,971	0,973	0,961	0,980	0,986	15,295
WXY	2,060	2,055	2,074	2,039	2,030	9,044
<u>Mg</u>	0,899	0,909	0,949	0,883	0,882	0,738
Mg+Fe+Mn						

* Analyses of forsterite grain adjacent to diopside grain.

*** Total iron as FeO

Monticellite alters to a mixture of hydrated minerals which include hydrogrossular, serpentine and talc. Small relicts of monticellite are invariably present in these mixtures. This mixture was analysed by microprobe with a defocused beam and found to contain a Ca:Mg ratio of approximately 5:1. If it is considered that the Ca:Mg ratio in the analysed monticellite is approximately 1, then the mixture has clearly been considerably depleted in Mg probably due to its greater mobility.

Both the monticellite and the forsterite in the monticellite felses contain exsolution lamellae of each other (Figs. 18 and 19). In both minerals the lamellae occur parallel to the (010) direction and attain a width of 0,01 mm. The exsolved forsterite in the monticellite is generally serpentinized, but the forsterite is occasionally preserved.

The monticellite lamellae in forsterite display the same optical characteristics as normal monticellite. Scanning by electron microprobe (Fig. 20) shows the lamellae to be enriched in Ca and depleted in Mg compared to the olivine host and that the Si-content of the lamellae is similar to that of the host. This is taken to be conclusive evidence that the lamellae present in the forsterite are monticellite.

Although forsterite exsolved from monticellite has been described from other localities (Willemse and Benck, 1964; and Tracy et al., 1978), the reverse, monticellite exsolved from forsterite has not, as far as the author is aware, been previously described. Iron-rich monticellite inclusions in olivine have however, been described from the Sharps chondrite and are considered by Dodd (1971) to be recrystallized exsolution lamellae.

The occurrence of these exsolution textures confirms the existence of a subsolidus miscibility gap between forsterite and monticellite as was suggested by the experimental work of Warner and Luth (1973). These authors found that very little CaMgSiO_4 is soluble in olivine at low temperatures. The molecular per cent of exsolved monticellite in olivine from Drenthe was tentatively determined by measuring the area covered by the lamellae relative to the area of an olivine grain which was orientated perpendicular to the (010) plane, so that the maximum number of lamellae could be observed. The unexsolved monticellite component represented by the Ca present in the olivine (analyses 3/45, Table 3)

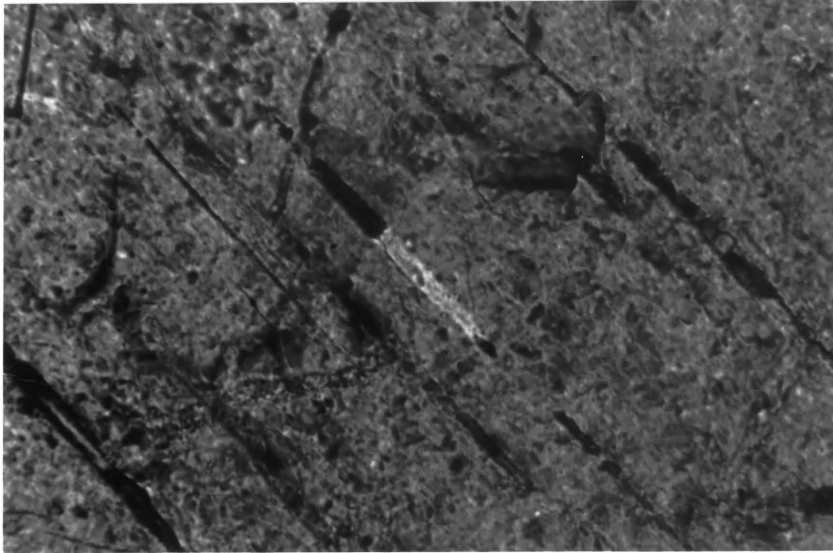


FIG. 18. PARTLY SERPENTINIZED FORSTERITE EXSOLUTION LAMELLA IN MONTICELLITE IN MONTICELLITE FELS. DR 3/42. TRANSMITTED LIGHT, CROSSED NICOLS, X 530.

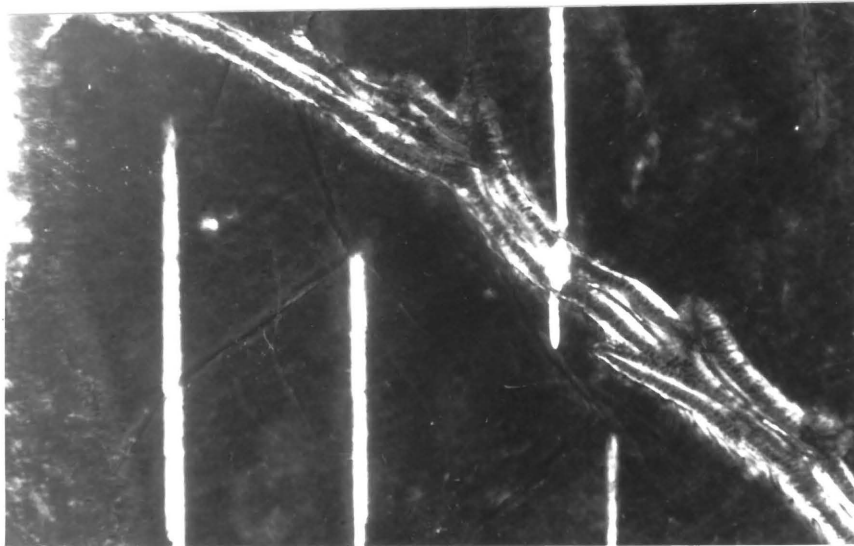


FIG. 19. MONTICELLITE EXSOLUTION LAMELLAE IN FORSTERITE IN MONTICELLITE FELS. NOTE ONE SERPENTINE VEIN CUTTING THROUGH ONE LAMELLA. DR 3/42. TRANSMITTED LIGHT, CROSSED NICOLS, X 530

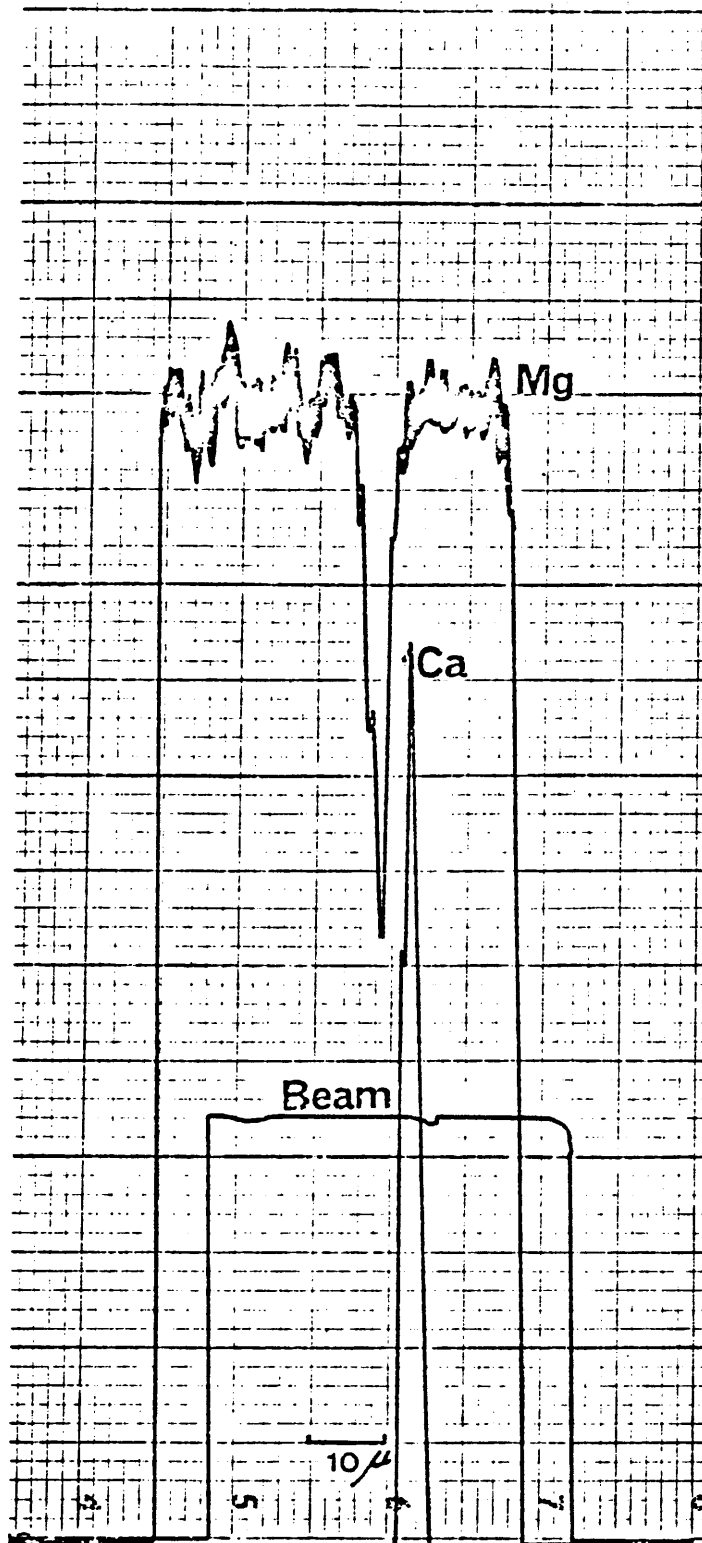


FIG. 20. VARIATION OF Ca AND Mg ACROSS AN EXOLUTION LAMELLA IN FORSTERITE. Si (NOT SHOWN) STAYED CONSTANT. SCANNING TRACE FROM ELECTRON MICROPROBE. DR. 3/45.

was added to the amount derived by measuring the lamellae, and a total of 3,1 mol. per cent of monticellite was obtained.

From the work by Warner and Luth (1973) who determined the solubility of monticellite in forsterite at various pressures and temperatures, it can be concluded that the temperature of metamorphism was at the order of 960°C. As the monticellite content at these temperatures is not very pressure dependent, the temperature of formation at an estimated pressure of 3 Kb could have been slightly higher (Fig.21).

5. OTHER MINERALS

Apart from calcite, which is a fairly abundant constituent in many of the xenoliths, various other metamorphic minerals have been identified.

A green spinel with a Mg:Fe ratio of approximately 3:1 (Table 3) is often associated with diopside and forsterite. This spinel is often replaced by magnetite.

An optically positive mineral with a small 2V was tentatively identified as vesuvianite. The mineral is rare and occurs interstitially between monticellite grains.

Some small xenoliths consist essentially of feldspar and quartz, although minor amounts of talc, calcite and garnet may also be present. The feldspar was identified by X-ray diffraction and optical measurements to be virtually pure anorthite.

6. CONDITIONS OF METAMORPHISM

The principles of chemical thermodynamics can be applied to mineral assemblages which are in equilibrium in order to determine conditions such as the temperature and pressure during crystallization of such an assemblage. It has generally been accepted that chemical equilibrium is approached during the history of many slowly cooled metamorphic rocks (Wood and Fraser, 1978). Thus, assuming equilibrium for the mineral assemblages in the xenoliths, certain reactions were considered.

Jackson (1969) developed a geothermometer from the reaction:

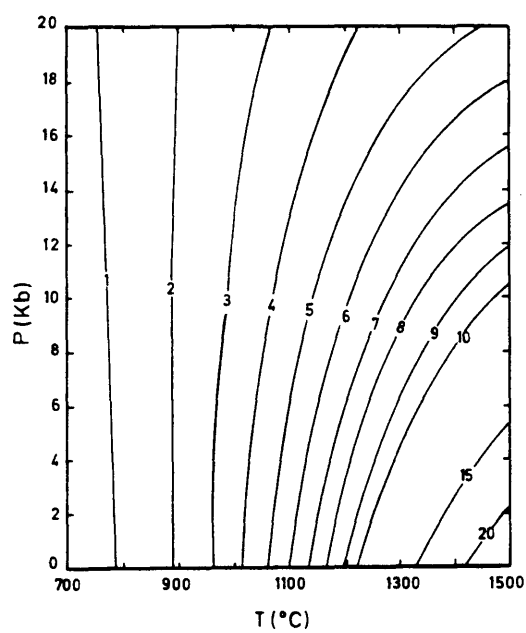
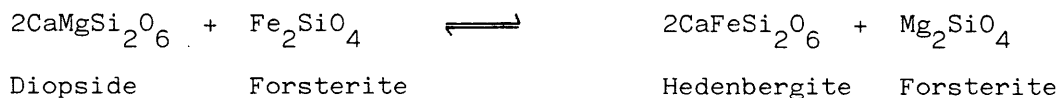


FIG. 21: MAXIMUM SOLUBILITY OF CaMgSiO_4 IN Mg_2SiO_4 AS A FUNCTION OF PRESSURE AND TEMPERATURE (AFTER WARNER AND LUTH, 1973.)

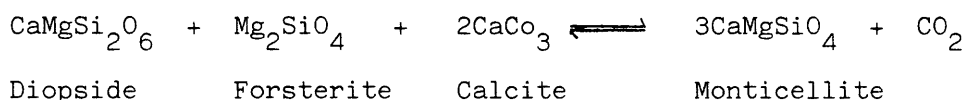


Unfortunately this reaction has been found to be unsuitable for the Al-rich, metamorphic spinels (Roeder et al., 1979) such as those developed on Drenthe. Another geothermometer based on the reaction:



was proposed by Powell and Powell (1974), but was shown to be unsound by Wood (1976). Here again, the high Al content of the diopside may cause inaccuracies because of the lack of thermodynamic data available for fassaite or Al-rich diopside. However, as an exercise, the equilibrium temperature for the reaction was calculated using the data available for normal diopsides. The calculated temperatures of 1012°C and 1018°C at 3 and 4 Kbar respectively seem very reasonable. They should, however, be treated with caution because of the objections raised by Wood (1976) on the Powell and Powell geothermometer, and the consideration regarding the Al-content of the diopside.

Tracy et al. (1978) have determined that monticellite forms according to the reaction:



when it is associated with minerals similar to those found in the xenoliths on Drenthe. Experimental data is only available for the magnesian end members of the minerals (Walter, 1963), but Tracy et al. (1978) concluded that small amounts of iron (as found in the minerals from Drenthe) would not lower the reaction temperature significantly. They found the calculated equilibrium temperature for the iron end members of the reaction to be less than 100°C lower than for the magnesian end members, at 1 bar. This calculation was based on theoretically obtained data. As has been noted before a constraint in any of the above calculations is the lack of thermodynamic data for Al-rich diopside.

Although Hegelson et al. (1978) have cast some doubt on the reliability of the experimental data of Walter (1963), these results, in lieu of any other, were used to calculate the equilibrium temperatures of the reaction at 3 and 4 Kbar, using the equation:

$\Delta G = \Delta H - T\Delta S = -RT \ln f_{\text{CO}_2} - (P-1)\Delta V$, where
G denotes the Gibbs Free Energy, H the Enthalpy, S the Entropy,
V the Volume, R a gas constant (approximately 1,987), f the fugacity,
P the pressure and T the temperature (K).

One constraint, however, is that the total pressure is assumed to be equal to the fluid pressure and that in turn, the fluid is taken to be saturated with CO_2 .

$$P_{(\text{total})} = P_{(\text{fluid})} = P_{\text{CO}_2}$$

The fugacity (f) was calculated from values presented by Mel'nik (1972) in Wood and Frazer (1978) according to the formula:

$f = P \cdot \gamma$ where γ is the fugacity coefficient.
(for calculation, see Appendix I).

The calculated equilibrium temperatures at 3 and 4 Kbar are 945°C and 955°C respectively. These temperatures correspond closely to the temperature of 960°C obtained by calculating the amount of monticellite exsolved from the forsterite. Although the single calculation of the mol. per cent monticellite exsolved from the forsterite is statistically subject to considerable error, the close agreement between the temperatures seems to indicate a reasonable accuracy in the measurements.

V RETROGRESSIVE METAMORPHISM

1. RETROGRESSIVE METAMORPHISM IN IGNEOUS ROCKS

Retrogressive metamorphism of the igneous minerals in the Platreef has occurred in the rocks adjacent to metasedimentary inclusions. Orthopyroxene has been replaced by serpentine, initially along cleavage planes and grain boundaries (Fig. 22). Serpentine pseudomorphs after pyroxenes are generally called bastite, but, because serpentine after amphibole, talc, chlorite and phlogopite may also be termed bastite, Wicks and Whittaker (1977) suggest that wherever possible, the bastite should be distinguished, e.g. enstatite bastite, tremolite bastite, talc bastite, etc. The bronzite bastite of Drenthe may consist of isotropic featureless plates of serpentine, or it may consist of a fine, interlocking texture of serpentine fibres. In all cases the mineral is colourless in thin section. The serpentine was tentatively identified by X-ray diffraction as lizardite which is in agreement with the findings of Wicks and Whittaker (1977) that pyroxene bastite usually consists of lizardite. Also in accordance with the findings of these authors, very little brucite and no magnetite was found in the bronzite bastites of Drenthe.

The Platreef clinopyroxene did not serpentinize as readily as the orthopyroxene. This results in the preservation of the exsolution textures of the clinopyroxene in the altered orthopyroxene (Fig. 22). Where the grains of clinopyroxene are replaced by serpentine, the latter is isotropic and it only rarely displays the fibrous serpentine texture.

Plagioclase has usually been replaced by prehnite and hydrogrossular but sometimes also by chlorite in conjunction with the clinopyroxene.

2. RETROGRESSIVE METAMORPHISM IN METASEDIMENTARY INCLUSIONS

The smaller xenoliths have generally undergone extensive retrogressive metamorphism and consequently the original high grade metamorphic mineralogy has only been preserved in small isolated spots.

Forsterite is replaced by serpentine, initially along grain boundaries and cracks to produce a rough polygon type texture. The

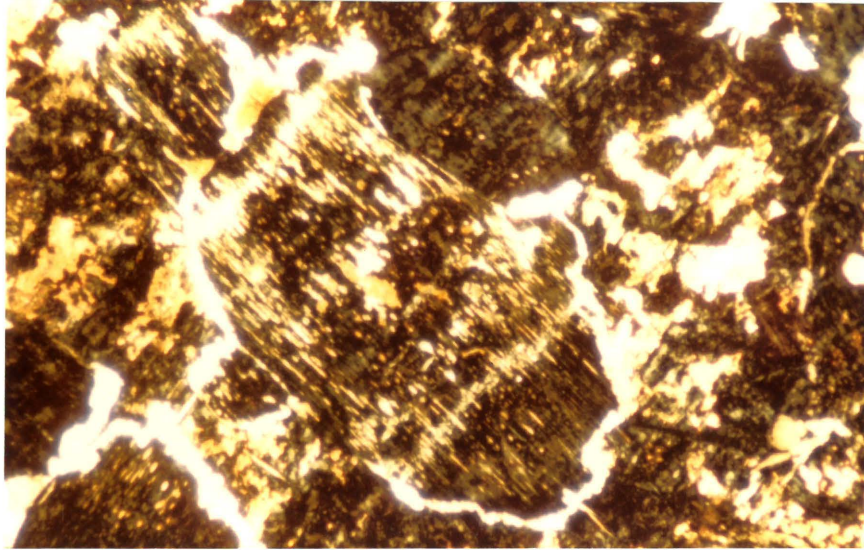


FIG. 22. PYROXENE BASTITES WITH ISOTROPIC SERPENTINE AFTER ORTHOPYROXENE (DARK GRAINS) AND TREMOLITE AFTER THE EXSOLVED BLEBS OF CLINO-PYROXENE. THE MATRIX CONSISTS OF PREHNITE AND HYDROGROSSULAR AFTER PLAGIOCLASE. HYDRATED FELDSPATHIC PYROXENITE. DR 3/9. TRANSMITTED LIGHT, CROSSED NICOLS, X 90.

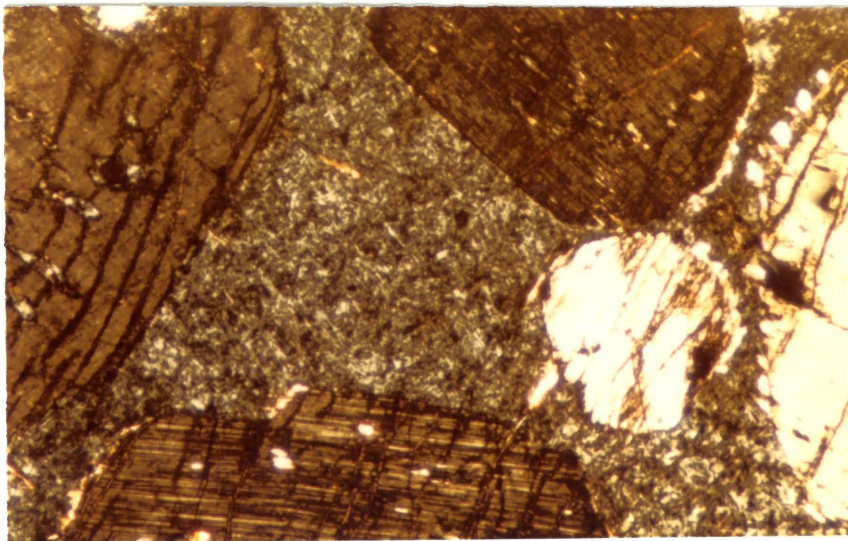


FIG. 23. UNALTERED PYROXENES IN A MATRIX OF CHLORITE FROM THE "SERPENTINTE" ZONE. HYDRATED FELDSPATHIC PYROXENITE. DR 4/82. TRANSMITTED LIGHT, CROSSED NICOLS, X 90.

rims of the polygon cells are formed by the serpentine veins while the centres contain olivine relicts which are also serpentinized with further alteration. Eventually a typical mesh texture is developed with the original veins forming the mesh rims.

The mesh rims consist usually of a colourless, coarse, fibrous serpentine, but occasionally also of a yellowish green variety. The mesh centres display hourglass textures and consist of finely interlocking fibrous serpentine. X-ray diffraction has shown the serpentine to be antigorite or lizardite or a mixture of both. Wicks and Whittaker (1977) found that when serpentine mesh rims surround hourglass mesh centres, any serpentine species may be present. Although magnetite is absent, brucite is a common accessory mineral.

Monticellite is replaced by a mixture of minerals in which hydrogrossular, talc and serpentine were identified. Serpentine and hydrogrossular become dominant when the alteration is in an advanced state. Diopside alters to a mixture of minerals containing hydrogrossular, talc and tremolite, the latter being replaced by serpentine with further alteration. In both the altered monticellite and diopside, the serpentine usually displays weakly developed or no mesh textures. Hydrogrossular occurs in veins and broad elongated patches in the serpentine while "islands" of talc (and brucite) are dispersed throughout the rock; the talc practically always being surrounded by hydrogrossular. The serpentine consists of fine interlocking fibres which X-ray diffraction indicated to be a mixture of antigorite and lizardite.

In some cases, serpentine, similar to the pseudomorphs after olivine, replaces the monticellite and diopside. It then becomes impossible to distinguish between the different serpentine pseudomorphs.

Spinel is replaced by magnetite while calcite is always present in the hydrated metasediments.

A rock type occurring in the "serpentinite" zone (see below), which is taken to have originated from sediments, is the brucite fels that occurs in borehole core lengths of up to 2 metres. These rocks consist of 80 per cent or more brucite with hydrogrossular, serpentine and sometimes, magnetite after sulphide. The brucite is of the

fibrous nemalite variety which displays a slight parallelism.

Brucite is a common alteration product of periclase which, according to Deer, Howie and Zussman (1962, Vol.5), forms from the dissociation of dolomite. According to these authors, brucite may also form directly from the dolomite.

3. THE "SERPENTINITE" ZONE

A large discontinuous zone at the top of the Platreef has undergone extensive retrogressive alteration (Fig. 3, Section C-D). This zone, which is loosely termed a "serpentinite" zone, contains igneous rocks and numerous small pieces of metasedimentary inclusions, as well as rocks which have been completely hydrated, so that their original mineralogy is totally obscured. Major sulphide mineralization is associated with this zone.

In some of the partly altered igneous rocks in the "serpentinite" zone, fresh cumulus orthopyroxenes are present in a matrix of chlorite (Fig. 23). This is thought to indicate that the intercumulus material contained a substantial amount of water and that the chlorite did not replace an earlier intercumulus mineral. If the chlorite has replaced an earlier intercumulus mineral, it is considered that the cumulus orthopyroxene would also have been altered and this is clearly not the case.

Cavities, partly filled with sulphide minerals, occur in some of the totally altered rocks. These cavities probably developed as a result of the decarbonization of dolomite sediments during prograde metamorphism.

The presence of the large amount of brucite mentioned earlier in the "serpentinite" zone, indicates that the original sediments in this zone were in places, very poor in silica. It is suggested that the lack of silica, or the larger proportion of carbonate resulted in a larger amount of degassing in the sediments per unit volume. Also, the paucity of the metamorphic silicates (e.g. olivine, monticellite and diopside) "weakened" the rock as there was no binding capability. This and the degassing resulted in a higher porosity in the sediments. The xenoliths then became unstable in the magma and broke up resulting in large quantities

of magmatic material mixing with water-rich emanations from the degassing sediments.

The H₂O derived from the degassing sediments is considered to have remained close to the xenoliths. Egger (1974) has postulated that tholeiitic melts are derived from partial melting of peridotitic mantle in the presence of H₂O-rich volatiles and Burnham (1979) has shown that basaltic magmas can contain up to 6 per cent H₂O. Thus, the presence of original H₂O in the melt would have inhibited some of the H₂O derived from the sediments from being absorbed. On the other hand, tholeiitic magmas probably contain very little CO₂, although Burnham has shown that CO₂ is quite soluble in basalts. It therefore seems reasonable to presume that while much of the CO₂ was dissolved in the magma, much of the sediment-derived H₂O remained in the proximity of the xenoliths. This H₂O then caused extensive hydration at lower temperatures which resulted in the formation of the hydrated mineral assemblage that is now present (Figure 24).

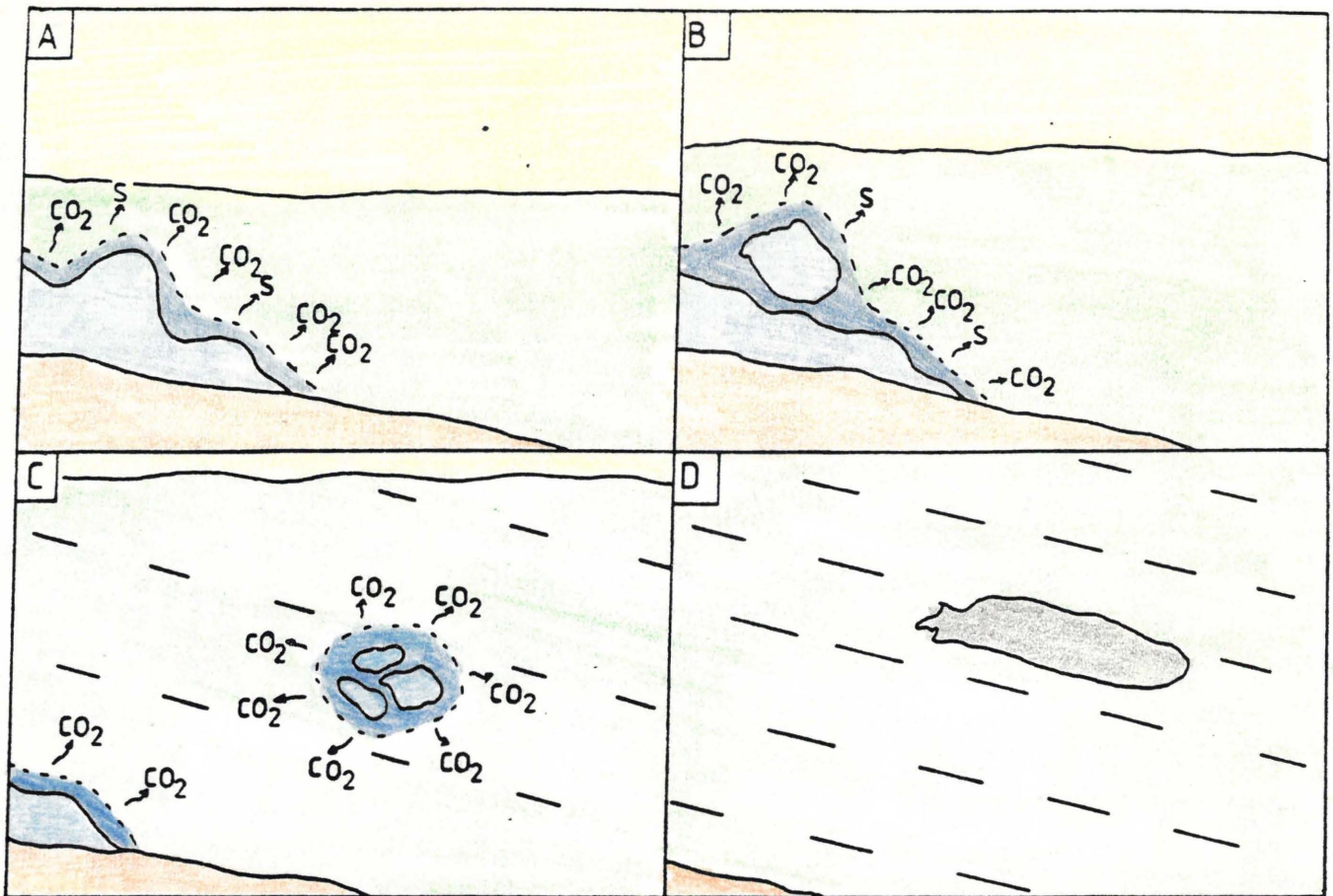


FIG. 24. ENVISAGED FORMATION OF THE "SERPENTINITE" ZONE.

- A. Intrusion of the magma over an uneven floor of dolomite. Onset of metamorphism resulting in the release of CO₂, H₂O and S from the dolomite.
- B. Dolomite raft breaks away from main dolomite body.
- C. Break up of the dolomite raft as a result of degassing. Formation of periclase or brucite due to the dissociation of dolomite. CO₂ is dissolved in magma, H₂O remains in close proximity to the dolomite.
- D. The development of stratification (possibly due to convection currents in the magma) has "flattened" the zone of the original dolomite xenoliths, H₂O which remained near the dolomite hydrated the zone at low temperatures.

VI THE SULPHIDE MINERALS OF THE PLATREEF

1. GENERAL

The sulphide mineral assemblages of the Platreef are similar to the Ni-Cu ores usually associated with mafic and ultramafic rocks. Pyrrhotite (and sometimes pyrite) is the most abundant sulphide mineral while pentlandite and chalcopyrite are the Ni- and Cu-carrying sulphides respectively.

The sulphides of the Bushveld Complex have been described in an extensive study by Liebenberg (1968 and 1970), and Von Gruenewaldt (1976) investigated the sulphides of the upper zone of the eastern Bushveld in detail. Numerous investigations on the Merensky Reef are available in the literature but very little has been published on the ore minerals of the Platreef. Schneiderhöhn (1929) described aspects of the Platreef ore minerals and Buchanan et al. (1981) investigated factors relating to the genesis of the sulphides in the Platreef to the south of Drenthe.

The sulphides of the Platreef on Drenthe occur in fresh igneous rocks and in the "serpentinite" zone, where the sulphide mineralization is particularly well developed. Although sulphide mineralization is patchy in the igneous rocks, it would seem that enrichment occurs at the top of the lower pyroxenitic layer. Sulphides are absent from the metasedimentary inclusions except in the small inclusions found in the "serpentinite" zone. The major sulphide phases in the "serpentinite" zone are, except for some alteration features, similar to those found in the fresh igneous rocks of corresponding stratigraphic positions in the Platreef.

2. THE DISTRIBUTION OF THE MAJOR SULPHIDE MINERALS

The sulphide minerals are not distributed homogeneously throughout the Platreef. Positions of sulphide enrichment differ from borehole to borehole and correlation along strike is difficult. Similarly, the Ni:Cu ratio fluctuates laterally as well as vertically, although there is a tendency for it to decrease with height (Fig. 25). This ratio was calculated from Ni and Cu values determined by an acid leach method during the exploration programme.

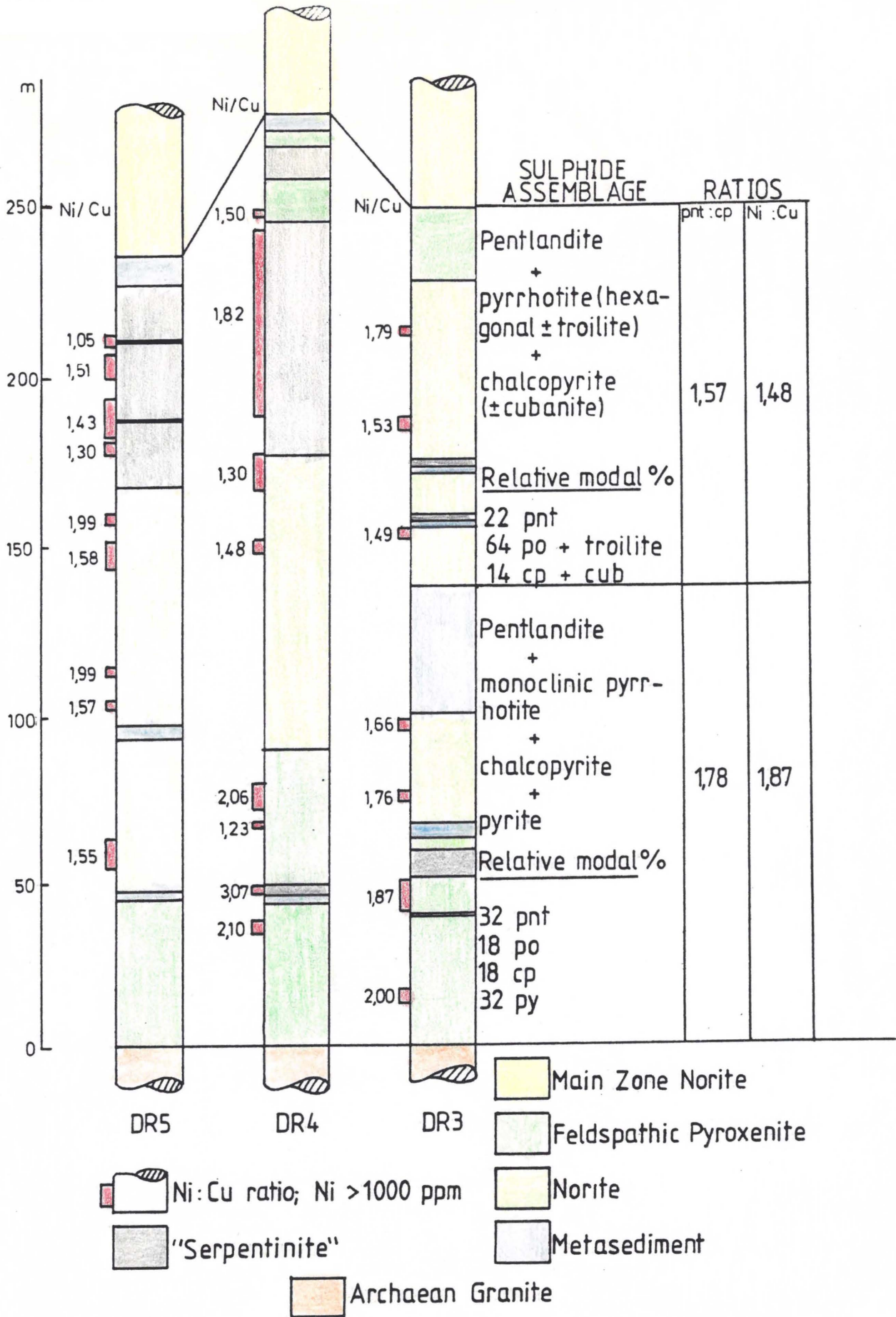


Fig 25. BOREHOLE PROFILES OF THE PLATREEF WITH Ni:Cu RATIOS WHERE Ni >1000 PPM. SULPHIDE ASSEMBLAGES ARE ALSO SHOWN.

As Ni and Cu values obtained in this way represent the amounts of these elements in the sulphide minerals and as the amount of Ni in pentlandite is similar to the amount of Cu in chalcopyrite, the analyses also give some measure of the relative amounts of pentlandite and chalcopyrite present in the rocks. Qualitative energy dispersive X-ray analyses of pyrite and pyrrhotite showed that very little Ni and Cu is present in these two minerals.

The relative modal abundances of the major sulphide minerals were determined with the aid of a Swift automatic point counter. As the rocks rarely contain more than 5 modal per cent sulphide, the analytical error is probably relatively high. This error was, however, not determined.

Two distinct sulphide assemblages occur in the Platreef on Drenthe (Fig. 25). In the lower 150 metres, pentlandite and chalcopyrite are always present in association with pyrrhotite or pyrite or both. The sulphide mineral assemblages in the upper 100 metres on the other hand, consist of pyrrhotite, pentlandite and chalcopyrite with or without cubanite and troilite.

It is clear from Figure 25 that the Fe-sulphides constitute the major sulphide minerals. Chalcopyrite plus cubanite is also more abundant relative to pentlandite in the upper 100 metres than in the lower 150 metres, a trend which is borne out by the variations in Ni:Cu ratios which are higher in the lower part than in the upper part of the Platreef (Fig. 25).

3. THE SULPHIDE MINERALS

3.1 Pyrrhotite

Pyrrhotite is the major sulphide mineral in the upper 100 metres of the Platreef. In the lower part it may occur as the most abundant sulphide, although it is usually subordinate to pyrite or it may be completely absent.

The mineral commonly forms the core of the sulphide grains with pentlandite and chalcopyrite occurring along the margins. Exsolved pentlandite parallel to the (0001) plane is practically always present. In rare cases the pyrrhotite part of the sulphide blebs consists of an aggregate of small pyrrhotite grains, each with a slightly different

crystallographic orientation. This feature, which can be observed under slightly crossed nicols, is indicative of recrystallization.

The relationship between pyrite and pyrrhotite is not always clear. In some cases embayments and protrusions of pyrite into pyrrhotite suggest replacement of the latter while in other cases the opposite was observed.

The three modifications of pyrrhotite, i.e. troilite (stoichiometric pyrrhotite), hexagonal pyrrhotite and monoclinic pyrrhotite have all been observed. It is very difficult to distinguish optically between the different forms, although after etching with chromic acid, the different phases can be identified quite readily. The hexagonal form etches slightly less than the monoclinic modification, whereas troilite is not affected by chromic acid.

If two modifications of pyrrhotite are present, one form is usually the host with the other variety forming sinuous lamellae, irrespective of which variety is present as the host (Figs. 26 and 27). The lamellae are, according to Liebenberg (1970), parallel to the (0001) direction or to a pyramidal plane of the host pyrrhotite.

Monoclinic pyrrhotite may occur together with the hexagonal modification but not with troilite. This is in accordance with the work of Desborough and Carpenter (1965) and the observations of Liebenberg (1970).

Hexagonal and monoclinic pyrrhotite usually occur together in the lower part of the Platreef, one as the host and the other as lamellae. The amount of lamellae may be so large that it is nearly impossible to distinguish the host from the lamellae.

Generally it would appear that where pyrite is present, especially as the dominant Fe-sulphide, the monoclinic form is the most abundant of the pyrrhotite modifications. This occurs in the lower 150 metres of the Platreef. Above this, where pyrite is absent, hexagonal pyrrhotite is the most abundant variety. Troilite is developed towards the top of the Platreef, either as lamellae in a hexagonal host or as host to hexagonal lamellae.

Monoclinic pyrrhotite contains less iron than the hexagonal modification, which in turn has less iron than troilite (Figure 28). From the observed occurrences of the different pyrrhotite modifications, the iron

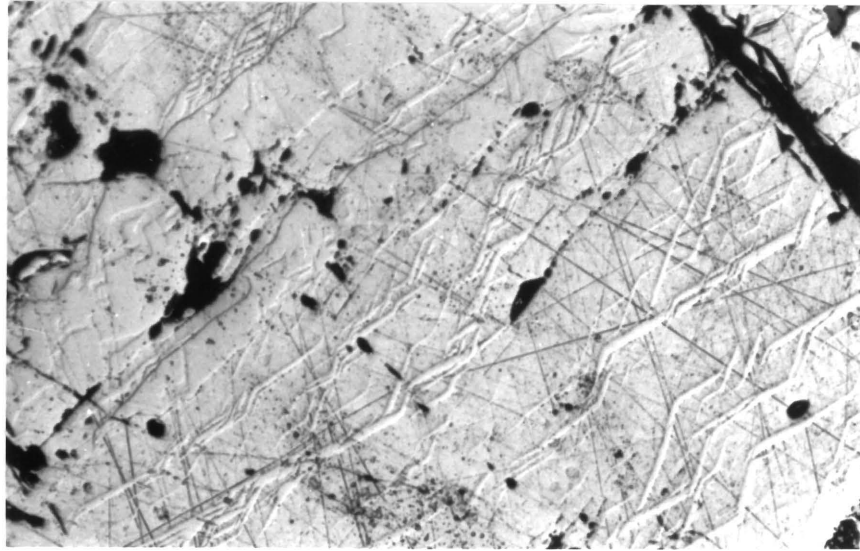


FIG. 26. TROILITE LAMELLAE IN HEXAGONAL PYRRHOTITE HOST. DR 5/20. REFLECTED LIGHT, X 270

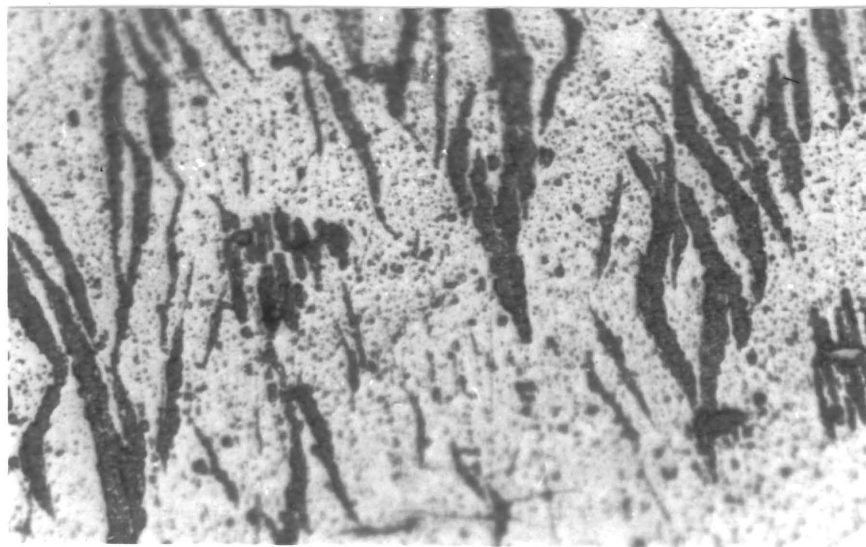


FIG. 27. ETCHED HEXAGONAL PYRRHOTITE LAMELLAE IN TROILITE (NOT ETCHED) HOST. DR 5/27. REFLECTED LIGHT, X 350.

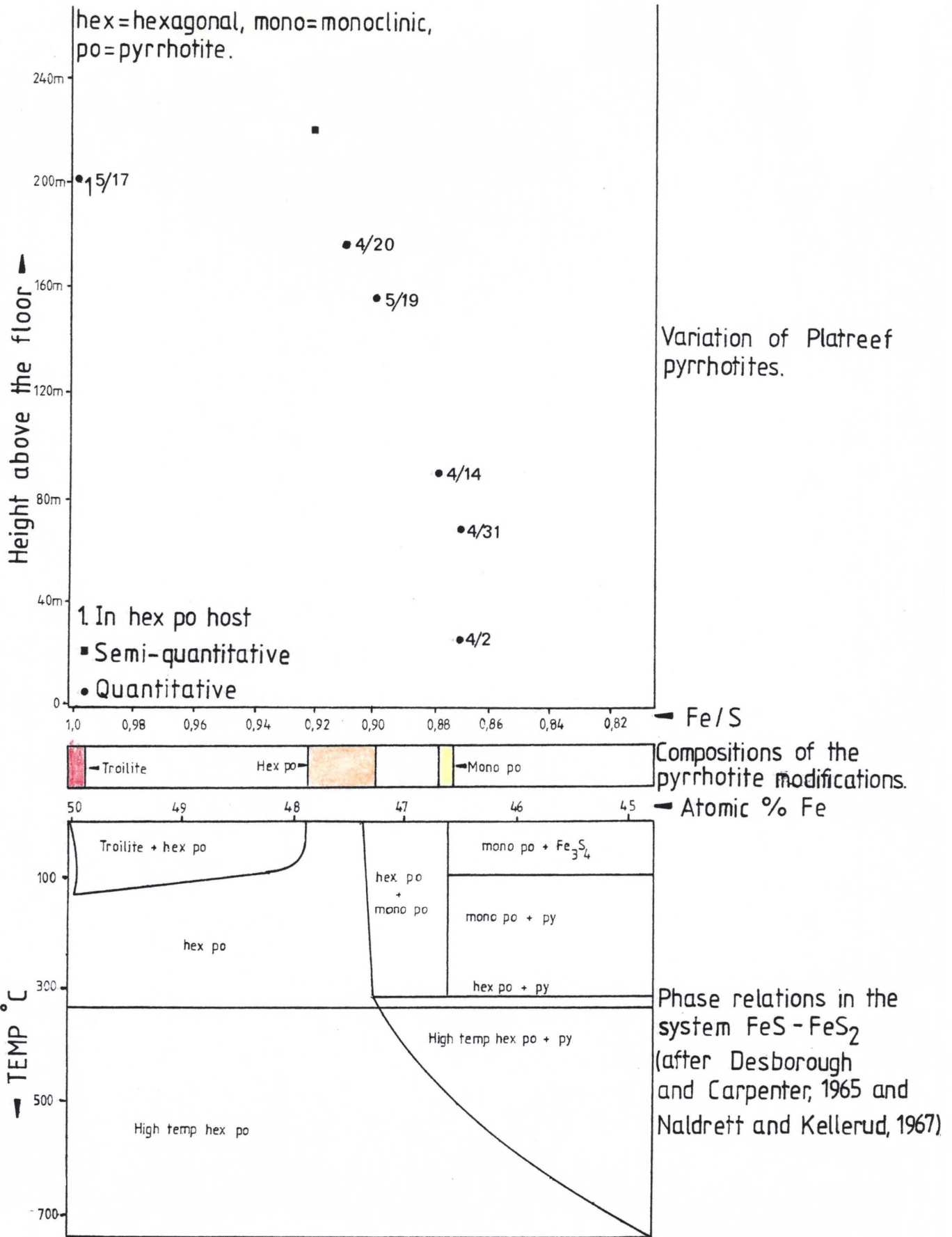


Fig 28. VARIATION OF THE COMPOSITION OF PYRRHOTITE WITH STRATIGRAPHIC HEIGHT AND THE PHASE RELATIONS IN THE SYSTEM FeS - FeS₂.

content of the pyrrhotites generally seems to increase with height above the floor; a trend which is also borne out to some extent by analyses of pyrrhotites from different stratigraphic positions in the Platreef (Figure 28 and Table 4).

TABLE 4: ENERGY DISPERSIVE X-RAY ANALYSES OF PYRRHOTITE FROM THE PLATREEF.

SAMPLE NO.	4/2	4/31	4/14	5/19	4/20	5/17
% Fe	59,73	59,79	61,17	60,42	60,36	62,88
% S	39,28	39,34	39,79	38,67	38,16	36,22
TOTAL	99,01	99,13	100,96	99,09	98,52	99,10
Fe:S ratio	0,87	0,87	0,88	0,90	0,91	0,99

Height above the floor increases from left to right (see also Figure 28).

The pyrrhotites were analysed by means of an energy dispersive X-ray analytical system coupled to an electron microscope. Troilite from the Okahandja meteorite was used as a standard. Ni could not be analysed for but qualitative investigation showed that very little Ni is present in the pyrrhotite. It should be noted that the troilite analysis from the upper part of the Platreef is from a troilite lamella in a hexagonal pyrrhotite host and it must, therefore, not be taken to indicate that troilite is the only modification present.

3.2. Pyrite

Pyrite occurs only in the lower 150 metres of the Platreef and is normally the dominant Fe-sulphide in the lower 100 metres. The mineral may form part of composite sulphide grains or it may occur as separate euhedral grains. The latter type of pyrite is normally slightly replaced by silicate and is not associated with any of the other sulphides. Also part of this generation is the pyrite which occurs as thin rims around silicates (Fig. 29).

The pyrite which is associated with the other sulphides occur in a variety of ways. It does not seem to take any preferential position in a composite sulphide grain. The most striking occurrence of the pyrite

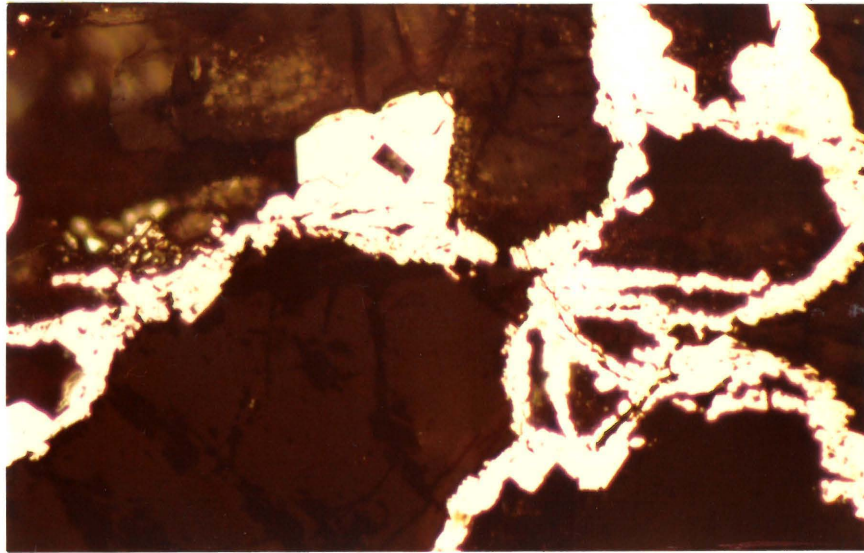


FIG. 29. EUHEDRAL GRAINS OF PYRITE, NOT ASSOCIATED WITH ANY OTHER SULPHIDES, AROUND SILICATE GRAINS. DR 5/8. REFLECTED LIGHT, X 450

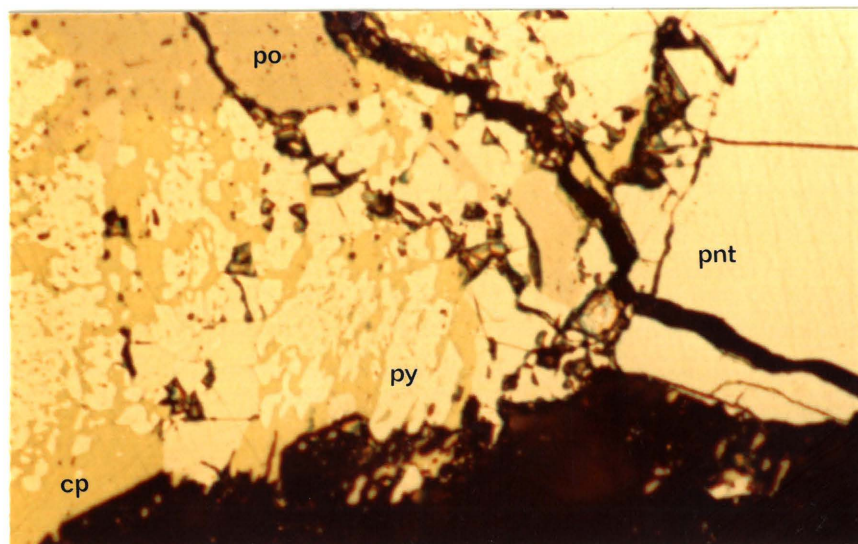


FIG. 30. WORM-LIKE INTERGROWTH OF PYRITE (PY) WITH CHALCOPYRITE (CP). ALSO PRESENT ARE PENTLANDITE (PNT) AND PYRRHOTITE (PO). DR 4/31. REFLECTED LIGHT, X 450.

is when it occurs with chalcopyrite as a myrmekite-like intergrowth (Fig. 30). This myrmekite-like intergrowth may constitute a whole sulphide grain or it may be associated with pyrrhotite and pentlandite. The derivation of this texture is ascribed by Liebenbrg (1970) to pyrite and chalcopyrite crystallizing together at 739°C from a pyrrhotite which contained some Cu.

3.3. Pentlandite

Pentlandite is, in common with this type of assemblage elsewhere, the only Ni-bearing sulphide mineral. It has, especially when associated with pyrite, a reasonably well developed cleavage, resulting in the formation of triangular pits when polished. The pits are larger and more numerous than those found in normal polished pyrite and as both minerals are isotropic and have similar reflectivity and colour, it serves as a characteristic feature when the Ni-sulphide is found enclosed in large pyrite grains.

Coarse pentlandite is found as anhedral, sometimes sub-idiomorphic grains in composite sulphide grains. The mineral may be enclosed by pyrite when the latter is the dominant Fe-sulphide, but when it is associated with pyrrhotite it occurs as a mosaic of grains along boundaries of the pyrrhotite grains.

Pentlandite exsolutions in pyrrhotite is very common and only rarely is pyrrhotite devoid of any pentlandite. Lamellae exsolved parallel to (0001) of pyrrhotite (or (001) of monoclinic pyrrhotite) are common and can attain a length of 0,3 mm and a width of 0,01 mm.

3.4. Chalcopyrite

The main Cu-bearing mineral is chalcopyrite and it is, like pentlandite, present throughout the Platreef. It is normally found as granular aggregates on the rims of composite sulphide grains, or as separate satellite grains in proximity to the larger sulphide grains. When associated with pyrite, the chalcopyrite and pyrite form a complex intergrowth as described above. In such grains the chalcopyrite is not concentrated along grain boundaries as is the case when it is associated with pyrrhotite.

The grains of chalcopyrite are commonly found to be polysynthetically twinned, a feature that is accentuated when the mineral is etched

with chromic acid. According to Ramdohr (1969), this twinning is parallel to the (111) direction. The feature becomes more common towards the top of the Platreef where cubanite (which is slightly stained by chromic acid), is sometimes found to be exsolved parallel to the twin plane.

3.5. Other Sulphides and Ore Minerals

Cubanite is not only present as an exsolved phase in chalcopyrite but also as part of composite grains consisting of pyrrhotite (hexagonal and troilite), pentlandite and chalcopyrite near the top of the Platreef. The cubanite occurs as separate bodies in pyrrhotite or pentlandite and may also be seen along cracks and grain boundaries in pyrrhotite. This latter mode of occurrence seems to point to a replacement nature of cubanite but Liebenberg (1970) considers the separate cubanite bodies to be an exsolution feature.

Sphalerite is found in small amounts, together with chalcopyrite in satellite grains around composite sulphide blebs. This mineral seems to occur more frequently towards the top of the Platreef.

A mineral that is very similar in appearance to sphalerite, and which is present in notable amounts is the manganese sulphide, alabandite. The mineral was positively identified with the aid of energy dispersive X-ray analyses and the spectrum obtained is shown in Figure 31. The alabandite is confined to the "serpentinite" zone where it replaces pyrrhotite along grain boundaries, veins and cracks. The manganese probably originated from the metasediments as alabandite is not common in the pyrrhotite- pentlandite- chalcopyrite-association. The high MnO content of the forsterite and monticellite (approximately 1 per cent) and the fact that the dolomite of the Transvaal Sequence can contain more than one per cent MnO (Visser, 1964) provide reasonable grounds for this assumption.

Magnetite is the only oxide mineral of the sulphide assemblage and occurs as small discrete grains enclosed in composite sulphide grains. The mineral is usually euhedral with slightly round edges.

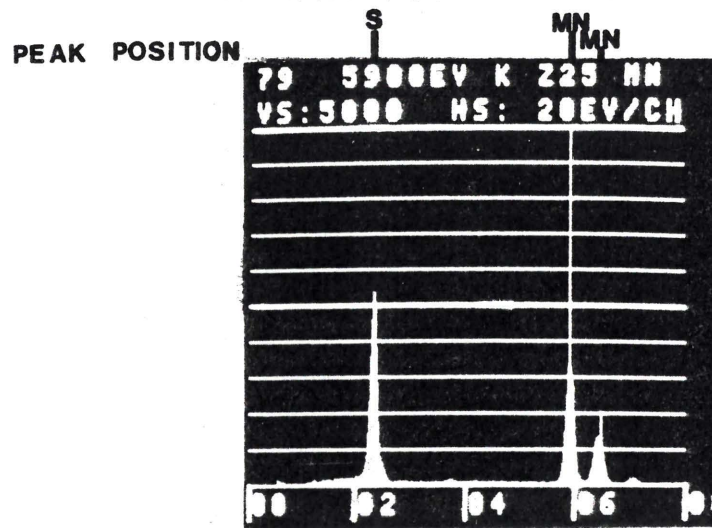


FIG. 31. ENERGY DISPERSIVE X-RAY SPECTRUM OF ALABANDITE FROM DRENTHE.

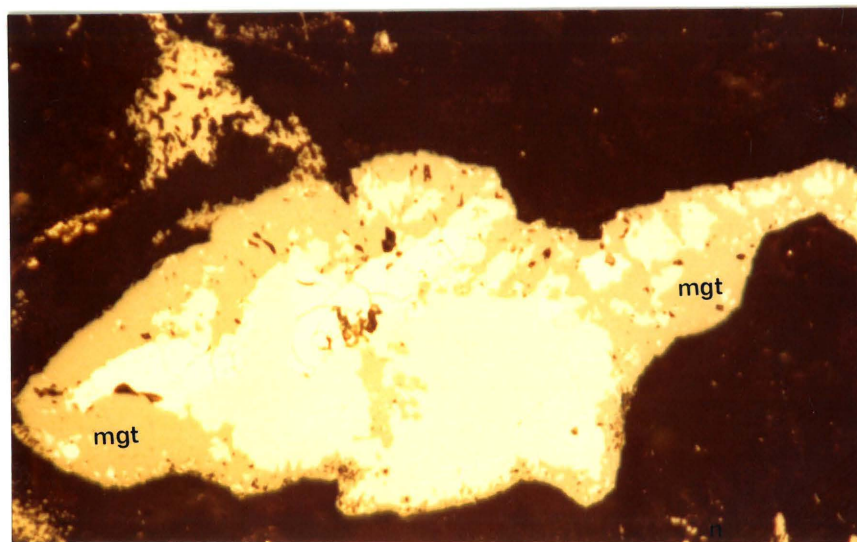


FIG. 32. MAGNETITE REPLACING A COMPOSITE SULPHIDE GRAIN IN THE "SERPENTINITE" ZONE. DR 4/28. REFLECTED LIGHT, X 200

4. THE SULPHIDES IN THE "SERPENTINITE" ZONE

The sulphides in the "serpentinite" zone differ in some respects from those in the fresh igneous rocks in that they have undergone some alteration. Generally, however, the mineralogy is very similar in all the rock types, although evidence exists that some of the sulphides may have been remobilized.

Where alteration has taken place, composite sulphide grains are often seen to be replaced by magnetite (Figure 32). Composite sulphide grains are also frequently replaced by rust coloured material (Figure 33) consisting of Fe, Cu, Ni, S, Mg and Al (determined by energy dispersive X-ray analysis). This material probably consists of a variety of finely interwoven alteration products one of which is magnetite (Figure 34).

Evidence for remobilization of sulphides is found in the linear arrangement of elongated sulphide grains in the brucite felses. Magnetite and brucite are seen to replace the sulphides in these rocks.

5. THE SULPHIDE MINERAL ASSEMBLAGES, TEXTURES AND PHASE RELATIONS

It is generally accepted that the sulphides in mafic and ultramafic rocks crystallized from an immiscible sulphide liquid that separated from a silicate magma. The compositions of the major sulphides all fall in the Cu-Fe-Ni-S system, the phase relations of which, or parts thereof, have been studied and described by Craig and Kullerud (1969) and Kullerud et al. (1969). The following descriptions of the phase relations in the Cu-Ni-Fe-S system are derived from these authors' work.

5.1. The Minerals involved in the Cu-Fe-S part of the system

Figure 35 shows a series of diagrams of the phase relations at different temperatures in the Cu-Fe-S system which pertain to the observed minerals in the Platreef. Also shown are the positions where the bulk sulphide compositions of the lower and upper parts of the Platreef plot onto this diagram. The bulk compositions were calculated from the relative modal percentages of the sulphide minerals given in Figure 35.

Crystallization of a Fe- and Ni-rich mono-sulphide solid solution (Mss) results in an enrichment of Cu in the residual sulphide liquid. At approximately 800°C the S-rich lower Platreef (LPR) sulphide consisted of

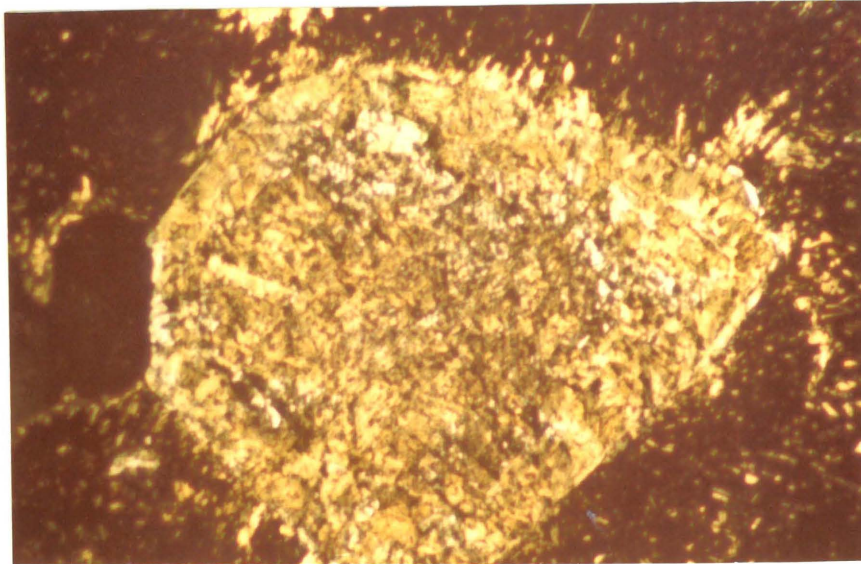


FIG. 33. RUST-COLOURED REPLACEMENT PRODUCT OF A SULPHIDE GRAIN. DR 4/83. REFLECTED LIGHT, X 120

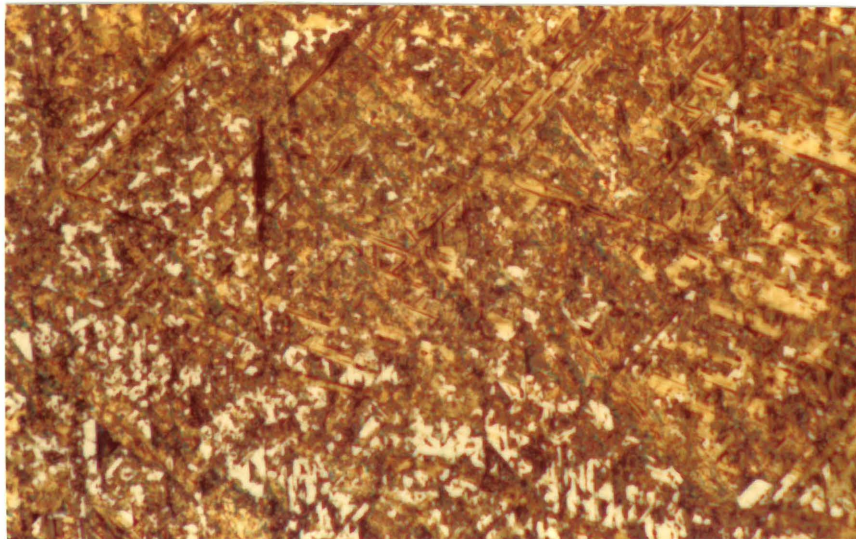


FIG. 34. MAGNIFICATION OF THE RUST-COLOURED MATERIAL IS SEEN TO CONTAIN A MIXTURE OF MINERALS WHICH INCLUDE MAGNETITE (WHITE). DR 4/83 REFLECTED LIGHT, X 450.

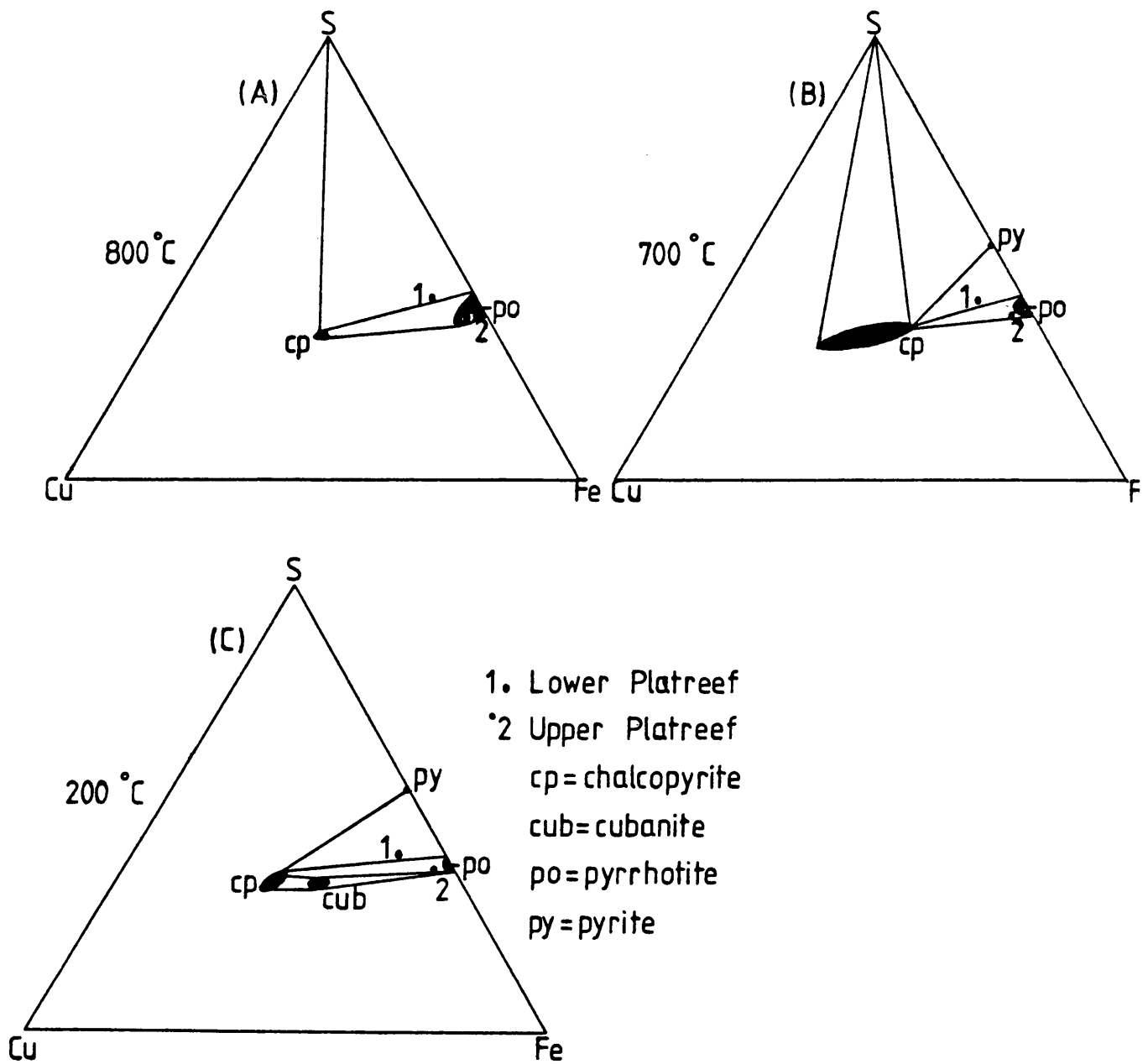


Fig 35. PHASE RELATIONS RELEVANT TO THE PLATREEF SULPHIDES. IN THE SYSTEM Cu-Fe-S AT (A) 800 °C, (B) 700 °C AND (C) 200 °C (AFTER KELLERUD et al., 1969).

a Cu-rich pyrrhotite, an early chalcopyrite phase and S-liquid..

On cooling, the Cu-content of the pyrrhotite decreased and at 743°C, pyrite formed as a result of the reaction between S-liquid and pyrrhotite. It is considered that the worm-like intergrowth between pyrite and chalcopyrite originated at about this temperature, although the mechanism of how this intergrowth could have formed is by no means clear.

At approximately 800°C the upper Platreef (UPR) sulphide consisted solely of a Cu-rich pyrrhotite, which exsolved chalcopyrite on cooling. Because of the S-poor nature of this sulphide assemblage, cubanite became a stable Cu-rich phase on break-up of the chalcopyrite solid solution. This resulted in the stable mineral assemblage at low temperature of cubanite, chalcopyrite and hexagonal pyrrhotite.

5.2. The Minerals involved in the Ni-Fe-S part of the system

Both the LPR and UPR sulphides lie in the stability field of the monosulphide solid solution that extends from the Fe-S join to the Ni-S join at 800°C. At approximately 600°C both still consisted of a monosulphide solid solution even though pyrite and pentlandite were already stable phases in the Fe-Ni-S system at this stage (see Fig. 36).

Further cooling results in a narrowing of the stability field of the monosulphide solid solution and consequently pentlandite only exsolved as a separate phase from the pyrrhotite at temperatures below 600°C for the UPR and at temperatures below 280°C for the LPR when pyrite and pentlandite become stable co-existing phases (Liebenberg, 1970).

According to the low temperature phase relations in the Fe-Ni-S system, the LPR sulphide lies in the pyrite-pentlandite-monoclinic pyrrhotite field and the UPR sulphide lies just inside the troilite-hexagonal-pyrrhotite-pentlandite field. This corresponds to the observed mineral assemblages.

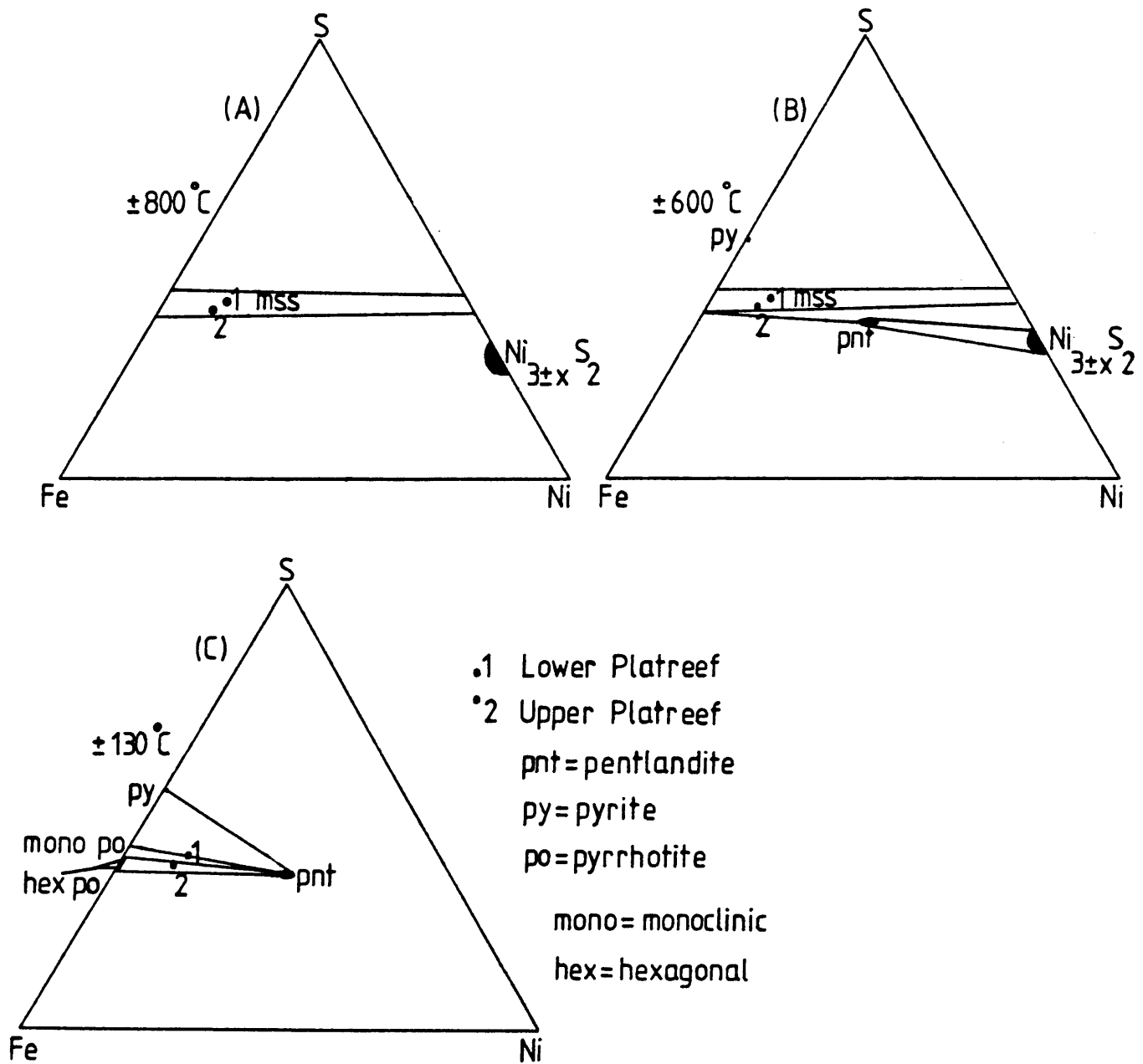


Fig 36. PHASE RELATIONS RELEVANT TO THE PLATREEF SULPHIDES IN THE SYSTEM Fe-Ni-S AT APPROX (A) 800 °C, (B) 600 °C AND (C) 130 °C (AFTER KULLERUD et al., 1969).

VII COMPARISON OF THE PLATREEF WITH THE MERENSKY REEF

It has been stated in Chapter II that the Platreef is considered to be part of the critical zone of the Potgietersrus limb. Van der Merwe (1978) considered it to be part of the main zone, but Buchanan et al. (1981) concluded that the Platreef was derived from a Merensky Reef type magma, which would put the Platreef at the top of the critical zone.

Correlation of the Platreef with other horizons in the other compartments of the Bushveld Complex can be based on parameters such as stratigraphic height above the floor, mineral content and mineral composition.

1. COMPARISON OF THE STRATIGRAPHIC POSITION OF THE MERENSKY REEF
IN THE RUSTENBURG LAYERED SUITE

The Merensky Reef is given by various authors to occur approximately 2000-3000 metres above the base in both the western and eastern Bushveld. Nowhere is the Merensky Reef in contact with floor rocks as is the case for the Platreef in the Potgietersrus limb. However, this may not be particularly significant, as it could be due to the downward transgression of the magma into the floor rocks caused by structural upwarp during the emplacement of the Potgietersrus limb, as postulated by Von Gruenewaldt (1979).

2. COMPARISON OF THE MINERAL CONTENT OF THE PLATREEF AND MERENSKY REEF

A comparison of the mineral content of the Merensky Reef and the Platreef is given in Table 5. It is evident that the mineral content of the Platreef on Drenthe differs from that at localities to the south of Drenthe.

Van der Merwe (1978) noted the presence of chromite and olivine in the lower part of the Platreef on Zwartfontein 814 LR. He showed that, in one sample from Zwartfontein, up to 37 percent of the mode is olivine. Although other authors do not refer to any amount of olivine in the Merensky Reef, sporadic olivine was observed by the author in the Merensky Reef from the Impala Platinum mines at Rustenburg. In general, it would also seem as if the Merensky Reef contains less plagioclase and clinopyroxene than the Platreef.

TABLE 5: COMPARISON OF THE MINERAL CONTENT OF THE MERENSKY REEF AND THE PLATREEF

LOCALITY	ORTHOPYROXENE %	CLINOPYROXENE %	PLAGIOCLASE %	OLIVINE %	% OTHER MINERALS
1. DE KAFFERSKRAAL 53 JT	75,75	-	20,25	-	4
2. DE KAFFERSKRAAL 53 JT	66,3	-	27,2	-	6,5
3. ATOK PLATINUM MINE	74,0	3,0	23,0	-	-
4. RUSTENBURG PLATINUM MINE	73	2,0	25,0	-	-
5. ZWARTKLIP 405 KQ	61,2	25,50	8,9	-	4,4
6. ZWARTKLIP 405 KQ	80,00	-	17,0	-	3,0
7. ZWARTFONTEIN 814 LR	7,0	49,0	4,0	37,0	3,0
8. ZWARTFONTEIN 814 LR	65,0	6,0	27,0	-	2,0
9. ZWARTFONTEIN 814 LR	66,0	5,0	21,0	-	8,0
10. TWEEFONTEIN 238 KR	57,0	12,0	25,0	-	2,0
11. DRENTHE 778 LR	61,0	7,0	31,0	-	1,0
12. DRENTHE 778 LR	28,0	18,0	50,0	-	4,0
13. DRENTHE 778 LR	38,0	15,0	45,0	-	2,0

- 1 & 2 : Merensky Reef, Lydenburg district, Eastern Transvaal (Roux, 1968)
- 3 : Merensky Reef, Burgersfort district, Eastern Transvaal (Schwellnus et al., 1976).
- 4 : Merensky Reef, Rustenburg district, Western Transvaal (Schmidt, 1952).
- 5 & 6 : Merensky Reef, Northam district, Western Transvaal (Van Zyl, 1960¹).
- 7 - 10 : Platreef, Potgietersrus district, south of Drenthe (Van der Merwe, 1978).
- 11 : Average for feldspathic pyroxenite layer, Platreef, Drenthe (this study).
- 12 : Average for norite sequence, Platreef, Drenthe (this study).
- 13 : Average for whole of Platreef, Drenthe (this study).

3. COMPARISON OF THE MAIN SILICATE MINERAL COMPOSITIONS

A comparison of the compositions of orthopyroxene (Table 6 and Fig.37) from the two reefs reveals that the orthopyroxene of the Merensky Reef is more magnesian. The compositions of orthopyroxenes from Atok Platinum Mine in the eastern Bushveld and from the Platreef on Tweefontein 238 KR correspond quite closely. The Tweefontein orthopyroxenes are slightly more Mg-rich (En_{77}) than those from Drenthe (En_{75}). The plagioclase compositions (Table 6) generally correspond closely, but it should be borne in mind that the Merensky Reef plagioclases are usually intercumulus and therefore usually more sodic than their cumulus counterparts. Thus it would seem that the minerals of the Merensky Reef are slightly more basic in composition than those of the Platreef on Drenthe.

4. COMPARISON OF THE MAIN ORE MINERALS

Vermaak and Hendricks (1976) give the average relative modal percent of the base metal sulphides for the Merensky Reef as pyrrhotite 44 percent, pentlandite 34 percent, chalcopyrite and cubanite 17,5 percent, and pyrite 4,5 percent. At Atok Platinum Mine, Schwellnus et al. (1976) derived the following from flotation concentrates: pyrite 45 percent, chalcopyrite 30 percent, pentlandite 13 percent, pyrrhotite 8 percent, and violarite, probably from the oxidized zone, 4 percent. Comparison of the above values with the Platreef sulphides (given in Fig. 25) shows a greater correspondence between the lower sulphide assemblage of the Platreef and the sulphides of the Merensky Reef at Atok than elsewhere in the Complex. In addition, both the Atok and Drenthe assemblages appear to be depleted in pentlandite relative to those of other areas of the Merensky Reef.

Although the thickness and nature of the Platreef is completely different from the Merensky Reef, the mineral compositions seem to indicate some similarity with the Merensky Reef of the eastern Bushveld. The Platreef on Drenthe however, is slightly less basic than the Platreef to the south of Drenthe or the Merensky Reef in general.

TABLE 6: COMPARISON OF THE COMPOSITION OF SOME OF THE SILICATES OF THE MERENSKY REEF AND THE PLATREEF

LOCALITY	ORTHOPIROXENE	PLAGIOCLASE	OLIVINE	PLATREEF OR MERENSKY REEF	PART OF COMPLEX
	Mol % En	Mol % An	Mol % Fo		
1. DER BROCHEN 7 JT	79,5	73 - 86	-	MERENSKY REEF	EASTERN
2. BUTTNSHOPE 51 JT	77,0	-	-	"	"
3. ATOK PLATINUM MINE	78	-	75,7	"	"
4. ZWARTKLIP 405 KQ	81,0	78	-	"	WESTERN
5. RUSTENBURG DIST.	85,0	81 - 84	-	"	"
6. RUSTENBURG DIST.	80,5	-	-	"	"
7. IMPALA PLATINUM MINE	80,5	-	80	"	"
8. ZWARTFONTEIN 814 LR	77,5-81,5	74 - 81	-	PLATREEF	POTGIETERS RUS
9. TWEEFONTEIN 238 KR	77	71 - 80	-	"	"
10. DRENTHE 778 LR	75	71 - 76,5	-	"	"

- 1 & 2 : Roux (1968)
 3 & 9 : Buchanan et al. (1981)
 4 : Van Zyl (1960)
 5 : Schmidt (1952)
 6 : Markgraaf (1976)
 7 : Own work, internally for Impala Platinum
 8 : Van der Merwe (1978)
 10 : This study

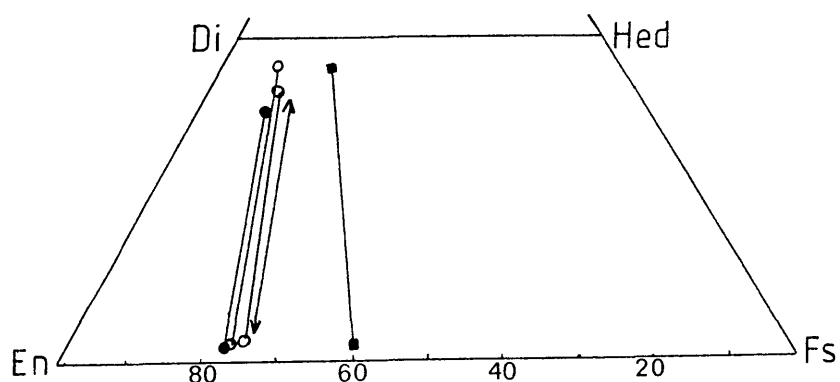


Fig 37. Microprobe analyses of associated pyroxenes from Drenthe, Tweefontein and Atok plotted on the pyroxene ternary.

- Tweefontein (Buchanan et al., 1981)
- Atok (Buchanan et al., 1981)
- △ 3/23 Platreef, Drenthe.
- 3/2 Above Platreef, Drenthe.

VIII PETROGENESIS OF THE PLATREEF

1. THE PARENTAL MAGMA OF THE PLATREEF

Various workers have used the compositions of the very fine-grained rocks on the margins of layered complexes to derive at the composition of the parental magma of such intrusions. In the case of the Bushveld Complex this approach has been complicated by many factors, one being that some evidence indicates that the Bushveld Complex crystallized from more than one magma, or that more than one magma pulse occurred during the intrusion (Von Gruenewaldt, 1973). Investigations in the eastern Bushveld Complex by Sharpe (1981) have led to the demarcation of four main magma influxes which in chronological order give rise to a laminated marginal zone and sills intruded into the floor rock of the Complex; a peridotite which was parental to the lower zone magma; a basalt which gave rise to the critical zone and a fourth influx from which the main and upper zones crystallized. The critical zone intruded in two phases, an earlier phase represented by a quench norite followed by a second phase, which is represented by a two pyroxene norite with abundant magnetite.

The composition of a very fine-grained rock from close to the footwall of the Platreef is given in Table 7. The very fine-grained nature of this rock and the radiating texture which is seen in thin section indicates that this is probably a "chill" of the Platreef.

Also shown in Table 7 are the composition of a similar rock from the farm Dorstland 768 LR situated to the north of Drenthe, and the bulk composition of the main body of the Potgietersrus limb as calculated by Van der Merwe (1978). The average compositions of the rocks which are considered by Sharpe (1978) to represent the parental magma of the two phases of intrusion of the critical zone and of the initial magma from which the main and upper zones crystallized are also given. Inspection of Figure 38 shows that the "chill" from this study plots between B3 and N, slightly closer to B3. The magma from which the Platreef crystallized was thus tholeiitic in character and the composition and mineral assemblages in the Platreef point to a similar magma that gave rise to the main and upper zones of the eastern Bushveld.

TABLE 7. COMPOSITIONS OF TWO PLATREEF "CHILLS", THE BULK COMPOSITION OF THE MAIN BODY OF THE POTGIETERSRUS LIMB AS COMPUTED BY VAN DER MERWE (1978) AND THE AVERAGE COMPOSITIONS OF THE ROCKS CONSIDERED BY SHARPE (1981) TO REPRESENT THE COMPOSITIONS OF THE ORIGINAL MAGMA OF THE CRITICAL AND MAIN AND UPPER ZONES.

SAMPLE NO	5/1	140	C	N	B2	B3
SiO ₂	52,73	55,32	49,93	50,81	48,50	50,70
TiO ₂	0,58	0,34	0,83	0,68	0,75	0,41
Al ₂ O ₃	13,90	11,90	17,50	15,97	16,49	16,03
Fe ₂ O ₃	0,30	1,08	2,19			
FeO	9,98	9,02	7,26	10,91*	12,41*	9,14*
MnO	0,20	0,18	0,16	0,19	0,19	0,17
MgO	8,16	11,30	7,76	7,86	7,57	9,21
CaO	11,77	8,01	10,96	10,78	11,15	11,14
Na ₂ O	2,96	2,91	2,09	2,17	2,17	2,52
K ₂ O	0,18	0,36	0,28	0,29	0,14	0,23
P ₂ O ₅	n.d	n.d.	n.d.	0,15	0,18	0,08
TOTAL	<u>100,76</u>	<u>100,42</u>	<u>98,96</u>	<u>99,81</u>	<u>99,55</u>	<u>99,63</u>

*where total iron is expressed as FeO

5/1 "Chill" from Platreef, Drenthe, this study.

140 "Chill" from Platreef, Dorstland 768 LR (Van der Merwe, 1978).

C Calculated bulk composition of the main body of the Potgietersrus limb.

N Average of rocks representing first phase of critical zone intrusion.

B2 Average of rocks representing second phase of critical zone intrusion.

B3 Average of rocks representing magma from which the main and upper zones crystallized (N, B2 and B3 from Sharpe, 1981).

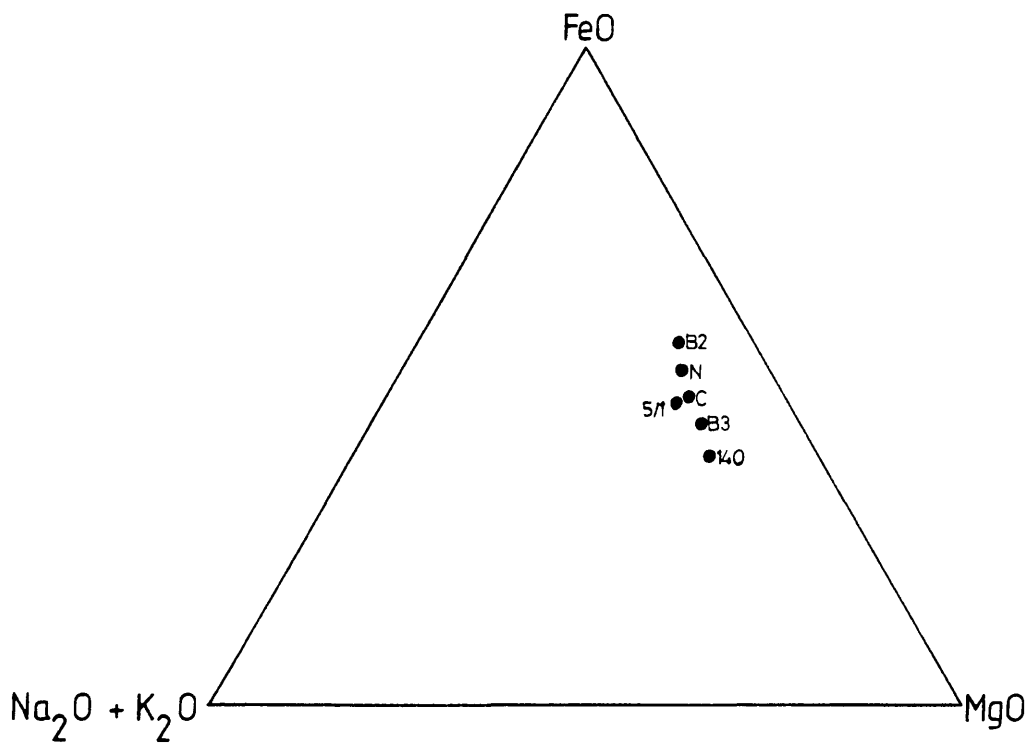


Fig. 38. Plots of the compositions given in Table 7.

Van der Merwe (1978) postulated that a new pulse of magma occurred 300 metres above the Platreef. Assuming that this new influx of magma took place south of Drenthe at the postulated feeder, a transgressive relationship similar to the upper zone and possibly the main zone, referred to earlier, may have brought this new pulse stratigraphically closer to the Platreef on Drenthe. This might explain the drastic change in the composition of the orthopyroxene just above the Platreef in this area. The postulated magma composition (Table 7, 5/1) can therefore only be considered as a possible parental to the Platreef on Drenthe.

2. THE CRYSTALLIZATION HISTORY OF THE PLATREEF

The crystallization of the Platreef is characterized by several stages. In the initial stages orthopyroxene crystallized as a cumulus phase. As equilibrium conditions did not exist during the initial stages of the intrusion, a reverse trend in the composition of the orthopyroxene resulted. After the crystallization of the lower feldspathic pyroxenite, plagioclase started to crystallize as a cumulus phase together with orthopyroxene. These two minerals crystallized together until clinopyroxene began to crystallize as a cumulus phase for a short period. Following this stage, in which 20 metres of Platreef crystallized, orthopyroxene and plagioclase were again the only two cumulus phases and near the top of the Platreef orthopyroxene became the only cumulus phase.

During crystallization of the Platreef dolomite xenoliths from the Transvaal Sequence were metamorphosed, at estimated equilibrium temperatures in the order of 950°C at between 3 and 4 Kbar.

3. ORIGIN OF THE BASE METAL SULPHIDES

It is generally accepted that base metal sulphides are formed by the separation of an immiscible sulphide liquid from a silicate melt. Haughton et al. (1974) experimentally studied the conditions which govern the solubility of sulphur in a mafic magma and derived the following conclusions.

(i) The bulk composition of the magma, especially the FeO content, exerts an important control on the sulphur solubility, so that an increase in the FeO content increases the solubility of sulphur. The authors found, however, that an increase in the SiO₂ and alkaline content decreases the capacity of the magma to carry dissolved sulphur.

(ii) The lowering of temperature decreases the solubility of sulphur.

(iii) An increase in the sulphur fugacity (f_{s_2}) results in the formation of sulphides.

(iv) Changes in oxygen fugacity (f_{o_2}) also influence the solubility of sulphur. An increase in the f_{o_2} decreases the sulphur-carrying capacity of the magma as this has the effect of oxidising Fe^{2+} to Fe^{3+} , thereby reducing the amount of FeO in the magma.

Buchanan and Nolan (1979) confirmed that increased f_{o_2} would lower the saturation level of the magma, although these authors showed that at high f_{o_2} conditions a high f_{s_2} would be required to saturate the magma with sulphur. Conversely, they demonstrated that the lower the f_{o_2} , the lower is the f_{s_2} required for sulphur saturation to be achieved.

Buchanan and Nolan (1979) considered the absence of widespread disseminated sulphide mineralization in the lower part of the Bushveld Complex to be indicative of a magma undersaturated with sulphur. In sulphide-enriched areas, such as the Platreef however, they considered the sulphur to be derived from an external source e.g. sulphur-rich sediments. Liebenberg (1968) and Buchanan et al. (1981) have concluded from isotope studies that some of the sulphur in the Bushveld Complex was derived from sediments. Buchanan et al. (1981) have postulated that evaporites in the Transvaal Sequence were the source of the sulphur in the Platreef to the south of Drenthe.

Based on the work of Haughton et al. (1974), De Waal (1977) reasoned that the localized areas of above average sulphide enrichment which occur in the Bushveld Complex (notably the Potgietersrus area, the Bethal area and the Vlakfontein pipes) may be due to one or more of the following conditions:-

- (i) localized high f_{s_2} in the magma,
- (ii) localized initial² low FeO content of the magma,
- (iii) localized sulphurization of the magma due to the degassing of sulphur rich sediments,
- (iv) the lowering of temperature,
- (v) local increases in f_{o_2} due to surface exposure or because of reaction with carbonate-rich sediments.

According to De Waal (1977), the incorporation in the magma of CO_2 and H_2O that is released from carbonate-rich sediments (e.g. dolomite) during metamorphism, would raise the f_{O_2} and cause sulphide to precipitate. Increased f_{O_2} may also result in the formation of spinel, notably chromite and magnetite, depending on the composition of the magma. De Waal (1977) considered that precipitation of the sulphide and spinel could commence directly when the CO_2 and H_2O entered the magma provided that the magma is saturated with respect of these minerals. If saturation is not achieved, gradual enrichment of the CO_2 and H_2O would take place in the residual liquid of the crystallizing magma until saturation is eventually achieved. Precipitation of sulphide or spinel on a more regional scale could then result.

The formation of the disseminated sulphides in the igneous rocks in the lower part of the Platreef on Drenthe is considered to be due to the lowering of the magma temperature as a result of the proximity of the floor rocks. This would necessarily imply that the magma was close to being saturated with sulphur. It is further suggested that the magma progressively became depleted in sulphur as more and more sulphide liquid separated from the crystallizing magma. At the same time the sulphur content of the sulphide liquid became depleted with respect to the metals. This is seen in the change of composition of pyrrhotite with increasing height in the Platreef.

The extensive sulphide mineralization associated with the "serpentinite" zone is considered to have been formed as a result of the reaction of the carbonate-rich sediments with the magma. The "serpentinite" zone is seen to have formed from a relatively SiO_2 -free dolomite and it is considered, as postulated by De Waal (1977), that H_2O and CO_2 released by the dolomite raised the f_{O_2} , thus causing saturation of the melt with sulphur.

Sulphur may also have been derived from the sediments. It is considered that much of the sulphur precipitated in the Platreef on Drenthe was present in the magma at the time of emplacement at Drenthe, firstly, because the country rocks in the Drenthe area are sulphur-poor basement granites and secondly, because some of the sulphur could have been derived from sulphur-rich sediments to the south of Drenthe, which have migrated northwards to the Drenthe area together with the magma.

IX SUMMARY AND CONCLUSIONS

The Platreef on Drenthe has been shown to consist of:-

- (a) a lower, 50 metre feldspathic pyroxenite layer consisting of cumulus orthopyroxene and intercumulus plagioclase and clinopyroxene,
- (b) a sequence of 170 metre of norites overlying the pyroxenitic layer
- (c) an upper 30 metre thick feldspathic pyroxenite in which only orthopyroxene is cumulus.

A strong reverse trend in the orthopyroxene composition, from En₆₀ to En₇₀ is present near the base of the Platreef. This may be due to dis-equilibrium conditions in the magma (Jackson, 1970).

At the top of the Platreef the composition of the orthopyroxene changes from En₇₅ to En₆₀, concomitant with the entry of inverted pigeonite. This change in composition may be due to a new influx of more Fe-rich magma, but with such a composition that it did not noticeably affect the An-content of the plagioclase.

The numerous metasedimentary inclusions in the Platreef contain amongst others the metamorphic minerals monticellite, forsterite and diopside. From this it was calculated that temperatures of above 900°C existed in the xenoliths during metamorphism.

It is considered that a relatively pure, silica-free dolomite dissociated to form a large zone of retrogressive alteration. Important sulphide mineralization is associated with this zone and it is considered that the addition of CO₂ resulting from the dissociation of the dolomite locally decreased the sulphur-carrying capacity of the magma and resulted in the separation of an immiscible sulphide melt.

Where sulphides are not associated with such zones of alteration, an immiscible sulphide melt probably formed as a result of a lowering in temperature due to the proximity of the country rocks. It is also considered that the sulphur was already present in the magma during emplacement at Drenthe, and that the sulphur may have been derived from sulphur-rich sediments further to the south, close to Potgietersrus, where the feeder of the intrusion is considered to be located.

In the lowermost 150 metres of the Platreef, pyrite is an important sulphide mineral but it is absent further upwards. This, and the variation in the composition of the pyrrhotite, which becomes sulphur-poor towards the top of the Platreef, led to the conclusion that the immiscible sulphide liquid was gradually depleted in sulphur with increasing height in the Platreef.

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* See p.81.

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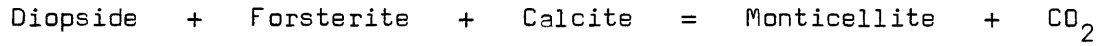
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APPENDIX 1 CALCULATION OF THE EQUILIBRIUM TEMPERATURE OF THE MONTICELLITE FORMING REACTION FROM THE EXPERIMENTAL DATA OF WALTER (1963)

A. The reaction is:



$$\text{Constraint: Total pressure (P)} = P_{\text{CO}_2}$$

B. $f_{\text{CO}_2} = P \cdot \gamma$ (γ after Mel'nik, 1972, in Wood and Frazer, 1978).

C. Data from Walter (1963) (i) products stable at 521,7b and 903°C, 1176K
(ii) products stable at 695,6b and 910°C, 1183K

D. Calculations of ΔH and ΔS

$$\begin{aligned} \Delta H - T\Delta S &= -RT \ln f_{\text{CO}_2} - (P-1)\Delta V \\ \text{Substitute (i) and (ii)} & \\ \Delta H - 1176\Delta S &= 1,987 (1176) 6,44 - 520(-0,7182) \dots\dots(1) \\ \Delta H - 1183\Delta S &= 1,987 (1183) 6,77 - 694(-0,7182) \dots\dots(2) \\ \Delta S &= 105,2 \\ \Delta H &= 10904 \end{aligned}$$

E. Equilibrium temperature at 3 Kbar

$$\begin{aligned} \Delta H - T\Delta S &= -RT \ln f_{\text{CO}_2} - (P-1)\Delta V \\ 10904 - T 105,2 &= -1,987(T) 8,83 - 2999 (-0,7182) \\ &= 1218K \\ &= 945^\circ\text{C} \end{aligned}$$