PEGMATITIC BODIES IN MAFIC ROCKS OF THE BUSHVELD COMPLEX, BAFOKENG LEASEHOLD AREA, WESTERN TRANSVAAL

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DECLARATION

I, Jorge Patricio JONES, do hereby declare that this dissertation is my own unaided work and no part of it has been submitted to any university for degree purposes. The information embodied in this dissertation was obtained from Impala Platinum Mines during my employment with Union Corporation Ltd.

J.P. JONES

ABSTRACT

Rocks of pegmatitic grain size were studied in the Bafokeng Leasehold area, Western Transvaal. These include pegmatoid nodules of pyroxenitic and noritic composition, late pegmatoids of ultramafic composition and salic pegmatites of tonalitic and granitic composition. Twenty nine new chemical analyses are presented. The mineralogy, mode of emplacement and formation of the different pegmatoids and pegmatites are considered. Pegmatoid nodules have similar mineralogy and chemistry with the overlying Merensky 'Reef' and the underlying pegmatoid pyroxenite which is found associated with the UG 2 chromitite layer. The nodules would explain the absence of a Pseudo 'Reef' at the Bafokeng Mine. On account of this and their mineralogy and shape, the nodules are considered to have formed during the breaking-up of a pyroxenite layer produced by movements within the magma chamber. The presence of depressions associated with the Merensky 'Reef' together with disordered layers in the Critical Zone is taken as further evidence of magma movements.

Late ultramafic pegmatoids show total iron contents up to 38 weight per cent. The high iron content is reflected in the compositions of silicate and oxide minerals found in the Late ultramafic pegmatoids. At the Merensky 'Reef' elevation two generations of sulphides were found within the Late ultramafic pegmatoids. One is replaced by magnetite and the second generation is found filling cracks in the magnetite. Relative to the layered rocks Late ultramafic pegmatoids show enrichment in Fe, Ti and depletion in alkalis. Relics of layered rocks in the form of partially resorbed orthopyroxenes, are found within Late ultramafic pegmatoids. In these instances a minor reaction relationship between layered rocks and Late ultramafic pegmatoids is indicated.

Sometimes olivine is introduced to the layered rock when in juxtaposition with the Late ultramafic pegmatoids. These olivines are usually rich in Mg (Fo 71 - 85) whereas olivine within the ultramafic pegmatoid are generally Fe-rich varying between Fo 38 - 57. Fine grained phases of the Late ultramafic pegmatoid develop in joints and along contacts with layered rock, olivine within fine-grained phases have Fo contents between 56 - 73.

The mode of emplacement of the Late ultramafic pegmatoids, along joints and parallel to layering suggest that pressure was an important factor in their genesis. The origin of Late ultramafic pegmatoids is discussed emphasizing the importance of the origin of the iron, several possibilities are presented, and it is considered that an interstratified magma origin is likely to be the origin of Late ultramafic pegmatoids. Water and iron-rich undersaturated fluids in equilibrium with this magma could account for several features observed.

Tonalitic pegmatites show a preference to occur in pyroxenite layers. Since pyroxenite layers are in many instances mesocumulates, and since tonalitic pegmatites are often more abundant within depressions in the Merensky 'Reef' than elsewhere, a segregational origin is tentatively suggested for tonalitic pegmatites.

Granitic pegmatites which very often transgress Late ultramafic pegmatoids remain to be more thoroughly studied.

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I - INTRODUCTION

The Bafokeng Leasehold area is situated in the western portion of the Bushveld basin 10 km NNW of the town of Rustenburg in the Western Transvaal (Fig. 1). At the commencement of this work, the Bafokeng Mine occupied the whole of the lease area which on account of its mining extension was subsequently divided into three different mines: Bafokeng North, Bafokeng South and Wildebeestfontein. As this work was nearly completed when the subdivision took place, this partition is not considered, and the whole of the lease area is referred to as the Bafokeng Mine (Fig. 1).

Rocks of the Bushveld Complex underlie the entire terrain held by the mine producing a flat topography, which is interrupted by hortonolite dunite and magnetite pipes which form 20 to 30m high hills. Outside this area, towards the northeast, rocks of gabbroic composition form the pyramid hills. To the southwest the Magaliesberg Quartzites dip to the north and form the floor rocks to the intrusion. To the north, the nearly circular Pilanesberg alkaline Complex cuts through the Bushveld Complex forming a prominent mountain rising approximately 400m above the surrounding plain.

The vegetation on the Bafokeng Mine property consists mainly of grass lands. Thorn bush is generally sparse but dense growth does, in places, prevent crop farming. The drainage pattern is dominated by the Magatasspruit which flows to the north, and is a non-perennial direct tributary of the Elands River. Black soil which is composed of clays produced by the weathering of mafic Bushveld rocks covers most of the area. Red sandy soil derived from the Magaliesberg Quartzite is present in the vicinity of the Magatasspruit. The slow rate of percolation makes the black soil a sticky clay in the rainy season.

At the Bafokeng Mine the Merensky 'Reef' is mined for its Platinum Group Metals content. The composite layered Merensky 'Reef' occurs within the Bushveld Complex and has an average dip of ten degrees in a northeasterly direction, and suboutcrops under approximately 3m of black soil for a strike length of 12,5 km (Fig. 10).

The main subject of this thesis is a petrochemical study of the Late ultramafic pegmatoids, their mode of emplacement and genesis; however other pegmatoids and salic pegmatites were also studied.

The use of the term pegmatoid has been governed by the following considerations. Pegmatoid, in contrast to pegmatite, has been defined by Rice (1963, p.298) as "a term suggested to denote very coarse-grained facies of igneous rocks having a pegmatite-habit, but differing from pegmatite proper by the absence of graphic texture". According to Rice (ibid. p.297) pegmatite is a term "applied to graphic-granite, and extended to coarse-grained modifications of granite characterized by irregular segregation of particular minerals rather than by interpenetration". However, the term pegmatite has also been applied to other igneous rocks whose names are used as a prefix, e.g. gabbroic pegmatites (Thayer, 1967, p.238), hornblende-plagioclase pegmatites (Irvine, 1967, p.92). Cameron and Desborough (1964, p. 197) applied the term pegmatite to rocks of dunitic and pyroxenitic composition. The author is of the opinion that the terms pegmatoid and pegmatite are best defined according to the terminology given by Rice (op. cit.)

At the Bafokeng Mine the layered rocks show the development of several pegmatoid layers, pegmatoid nodules and lenses. Pyroxenitic and noritic nodules are contained in an anorthosite layer which has been named the 'anorthosite containing nodules' and henceforth will be abbreviated to a.c.n. Sometimes the advanced state of alteration of the nodules, made the determination of mineral compositions by optical methods difficult. Pegmatoid pyroxenite lenses, were only briefly studied, mainly because of their sparse occurrence. In addition to these pegmatoids, Late ultramafic pegmatoids are abundant on the Bafokeng Leasehold area, and show conformable but mainly transgressive relationships to the layered rocks. The main problem to be resolved was to compare and contrast the chemistry and mineralogy of the Late ultramafic pegmatoids with that of the layered rocks. At times the limits of error of the determinative methods made it difficult to establish real and apparent differences. In these cases more than one determinative method was used. Mapping of the Late ultramafic pegmatoids was limited to those which outcrops in the Bafokeng Lease area. A compilation of data from the geological sheet No. 4 (Von Backström et al., 1960) and internal reports (Union Corporation Limited) together with the relevant work from both sources is presented in Fig. 10.

Previous work on the Late ultramafic pegmatoids in the Rustenburg area was done by Wagner (1973) and Coertze (1969) among other authors. Coertze (ibid. p.15) stresses the association of magnetite with hortonolite dunite and diallage pegmatite in composite pipe-like bodies, and remarks that although they may occur in any rock unit, most of them are found in the ferrogabbro (Fig. 1). This is especially true north of the Pilanesberg alkaline Complex where approximately thirty occurrences are found within the ferrogabbro of the Upper Zone. This relationship is however not evident southeast of the Pilanesberg, where only two pipes outcrop in the ferrogabbro and almost forty occur between the Merensky 'Reef' and the lower magnetite layer, that is to say in the Main Zone. Cameron and Desborough (1964) have studied Late ultramafic pegmatoids in the Critical Zone of the Eastern Transvaal, and proposed a metasomatic re-arrangement of material within the Bushveld rocks to explain their origin. Ferguson and McCarthy (1969) describe a forcefully emplaced ultramafic pipe, which emphasises the different modes of occurrence of the Late ultramafic pegmatoids.

The pegmatites found at the Bafokeng Leasehold area have a salic nature being of tonalitic and granitic composition. Tonali ic pegmatites are contained mainly in pyroxenitic layers, and occur as veinlets rarely transgressing individual layers. Granit c pegmatites which transgress both the layered rocks and Late ultramafic pegmatoids, were difficult to study mainly due to the sparseness of outcrop and underground exposures. The coarsely crystalline nature of all the rocks studied caused difficulty in obtaining representative specimens; this problem was partially resolved by cutting numerous sections. Most of the work done during 1971-1972, while the author was a member of the geological staff of Bafokeng Mine. After sampling and mapping were completed, laboratory work was undertaken during the latter part of 1972 and early 1973, at the University of the Witwatersrand.

II - THE LAYERED ROCKS

The Plutonic Phase of the Bushveld Complex comprises rocks which are markedly layered and late pegmatoids and pegmatites. The grouping of the rocks representing the Plutonic Phase has been taken from a preliminary report of the South African Committee for Stratigraphy*. From the base upwards the layered rocks have been divided into Marginal, Basal, Critical, Main and Upper Zones. The whole succession of rhythmically and cryptically layered rocks form the Plutonic Phase (Fig. 2), portions of it are referred to, throughout this thesis, as the layered rocks. A cumulate terminology is used throughout the paper (Wager and Brown, 1968).

To introduce the unacquainted reader to the Layered Rocks of the Plutonic Phase of the Bushveld Complex, figure 2, was modified from Wager and Brown (1968, p.351). Wager and Brown (op.cit.) state that this data is "based on traverses chiefly in the eastern part" of the Bushveld Complex. In figure 2, cumulus mineral compositions are indicated in full lines. Broken lines indicate the compositions of the intercumulus minerals. The first appearance of a cumulus phase is also indicated (e.g. Pig+). The olivine composition in parenthesis refers to its occurrence in the Western Bushveld.

The portion of the layered rocks suboutcropping in the Bafokeng Mine extends from a distance which varies between 0 to 100m below the Merensky 'Reef', to approximately 900m (true thickness) vertically above it (Fig. 3). However, drilling has facilitated exploration to approximately 650m vertically below the Merensky 'Reef'. The layering dips at 10° to the north.

According to the South African Committee for Stratigraphy (Working Group Bushveld Igneous Complex) the first appearance of chromitite layers associated with pyroxenite marks the base of the Critical Zone and the Merensky 'Reef' forms the base of the overlying Main Zone. In the Western Transvaal the main chromitite layers which occur in the Critical Zone have been subdivided into three groups by Cousins and Feringa (1964, pp. 183-202). The upper group (UG) comprises

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*The South African Committee for Stratigraphy. Interim report by the Working Group of the "Bushveld Igneous Complex".

FIG. 1. The mafic portion of the Bushveld Complex in the Western Transvaal (modified after Coertze, 1969).

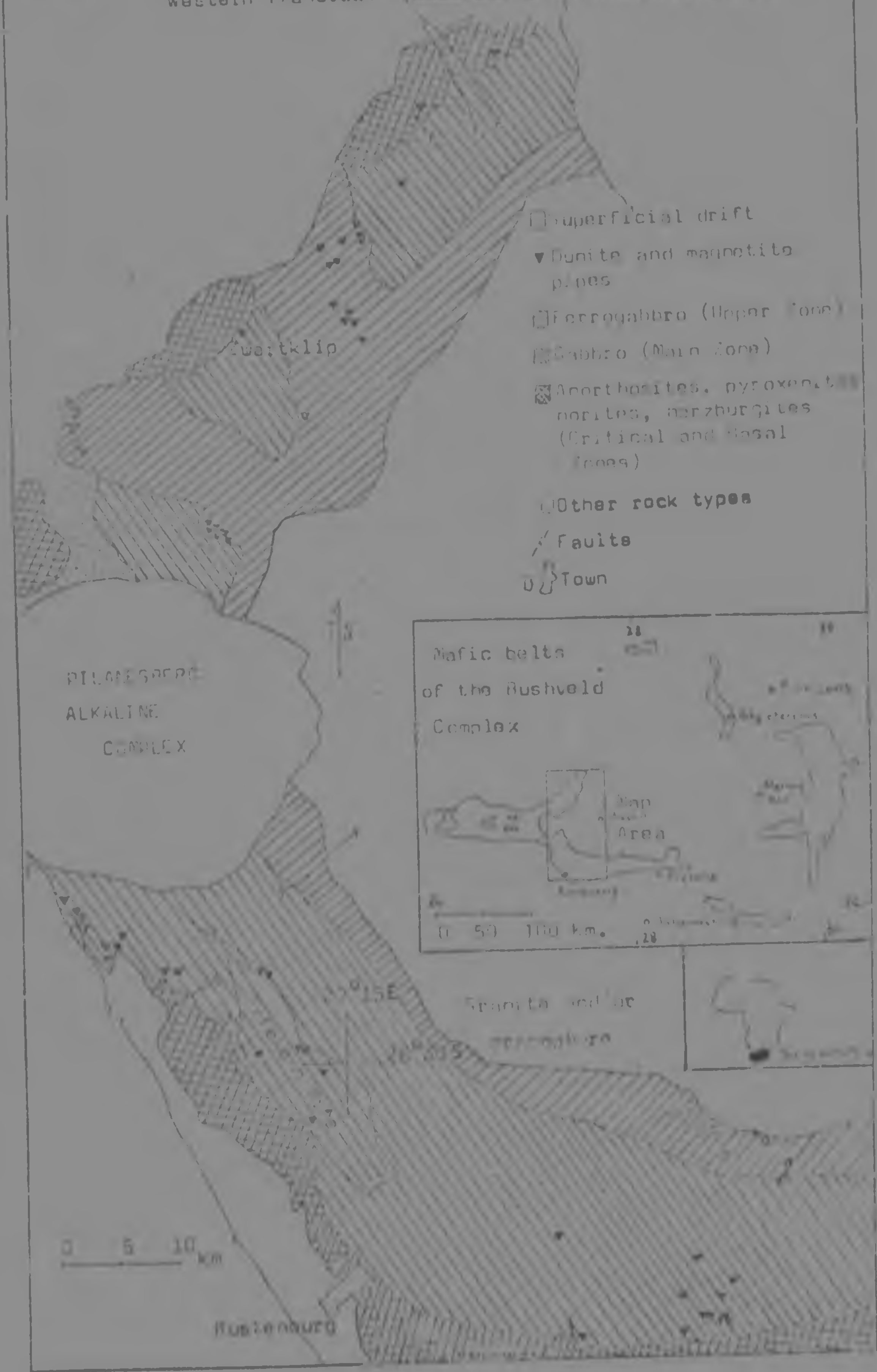


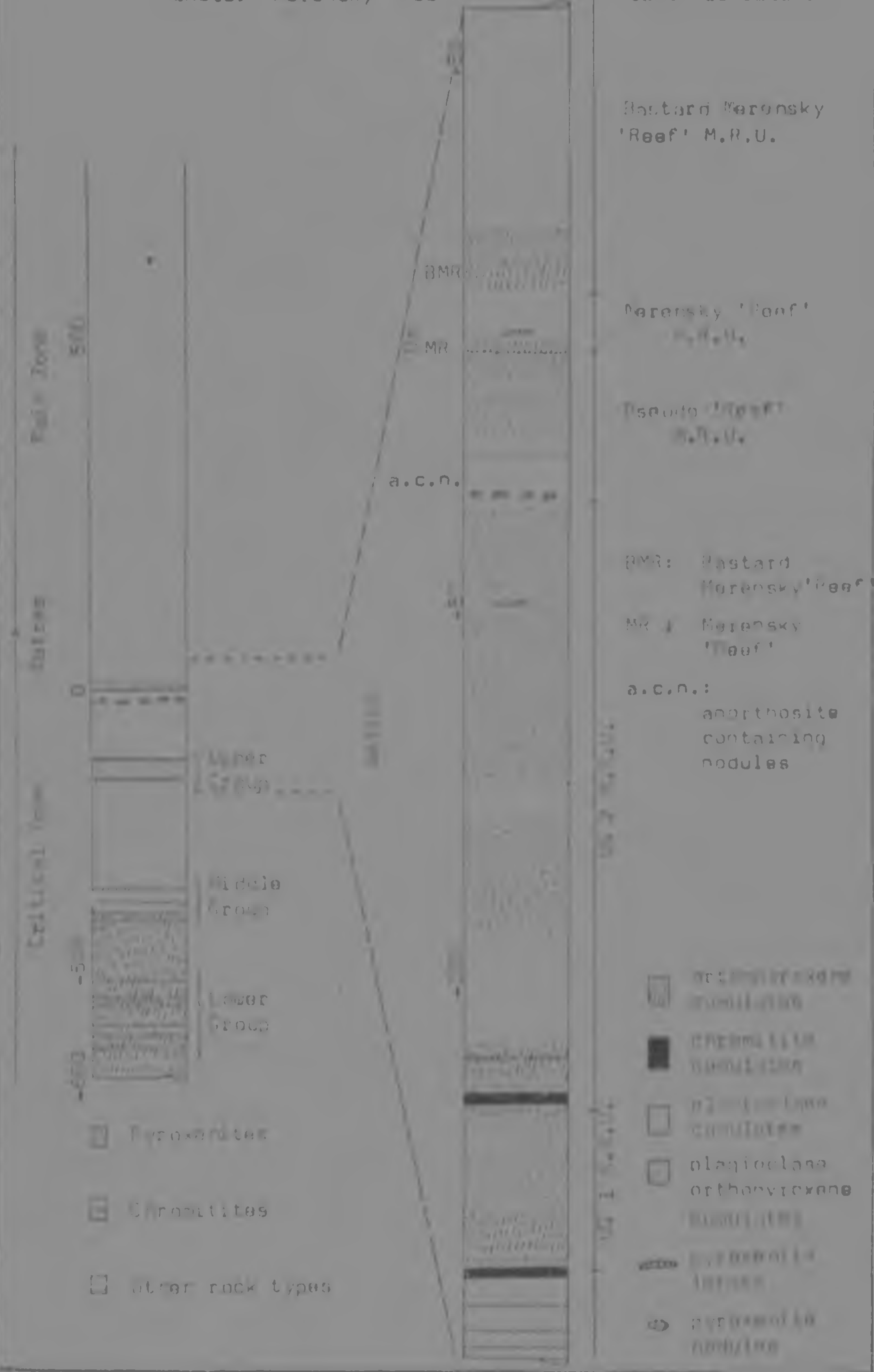
FIG. 2. The cryptic layering in the Plutonic phase of the Bushveld Complex (modified after Wager and Brown, 1968).

two chromitite layers, the UG 1 and overlying UG 2, figure 3, which at Bafokeng occur from 100 to 150m below the Merensky 'Reef'. The middle group (MG) comprises four chromitite layers and the lower group (LG) seven chromitite layers; which are found between 320-380m and 420-520m, respectively, below the Merensky 'Reef'. At Bafokeng the section most readily available for study is that which comprises the top 100m of the Critical Zone and the bottom 50m of the Main Zone. Over this 150m interval five cumulus phases are present: plagioclase, orthopyroxene, chromite and sporadically olivine and clinopyroxene. The rock types produced by accumulation in this interval have been described by Wager and Brown (1968, p.368) who reinterpret the data presented by Feringa (1959). Feringa grouped the rock types into eight subzones; Wager and Brown (op.cit.) on the basis of repeated cumulus cycles, named each of these repetitions a macrorhythmic unit (M.R.U.). Each M.R.U. is, in fact, comprised of a lower part formed by cumulus chromite and orthopyroxene with plagioclase, clinopyroxene, and less commonly olivine. A gradation in which plagioclase increases mainly at the expense of orthopyroxene results in anorthositic rocks towards the upper part of each M.R.U.

At Bafokeng the UG 1 chromitite layer is overlain by orthopyroxene, and plagioclase orthopyroxene cumulates. This sequence of cumulates forms the UG 1 M.R.U. (Fig. 3). The uppermost chromitite layer, together with the pegmatoid pyroxenite which in pla[illegible]nderlies it, forms the base of the UG 2 M.R.U., and grades u[illegible]rthopyroxene, and plagioclase cumulates, before giving way to [illegible]e in which plagioclase orthopyroxene cumulates are predomi[illegible] This sequence generally extends to approximately 25 to 30m below the Merensky 'Reef'.

Above this sequence Wager and Brown (op.cit.) have defined the Pseudo 'Reef' M.R.U. The Pseudo 'Reef', which has been described by Feringa (op.cit., p.222) is a pyroxenitic sometimes pegmatoid layer which forms the base of the Pseudo 'Reef' M.R.U. According to Van Zyl (1969) on the farm "Swartklip 988" Rustenburg District, the Pseudo 'Reef' is 3m thick. At Bafokeng, pegmatoid pyroxenite nodules contained in an anorthositic layer (a.c.n.) form the base of the Pseudo 'Reef' M.R.U. The sequence between the nodules and the Merensky 'Reef' is composed of layers which have plagioclase as the main cumulus phase, although occasionally orthopyroxene is the predominant cumulus material. Between the Merensky 'Reef' and the pyroxenite nodules several complexities were observed in the layering. Layers

FIG. 3. Sections showing the layered rocks at the Bafokeng Leasehold area, and its subdivision into macrorhythmic units. Merensky 'Reef' taken as datum.



which grade upwards from pyroxenite to anorthosite, also grade laterally from pyroxenite to norite, and therefore contacts between underlying anorthosite cumulates and overlying noritic ones, are sometimes produced without a pyroxenitic cumulate being developed. A more marked example of the complexities and also of the short duration of the rhythmic episodes is seen in a 0,4 to 0,8m layer which underlies the Merensky 'Reef' throughout the mine. This layer shows a transition between orthopyroxene cumulate, in the lower portion, to plagioclase mesocumulate in the upper portion.

In the section between the Merensky 'Reef' M.R.U., and the uppermost chromitite layer of the UG 2 M.R.U., thinning of some layers takes place towards the northwest.

The Merensky 'Reef' M.R.U. is perhaps the best example of the gradation between cumulates which defines a M.R.U.; this gradation is produced by an increase upwards in the proportion of the cumulus plagioclase at the expense of cumulus orthopyroxene, until the latter, at the top of this M.R.U., occurs only as an intercumulus phase. The rock types produced are pyroxenitic at the bottom of this M.R.U. and anorthositic at the top. The Merensky 'Reef' is composed of various layers, the rock types are essentially orthopyroxene chromite and chromite cumulates, with minor amounts of plagioclase, clinopyroxene and olivine. Both plagioclase and clinopyroxene occasionally attain cumulus status within the Merensky 'Reef'. It must be stressed that the feldspar content varies both laterally and vertically, and in many instances the rock is described as feldspathic pyroxenite. Trace amounts of mica and tremolitic amphibole, are also found within the Merensky 'Reef'. The pyroxenitic portion of the Merensky 'Reef' varies in thickness between 0,7 and 3,0m may or may not develop into a pegmatoid layer. At Bafokeng both pyroxenitic or pegmatoid layers may form the basal portion of the Merensky 'Reef'. The thickness of the pegmatoid pyroxenite is very variable, usually being thicker within depressions. Cumulus chromite usually forms a 10mm thick chromitite layer within the Merensky 'Reef', but examples of three chromitite layers are reported from the Rustenburg Platinum Mine (Liebenberg 1969, Fig. 45, p.182). The chromitite layer can be found at the bottom of the Merensky 'Reef' separating the Merensky 'Reef' from its immediate anorthositic footwall or, if a pegmatoid layer has developed, it can be situated at variable distances above the contact between the pegmatoidal pyroxenite layer and its immediate anorthositic footwall. In addition to this, the chromitite layer found at the bottom of the Merensky 'Reef', may bifurcate and anastomose enclosing a pegmatoidal portion above which the pyroxenite is developed. When the chromitite layer is resting upon anorthositic or noritic footwall, a sharp and well defined contact exists. However, its outline sometimes shows irregularities or 'dimples', as they are termed by Cousins (1964, p.232). When the chromitite layer is resting against the pegmatoid layer of the Merensky 'Reef', scattered chromite crystals may sometimes form an 1 mm layer at the contact between the pegmatoid pyroxenite layer and its immediate anorthositic footwall. The mineralogy of the chromitite layer has previously been described by Schmidt (1952). It consists of euhedral chromite crystals, which are included in poikilitic plagioclase, diallage and orthopyroxene anhedra.

Above this M.R.U., the Bastard Merensky 'Reef' pyroxenite (B.M.R.) forms the base of the last M.R.U.; progressing upwards noritic and anorthositic cumulates complete the Bastard Merensky 'Reef' M.R.U. Above the B.M.R. M.R.U. there is a gradation to a sequence of cumulates in which the layering is poorly developed, but is nevertheless present. From about 70m to about 900m above the Merensky 'Reef' the predominant rock type is a gabbroic cumulate, which is occasionally interrupted by anorthositic cumulates.

A. Structures

The layered rocks between the top chromitite layer, the UG 2, and the B.M.R., has received special attention in connection with depressions, or 'pot-holes' as they have been called by Feringa and Cousins (1963). Ferguson and Botha (1963, p.268) have called them circular depressions. Henceforth these structures will be referred to as depressions, mainly because of their tendency to coalesce and change shape with depth so that they do not always warrant the adjective circular. According to Ferguson and Botha (op.cit.) depressions may vary between 1 and 26m in depth, and attain a maximum diameter of 600m. The layering of the rocks is truncated by the depressions but remains otherwise undisturbed. Within depressions the layering of the rocks roughly conforms the outline of the depression. Most observations concerning depressions were made in the vicinity of the Merensky 'Reef' resulting from the abundance of exposures opened up by mining operations, however depressions in the chromitite layers have been observed by Fourie (1959, pp.88-9), and Cousins and Feringa (1964, p.195), and depressions in the B.M.R. have been reported by Feringa and Cousins (1963, p.280). Structures other than depressions, affecting the Merensky 'Reef' and its immediate footwall were found in the 5 Shaft area, and are described in connection with a transgressing ultramafic pegmatoid. Transgressions of small (0,15m) mushroom shaped pods of anorthosite into overlying norite cumulates, and bigger (4 to 5m), transgressive anorthosite bodies were occasionally found.

B. Mineralogy

The object of the study of the different minerals in the layered rocks was to be able to compare their composition with similar minerals within Late ultramafic pegmatoids at the same elevation. The description of methods used in obtaining the compositions of the [illegible] minerals is given in Appendix I.

1. Plagioclases. Plagioclase samples from the layered rocks were mainly collected from anorthositic cumulates because they are the more abundant host rock for Late ultramafic pegmatoids.

The zoned nature of cumulus plagioclase, reported by Wager and Brown (1968) and Ferguson and Wright (1969), was confirmed. Reversed zoning was found approximately 20m below the Merensky 'Reef'. In the only measurement obtained, the plagioclase in the core analysed An 76, and the margin An 80.

According to Van Zyl (1969), plagioclase compositions show distinct changes in the An content upwards from the UG 1 chromitite to the B.M.R. These changes displace the plagioclase chemistry towards more calcic compositions. These changes were not studied in detail, but intercumulus plagioclase from the Merensky 'Reef' and cumulus plagioclase from its immediate mainly anorthositic footwall were analysed with the following results: An 67, and An 65 per cent respectively.

Intercumulus plagioclase within the Merensky 'Reef' was analysed by X-ray diffractometry in three different localities (Table 1).

Several analyses, made of plagioclase by X-ray diffractometry from rocks in the Main Zone showed a steady An enrichment from 72,3 per cent at a distance of 34m above the Merensky 'Reef', to a value of 75,8 per cent at a height of 690m above this marker. A similar pattern of enrichment was obtained from boreholes 680 and 681. This is in agreement with the data of Ferguson and Wright (1969, p.64), who showed an increase in An with differentiation for the plagioc... of the Western Bushveld immediately above the Merensky 'Reef'.

Table 1. Anorthite content of intercumulus plagioclase within the Merensky 'Reef'. X-ray diffractometry.

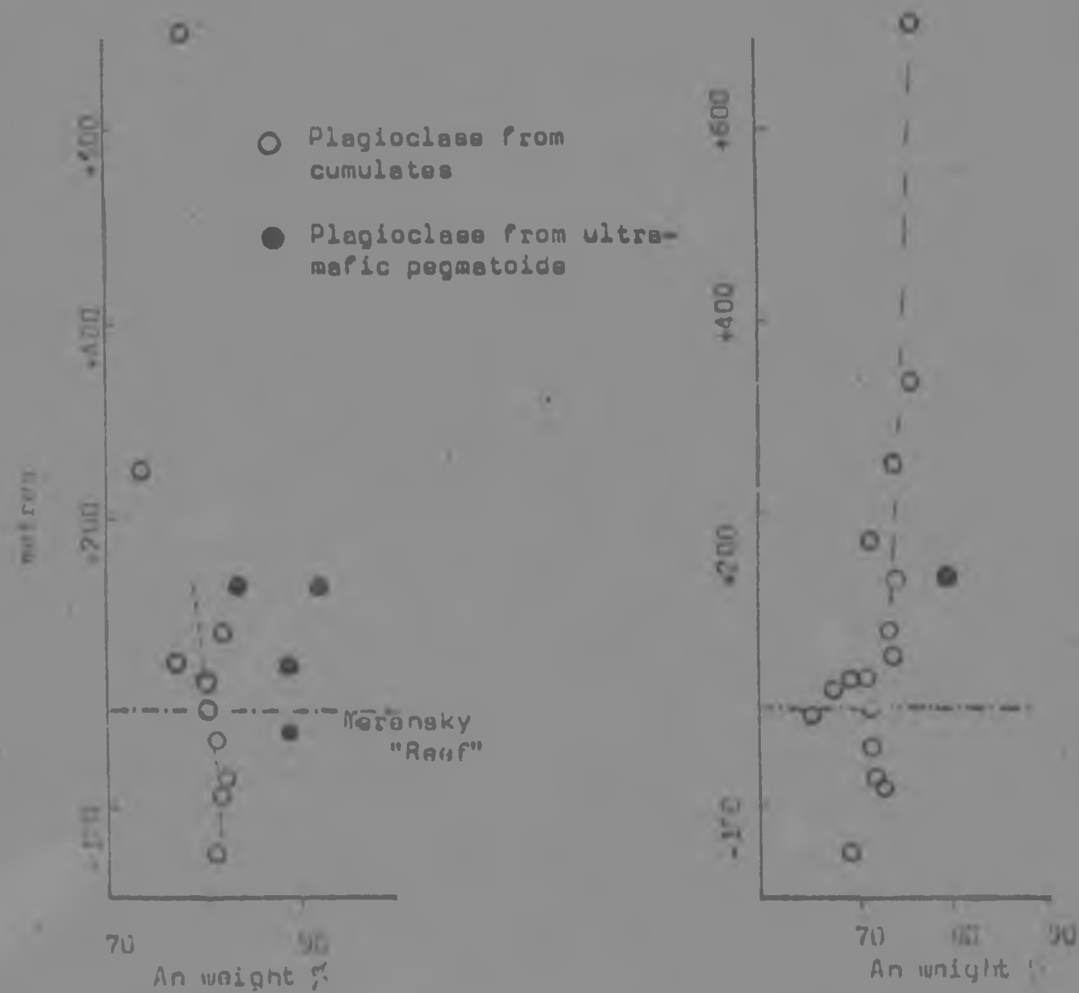
Locality	An content of intercumulus plagioclase	Rock type
287 Raise	67	Undisturbed Merensky 'Reef'
284A Raise	70	Merensky 'Reef' within a 3m deep depression
240 Raise	73	Merensky 'Reef' within a 4m deep depression

Ten samples analysed by X-ray diffractometry were checked by X-ray fluorescence. The vertical distance was from 180m below the Merensky 'Reef' to approximately 690m above it, plagioclase samples analysed by X-ray fluorescence showed An contents between 73 and 82 per cent respectively (Fig. 4). The differences obtained by both methods are discussed in Appendix I. Results obtained by X-ray fluorescence showed higher (9 per cent) An contents for the same samples than when analysed by X-ray diffractometry (Fig. 4).

2. Orthopyroxenes. Orthopyroxenes and plagioclase, are the commonest cumulus mineral found at the top of the Critical Zone and lower portion of the Main Zone. Clinopyroxene exsolves along cleavages and partings in orthopyroxene. In borehole 588, at a distance of 5m above the B.M.R., orthopyroxenes are intergrown with clinopyroxenes, additionally up to three sets of clinopyroxene exsolution lamellae occur in the orthopyroxene grain (Photo 1). One set of exsolution lamellae is orientated parallel to the (100) plane of the orthopyroxene, the other two sets are orientated parallel to 010.

Van Zyl (1969, p.96) records four chemical breaks which are reflected in the composition of orthopyroxenes at the top of the Critical Zone. "The first break is between the mottled anorthosite which lies directly below the chromitite band UC 1 and the porphyritic melanorite which lies directly above the chromitite band UG 1. The second break is between the pegmatitic reef and the mottled anorthosite below it, and the third break is between the Bastard Reef and its footwall of mottled anorthosite. A fourth break occurs between the pseudo-

FIG. 4. An content of plagioclases from the layered rocks and ultramafic pegmatoids as analysed by X-ray fluorescence and X-ray diffractometry.



X-ray fluorescence

X-ray diffractometry
Plagioclase composition from ultramafic pegmatoids was obtained only once (Appendix I).

reef and its hanging wall of norite and foot-wall of porphyritic melanorite". These zones were not studied in detail, but the break between the Merensky 'Reef' M.R.U. and its immediate footwall was confirmed.

Below the Merensky 'Reef' cumulus orthopyroxene was analysed in three noritic cumulates (Table 2), and it was found that the magnesium content decreases progessively from En 82 at 80m below the Merensky 'Reef' to En 76, 4m below the Merensky 'Reef'.

In a 0,4 to 0,8m thick layer which is found 3m below the Merensky

'Reef' throughout the mine, cumulus orthopyroxene decreases sharply from the bottom to the top. Cumulus orthopyroxene showed the following compositions: En 81 at the bottom of the layer, and En 77, 0,4m above. Intercumulus orthopyroxene at the top of the layer shows iron enrichment, the En content being 69 to 71.

Table 2. En content of Orthopyroxenes in the layered rocks.

Location		En ± 1
850m above the B.M.R.		67 c
B.M.R.		78 c
0,5m below the B.M.R.	Merensky 'Reef' M.R.U.	69 to 70 i
5,0m below the B.M.R.	Merensky 'Reef' M.R.U.	75 c
Merensky 'Reef' pyroxenite	Merensky 'Reef' M.R.U.	76 c
Merensky 'Reef' pegmatoid	Merensky 'Reef' M.R.U.	81 to 83 c
4m below the Merensky 'Reef'	Noritic cumulates	76 c
6m below the Merensky 'Reef'	Noritic cumulates	79 c
80m below the Merensky 'Reef'	Noritic cumulates	82 c

c indicates cumulus character

i indicates intercumulus character

En differences were found between cumulus orthopyroxene (En 75) in a noritic cumulate, and cumulus orthopyroxene (En 82) in the immediately overlying Merensky 'Reef' pegmatoid. Furthermore intercumulus orthopyroxene 0,2m below the Merensky 'Reef' pyroxenite analysed En 69, as compared to En 76 to 77 of cumulus orthopyroxene in the Merensky 'Reef' pyroxenite. Within the Merensky 'Reef' M.R.U. there is a conspicuous iron enrichment in orthopyroxene cumulus from the bottom upwards. Orthopyroxene in the pegmatoid pyroxenite analysed En 81 to 83, in the overlying pyroxenite En 76 and 5m below the B.M.R. En 75 (Table 2). At the top of the Merensky 'Reef' M.R.U. there is a difference in composition between intercumulus orthopyroxene (En 69 to 70) in the footwall of the B.M.R., and cumulus orthopyroxene (En 78) within the B.M.R.

The Mg content of cumulus orthopyroxene varies from En 78 at the B.M.R. to 67 per cent En at a height of 850m above this level.

3. Clinopyroxenes. Clinopyroxenes are conspicuous intercumulus phases throughout the Critical and lower part of the Main Zone, although occasionally they are found as cumulus phases during this interval. Cumulus clinopyroxene appear mainly in porphyritic pyroxenite layers associated with the Upper Group of chromitite layers, and in the Merensky 'Reef'. Within the Main Zone they are not regular cumulus minerals until 60m above the B.M.R.

The cumulus clinopyroxenes at the top of the Critical Zone gave the composition: Ca 44, Mg 47, Fe 9, which is slightly enriched in Mg when compared with the composition given by Atkins (1969) for cumulus clinopyroxene at the same height; namely Ca 44, Mg 46, Fe 10. Intercumulus clinopyroxene, which occurs in pegmatitic pyroxenite lenses at the bottom of the Main Zone approach the following composition: Ca 45, Mg 43, Fe 12, which is enriched in iron when compared with that of cumulus clinopyroxene at the top of the Critical Zone (Fig.14).

4. Olivines. The only olivine found within the layered rocks, other than those found within the Merensky 'Reef', are those present in nodules (Photo 2), and will be described with the mineralogy of the nodules.

Olivine in the Merensky 'Reef' has been reported by various authors. Wagner and Brown (1968, Fig. 192) reported Fo 68 for this olivine. Coertze (1969, p.17) reports Fo 78-80 in olivines from the Merensky 'Reef' in the Western Bushveld. Van Zyl (1969, p.96) reports Fo 79 for the olivine in the pegmatoid layer of the Merensky 'Reef' and Fo 78 for the olivine in the Pseudo 'Reef'. At Bafokeng olivine within the Merensky 'Reef' was only found adjacent to contacts with ultramafic pegmatoids and will be dealt with later.

5. Oxides. In the portion of the layered rocks which was studied, oxides are mainly chromite spinels, which are still present at the base of the B.M.R. Willemse (1969a, p.12) notes that chromite and magnetite are mutually exclusive spinels. "From the vicinity of the Merensky 'Reef' downwards, we are in the realms of chromiferous rocks and magnetite is absent for all practical purposes". Wager and Brown (1968, p.394) found that there is a gap where no cumulus spinel crystallized, between the last chromitites which were enriched in iron and the crystallization of titaniferous magnetite. Van Zyl (1969) has reported the possibility of iron solid solution in chromitite from the upper chromitite layer of the pegmatoid 'Reef' in "Swartklip" 988, and

furthermore he reports that this chromitite layer is locally composed of magnetite and ilmenite. Cousins (1964), noted the presence of secondary magnetite, "of unknown genetic origin", in the pegmatoid pyroxenite of the Merensky 'Reef'. At Bafokeng no certain indication as to when intercumulus magnetite started to form could be found; it was probably in the early stages of deposition of the Main Zone. At Bafokeng magnetite is present within the Merensky 'Reef' as irregular patches within sulphides and on the margins between sulphides and chromitite in a sulphide bleb included in a chromite cumulus. A magnetitite pegmatoid was found underlying the exposure where magnetite was found within the Merensky 'Reef'. Van Rensburg (1962, p.106) has reported magnetite and ilmenite from the Merensky 'Reef' in the Eastern Transvaal.

6. Sulphides. The sulphides in the layered rocks have been studied by Liebenberg (1969), De Bruyn (1944), Van Rensburg (1962) among others. From an economic s id point the most important sulphide phase in the Bushveld Complex, is that associated with the Merensky 'Reef'. A volumetric study of the sulphides contained in the pegmatoid phase of the Merensky 'Reef' was carried out when ultramafic pegmatoids underlie the Merensky 'Reef' and a comparison (Table 3) made with data presented by Liebenberg (op.cit.) from the Rustenburg District.

Table 3. Volumetric percentages of sulphides in the Merensky 'Reef' pegmatoid layer.

Sulphide	Merensky Pegmatoid Liebenberg (1969)	Pegmatoid of Merensky 'Reef' Bafokeng optical determinations	X-ray fluorescence (average)
Pyrrhotite	50,3	48	46,6
Pentlandite	31,8	30	35,1
Chalcopyrite	13,8	19	18,2
Pyrite	4,3	3	-

Data was obtained by optics and X-ray fluorescence (Appendix I).

The textures of sulphides within the Merensky 'Reef' were studied only when a magnetitite pegmatoid underlies the chromitite layer of the Merensky 'Reef'.

Besides exsolution of pyrrhotite in pentlandite, there are massive (30mm) blebs of pyrrhotite showing birds-eye texture (Stumpfl, pers. comm.). This texture is produced by the concentric arrangement of other minerals within the sulphide which gives the blebs an exfoliated appearance (Photo 3). There are at least two minerals present in the 'exfoliated' portion; one is evidently a silicate, but the other shows higher refractive index intermediate between those of silicate and oxides and could not be identified. Stumpfl (pers.comm.) reported that the birds-eye texture is characteristic of pyrrhotite in the weathered zone and in hydrothermal deposits.

C. Chemistry.

The chemical analyses and C.I.P.W. norms of the layered rocks and Late ultramafic pegmatoids from Bafokeng Mine are presented in Table 4, (Appendix I). All rocks analysed from Bafokeng are plotted in a triangular, $(Na_2O + K_2O)$ - MgO - FeO, diagram. Fig. 5. In this diagram the iron is calculated as FeO, and chemical analysis presented by Van Zyl (1969, Table 2) are also plotted for comparison.

In Fig. 5 it can be seen that some layered rocks show a tendency towards alkali enrichment. Analysis 518 and 680 of Bafokeng and Z 243 of Van Zyl (op.cit. Table 2) which were taken at the same depth, approximately 30m above the bottom contact of the B.M.R. are the samples more displaced towards the alkali corner of the diagram. Furthermore anorthosites Lieb 31 and Lieb 51, Liebenberg (1960, Table 216) which come from the Critical Zone and from above the Merensky 'Reef' respectively and are not shown in Fig. 5, show the same displacement towards the alkali corner of the diagram.

C.I.P.W. normative components and modes vary considerably in most cases. In the layered rocks the main difference encountered, was the appearance of normative nepheline in one of the four anorthosites analysed. This anorthosite was taken in the proximity of nodules containing modal olivine (Table 4 anal. 126). Normative components were also calculated for analysis Lieb. 31 and 51., Lieb 51 (Liebenberg, op.cit.) shows 0,15 per cent normative nepheline. The other three anorthosites show normative olivine.

If all K^+ is calculated as normative orthoclase, when in fact some may be present in mica which is a modal mineral at the top of the Critical and bottom of the Main Zone, depletion in SiO_2 may occur. The result of this depletion would account for the presence of olivine in the norm. One of the anorthosites, analysis 518 also shows normative corundum, like analysis Z 242, Van Zyl (Ibid, Table 2).

FIG. 5. Plots of analysed rocks in a FeO-MgO-Alkalis diagram.

▢ Micaceous carbonatite pipe	◒ Intermittent noritic layer within the a.c.n. Critical Zone
✱ Layered granitic rocks Western Transvaal (Visser, 1964).	○ Nodules and intermittent pyroxenite layers within the a.c.n. Critical Zone
↑ Granitic pegmatite	◐ Pegmatoid pyroxenites Critical Zone
○ Ultramafic pegmatoids	▲ Anorthositic cumulates Critical Zone, ±30m below the Merensky 'Reef'
↓ Tonalitic pegmatite vein	△ Noritic cumulates Critical Zone
▽ Anorthositic cumulates Main Zone	
▽ Gabbroic cumulates Main Zone	
◑ Pegmatoid pyroxenites Main Zone	

The same symbols with a horizontal line show data from Van Zyl, 1969.

Z257 is a melanorite, Z295 is a picronorite and Z1046 an olivine melanorite.

The FeO/Fe_2O_3 proportions of samples MRIS and MR284 are not correct because the iron contained in the sulphides was not dissolved by the titration method and was therefore recorded as Fe+++ (Table 4).

C.I.P.W. norms on samples MRIS and MR284 (of the Merensky 'Reef' pegmatoid) were done without taking S, Ni and Cu into account. Therefore variable amounts of FeO which enter some sulphides are recorded as magnetite and hematite. Most of the pyroxenites analysed at Bafokeng show normative quartz.

The layered rocks were analysed for Ni, Cu, Zn (Tables 5 and 6), S (Table 7), and Rb, Sr (Tables 8 to 10) Appendix I. The methods used are also described in Appendix I. Generally in mafic layered intrusions, the distribution of copper is not so much controlled by the silicate phase as it is by the sulphide phase. Wager and Brown (1968, p.199) suggest that in Skaergaard the copper distribution is rather variable "probably as a result of the irregularities in the amount of sulphides". For the Bushveld Complex Liebenberg (1960, p.35) states: "Geochemically the occurrence of copper in silicate and oxide minerals is of minor importance as compared with the formation of sulphides".

Although Ni tends to covariate with Mg and enter olivine and orthopyroxene composition, (Wager and Mitchell, 1951, p.187), (Liebenberg, 1960, p.25), at the top of the Critical Zone and bottom of the Main Zone, its composition may have been controlled by the sulphide phase.

Few selected samples of the layered rocks were analysed for S (Table 7). The Merensky 'Reef' pegmatoid, samples MRIS and MR284, shows the highest S contents of the rocks analysed. Other pyroxenites, like the nodules and layers associated with the UG 2 chromitite layer do not show a S enrichment comparable to that of the Merensky 'Reef' pegmatoid. Liebenberg shows (1969, p.200) that the path of enrichment of S in the Bushveld magma may have been complicated by the addition of new pulses of magma. It is worthy of note that extreme enrichment of S as well as Ni and Cu occur more than once in the Bushveld (Liebenberg, Table 50), and that the S content as given by this author is higher in the Main Magnetite layer and Upper Zone than it is in the Merensky 'Reef'.

According to Wager and Mitchell (1951) Rb is residual during fractionation, being enriched in the late granitic fraction, whereas Sr shows considerable spread during fractionation being mainly related to plagioclase distribution where it replaces Ca++, but on the whole shows little change during differentiation. Rb^{+} has a similar ionic radius to K^{+} and is admitted to this site in K-feldspars and micas, (Liebenberg, 1960, p.53). This is especially significant because development of micas has been noted not only in the pegmatoid pyroxenites but in the rocks taken as 'average country rock' (Appendix I), and generally at the top of the Critical Zone and bottom of the Main Zone variable amounts of mica are present within the layered rocks. In addition to this, Davies et alii (1969, p.586) have shown that alkali feldspar is an important factor which affects the Rb/Sr content of plagioclase-poor pyroxenites, increasing the Rb and radiogenic Sr 87 of the rock. The layered rocks average between 6 and 12 p.p.m. Rb (Table 9). The average value of 12 p.p.m. Rb for the pegmatoid pyroxenites has been noticeably enriched due to the development of hydrous alteration products in specimen PPUG 4(Table 8). The Sr contents of noritic and anorthositic cumulates, compares well with that given by Davies et alii (Ibid) and also with data of Liebenberg (1960, Table 19); for the same rock types whereas Rb contents are on the whole slightly higher (Table 10).

D. Pegmatoids in the layered rocks

1. The anorthosite containing nodules (a.c.n.)

a. General.- The anorthosite containing nodules (a.c.n.) is the name proposed to describe an anorthosite cumulate containing pegmatoid to coarse-grained pyroxenite nodules as they were called by Ferguson and Botha (1963, p.267), or boulders as called by Cousins (1964, p.228).

Boulders in inverted commas has already been used by several geologists to describe oval shaped forms; e.g. Van Biljon (1964) has used the word boulder to describe oval shaped dark green serpentine masses in the Stolzburg Asbestos Mine, however, as the term implies a genetic mode of formation, nodules will be used throughout to describe the forms found at Bafokeng.

The layer containing the nodules is an anorthositic cumulate or mottled anorthosite. The mottling effect is a result of the clustering of intercumulus clinopyroxenes and orthopyroxenes, showing sub-poikilitic textures. Occasionally the a.c.n. also contains intermittent pyroxenitic and noritic layers. The a.c.n. is by no means the only layer to show the development of nodules. Van Zyl (1969) has described chromitite nodules which are found below the pegmatitic layer of the Merensky 'Reef' and in the anorthosite below the UG 1 chromitite layer, both within the Critical Zone. However, to our actual knowledge all nodules, including those found at Bafokeng and those reported by Van Zyl (1969), occur in the Critical Zone. Evidently this must be borne in mind when postulating any particular set of conditions operative at the time of their formation. At Bafokeng two pyroxenite nodules were found 50 cm below the Merensky 'Reef' in the 6 Shaft area.

The a.c.n. layer has been intersected in surface boreholes and underground exposures throughout the mine, at a vertical distance of approximately 25m below the Merensky 'Reef'. This distance varies throughout the mine, depending on the irregularities of the bottom contact of the Merensky 'Reef'. At Bafokeng exceptional cases are known of depressions where the Merensky 'Reef' is resting on the a.c.n.; Cousins (1964, p.235) also drew attention to this feature, at the Rustenburg Platinum Mines the vertical distance between the a.c.n. and the overlying Merensky 'Reef' is 110 feet (34m ±). From the isopach plot of the a.c.n. (Fig. 6) it can be seen there is a thinning of this particular layer towards the northern portion of the property. The lower contact of the a.c.n. layer against a noritic layer is sharp (Photo 4). The upper contact is distinct in the 5 and 6 Shaft areas, where the a.c.n. is overlain by 100 mm of pyroxenite cumulate which grade upwards into a plagioclase orthopyroxene cumulate. Elsewhere in the mine this pyroxenite is not developed, and the position of the upper contact of the a.c.n. is based on textural differences between the a.c.n. which shows intercumulus pyroxenes and the overlying layer which shows cumulus pyroxenes. This contact is gradational.

The grain size of the nodules varies, sometimes in the same exposure. According to Van Reysen (1969), 60 per cent are medium grained and 40 per cent comprise pegmatoidal dimensions. Usually the nodules exhibit a marked regularity in shape and size. The nodules have a biaxial ellipsoid shape. In a section cut parallel to the layering the nodules exhibit a circular outline (Photo 5) the long axis being parallel to the layering. The short axis is vertical, the lower surface being more regular and convex than the upper one. An average of fifty measurements gave the following results: long axis = 160mm, short axis = 110mm. Occasionally bigger nodules are sparsely found towards the bottom of the a.c.n.

Fig 6
Plan showing depths of the anorthosite containing nodules layer contoured at 1m intervals

There are rare occurrences of elongated nodules, where the long axis tends to be three or more times larger than the short axis. A bleaching of the anorthosite around individual nodules is frequently observed. Zones of up to 50 mm and in exceptional cases 100mm of pure anorthosite can be seen surrounding some nodules.

In the northern portion of the 5 Shaft area, and the 6 Shaft area, where the thickness of the a.c.n. is less than 3m, the nodules are distributed throughout the width of the layer. The highest concentration of nodules is nevertheless approximately 1m above the bottom contact of the a.c.n. In the 5 Shaft area, seldomly was a nodule found to overlie the pyroxenite layer occurring within the a.c.n. (Fig. 7). In the 6 Shaft area the a.c.n. is overlain by a pyroxenite cumulate, the lower contact of which undulates sharply, alternatively exhibiting concave and convex outlines upwards. Immediately underneath convex portions pyroxenite nodules are present.

Throughout the rest of the mine the nodules are occasionally found between 2 and 4m above the bottom contact of the a.c.n. Within the bottom metre of the a.c.n., coalescence and grouping of nodules are common producing irregular shapes and affecting their average areal distribution. Although in 2 W. Drive, 3 Shaft the nodules are set at 0,25 to 0,3m intervals, more commonly they are set at 0,6m to 1m centres.

In the western portion of the 5 Shaft area there is a 0,3m pyroxenite layer which is found 0,7m below the upper contact of the a.c.n. This layer is pegmatoid at the base, grades upwards into a medium grained pyroxenite, and in many places exhibits bulging on the underside (Photo 6), and is over- and underlain by anorthosite. The occurrence of this particular layer is restricted to the western portion of 2 West Drive, as is shown by the fact that it was not found in 3 West Drive (40m ± distance) immediately down dip. In the 1, 5 and 6 Shaft areas, intermittent noritic layers were found towards the bottom contact of the a.c.n. Shearing at the bottom contact of the a.c.n. is occasionally present below intermittent noritic layers. In other parts of the mine, intermittent pyroxenitic and noritic layers were also found towards the bottom contact of the a.c.n. (Photos 4 and 6). All intermittent layers show cumulate textures.

Besides the development of nodules and intermittent layers, the a.c.n. also shows the development of 'mottles' which are produced by the clustering of intercumulus clinopyroxene and orthopyroxenes showing sub-poikilitic textures. When the thickness of the a.c.n. is less than 5m, the amount of intercumulus material increases towards the bottom of the a.c.n. When the a.c.n. is greater than 5m thick, changes in the size of the sub-poikilitic pyroxenes are in evidence. In these cases two 10-20mm thick layers (Fig. 7, Photo 7) occur at approximately 3 and 5m above the bottom contact of the a.c.n. In the area sandwiched between the two pyroxenite layers, the intercumulus pyroxenite annedra are smaller than above and below (Fig. 7). The intercumulus pyroxenes attain their maximum concentration and the anhedra attain their maximum proportions between 1 and 3m above the bottom contact of the a.c.n.

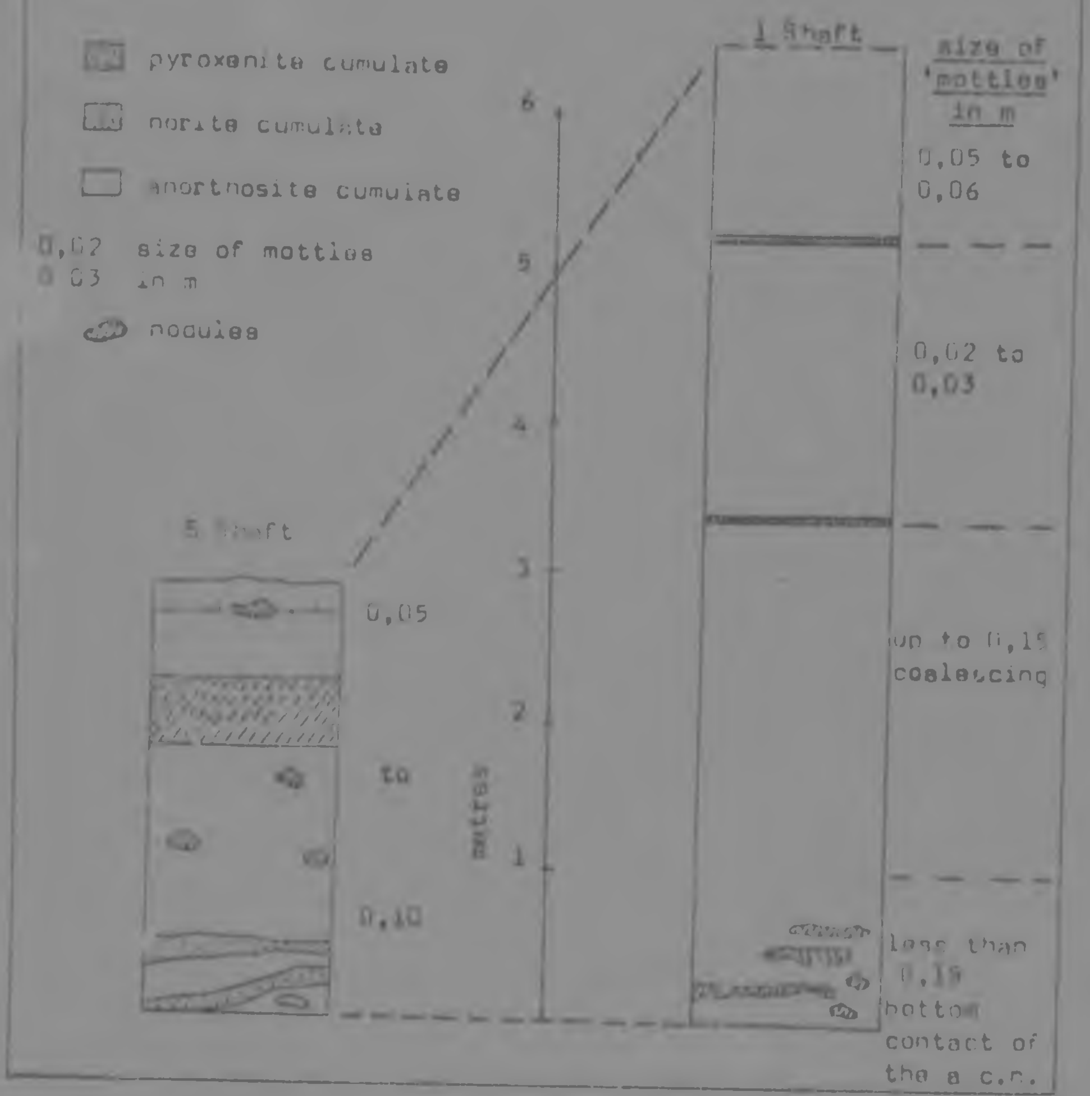
b. Mineralogy. - Mineralogically there are three different types of nodules, being:

- pegmatoidal or medium grained pyroxenite,
- feldspathic pyroxenite,
- norite.

The first two types are most common, and the third type was found only near intermittent noritic layers, which have been described. Pegmatoidal pyroxenite nodules could well be described as ultramafic pegmatoids.

At Rustenburg Platinum Mines, Ferguson and Botha (1963) describe the nodules as being composed of coarse feldspathic pyroxenite, whereas Cousins (1964) states that they are composed of coarse to

FIG. 7. Section showing thicknesses and distribution of intermittent layers within the a.c.n. in the No. 5 and No. 1 Shaft areas.



pegmatitic pyrox[illegible]. At Bafokeng, the nodules are composed mainly of orthopyroxene and variable amounts of plagioclase which shows intercumulus relationship to the orthopyroxenes. Clinopyroxene is present as exsolution products along orthopyroxene cleavages and also as irregular intercumulus crystals.

According to Van Reysen (op.cit.) 60 per cent of the nodules have a thin chromite stringer, or alternatively scattered chromite crystals, at their base. The chromite percentage varies with the exposure examined, and in some of them is absent. In addition, chromite was found to occur a few mm above the base of the nodule, and in one instance, occurs on the upper side of a pyroxenite nodule. Chromite is a very common constituent of the a.c.n. In the 6 Shaft area a one to two mm chromite layer is found approximately one metre above the bottom contact of the a.c.n. This layer seems to be fairly consistent throughout the area as it was present in all three exposures seen. In the 4 Shaft area and 1 Shaft area a chromite layer of the same thickness, is intermittently present within the bottom 0,3m of the a.c.n.

Plagioclase within the a.c.n. was analysed (Table 11), by the [illegible] described in Appendix I. Reversed zonation of plagioclase [illegible] was present in the thin sections observed. Only one measurement was obtained in which the core gave An 76 and the margin An 60.

Table 11. An content of the plagioclase within the a.c.n. as obtained by different methods, and comparison with the An content of plagioclase from ultramafic pegmatoids contained in the a.c.n.

	An content of plagioclase	Method
a.c.n.	78,83	Chemistry (full analysis)
	80	X-ray fluorescence (Na peak)
	76	X-ray spectrography
	74	Optics
Ultramafic pegmatoid within the a.c.n.	82,89	Chemistry (full analysis)
	85	X-ray fluorescence (Na peak)
	-	X-ray spectrography
	80-82	Optical determinations

The nodules show variable amounts of hydrous alteration, those from the 4 Shaft area are the most altered. The alteration products are amphiboles of the tremolite-actinolite series and chlorites which form at the expense of orthopyroxene and plagioclase respectively.

In some intermittent pyroxenite layers found within the a.c.n., this alteration amounts to 6 per cent of the total volume (Fig. 8).

Olivine occurs as an irregular mineral in the nodules, in the 5 Shaft area it is present in trace amounts in both nodules and intermittent pyroxenite layers. In the 1 Shaft area olivine is a conspicuous component of all the nodules examined from the available exposures (Photo 2). It is noticeable that plagioclase analysis of the a.c.n. around these olivine-bearing nodules gave four to five per cent higher An contents than elsewhere in the mine. The olivine in these nodules is Mg-rich, being Fo 82-85, and in one instance Fo 91. Orthopyroxene compositions were obtained from intermittent pyroxenite layers, nodules and intercumulus orthopyroxene within the a.c.n. (Table 12). Averages and comparisons with under- and overlying pyroxenite cumulates are given in Table 12.

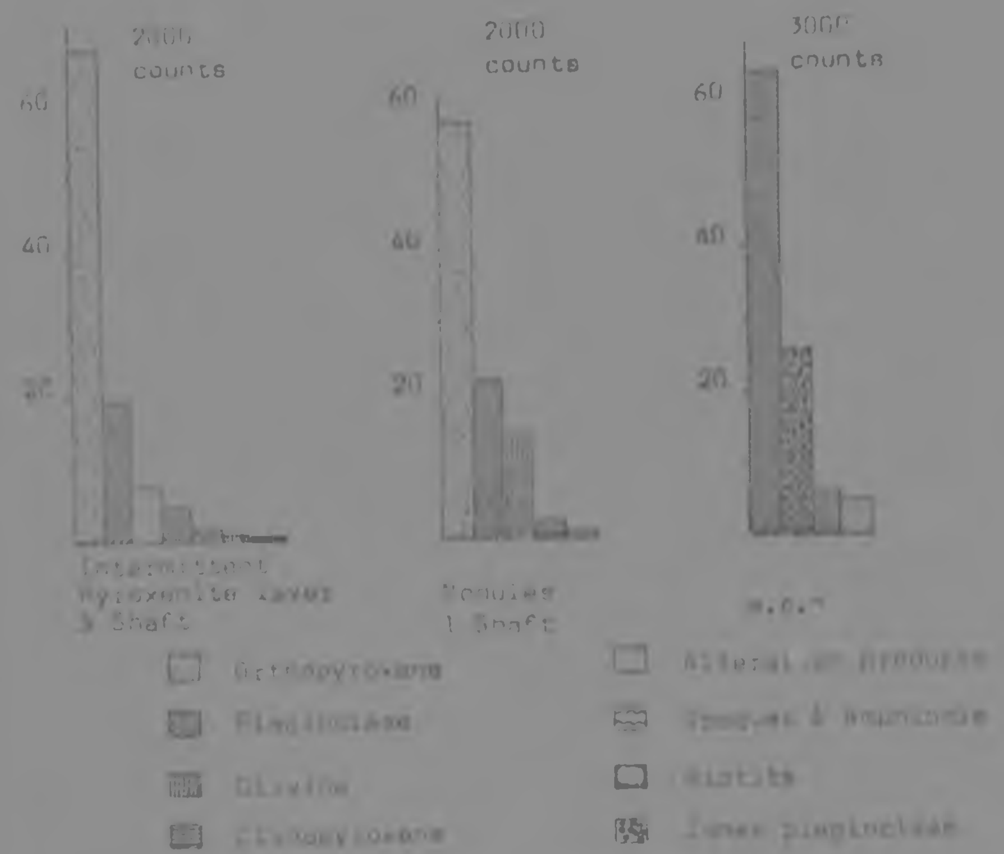
Table 12. Variation in the En content of orthopyroxenes within the a.c.n. and in related rocks.

Rock type	2 Vx	En % ± 1
Anorthosite (intercumulus opx) a.c.n.	75	76
Intermittent noritic layer bottom of a.c.n.	75	79
Intermittent pyroxenitic layer top of a.c.n.	72-73	77
Nodules	78-80	81-82
UG 2 Pyroxenite pegmatoid	78	81
Merensky 'Reef' pegmatoid	80	82

c. Chemistry. - The sampling methods are described in Appendix I. Nodules from the 5 Shaft area and 4 Shaft area were chemically analysed. The analyses are designated Nod 5 and Nod 4, respectively. Intermittent layer of pyroxenite, sample Pxnfw, and noritic layers, sample Annacn; analysed are from the same exposure as sample Nod 5 (Table [illegible]). Samples 163 and 126 are of the a.c.n., they do not include nodules or intermittent layers. Nodules in the 1 Shaft area were not chemically analysed; however a modal count was done. Modal counts of the a.c.n., intermittent pyroxenite layers are presented as well in Fig. 8.

In the MgO-FeO-K_2O+NaO diagram (Fig. 5) the nodules plot very close to the rest of the pyroxenites analysed from the Critical Zone. The main difference between them are the overlying pegmatitic layer

FIG. 8. Modal analysis of rocks associated with the a.c.n.



of the Merensky 'Reef' is, that the latter is displaced towards the FeO corner, due to much higher Fe sulphide content. Data produced by Van Zyl (1969) is also plotted in this diagram.

The effect of the iron-sulphides on the analysis is well emphasized by the displacement of analysis Z1046, the unmineralized Merensky 'Reef' of Van Zyl, towards the MgO corner with respect to the analysis of pegmatitic portions of the sulphide-rich Merensky 'Reef' at Bafokeng. Another fact which needs to be emphasized is that analysis Z257, the B.M.R.; and Z295, the Pseudo 'Reef'; plot nearer to the MgO corner than the analysis of the unmineralized Merensky 'Reef' (Z1046). At Bafokeng, the nodules as well as PP064, the pegmatoid pyroxenite associated with the UG 2 chromitite layer, are displaced towards the MgO corner with respect to the pegmatoid layer of the Merensky 'Reef'. Normative analysis of the nodules showed quartz in one case and olivine in the other.

Cationic contents on the basis of 100 oxygens, were calculated for the analysis done and some of the analyses presented by Van Zyl

(Ibid, Table 2), and are presented in Table 13. The main object was to compare the nodules with analysis of the Pseudo 'Reef' which shows higher water and Mg contents than any of the other pyroxenites, and the lowest Si content. The K content of rocks from "Swartklip 988" (W. Transvaal) is higher than those from Bafokeng. Analysis Z280, which, according to Van Zyl (op.cit.), is a porphyritic melanorite 5m above the Merensky 'Reef', gave 1,2 K as compared with 0,2 K which was the highest analysed at Bafokeng.

Nickel contents in nodules and intermittent layers within the a.c.n. vary between 523-755 p.p.m. (Table 5, Appendix I). These values are higher than those of:

- the norite cumulate which underlies the a.c.n., which is 324 p.p.m.
- the a.c.n. which averages 54 p.p.m.

The Cu content in nodules and intermittent pyroxenite layers within the a.c.n. varies from 17 to 23 p.p.m. (Av.), as compared with:

- 10 p.p.m. Cu in the noritic cumulate which underlies the a.c.n.
- 7 p.p.m. Cu of the a.c.n.

It is worthy of note that two nodules in the 4 Shaft area, analysed by the Assay Department, Bafokeng Mine, gave the following values: 16650 p.p.m. Ni and 6500 p.p.m. Cu, proving that Cu Ni concentrations vary. Although these values are exceptionally high, the a.c.n. is of no economic importance due to the erratic occurrence of the mineralization and to the fact that the nodules represent a minimum volume within the a.c.n.

The Ni/Cu ratios of the nodules and the pegmatoid pyroxenite layer associated with the UG 2, sample PPUG4, are similar, being slightly higher than the Ni/Cu ratios of the pegmatoid layer of the Merensky 'Reef'.

In pyroxenitic rocks Rb is closely related to the amount of alteration and the presence of mica. The less altered nodules, like 3 and 5, show less Rb, whereas PPUG4 shows 17,7 p.p.m. Rb. The pegmatoid layer of the Merensky 'Reef' averages 6,4 p.p.m. Rb, as compared with 6,1 which is the average of the nodules. Strontium varies from 30 p.p.m. to 144 p.p.m. in pyroxenites and nodules, and its concentration differs from 144 to 87 p.p.m. in the nodules probably due to different plagioclase contents, (Table 8, Appendix I).

2. Lenses. The top portion of the Critical Zone and bottom portion of the Main Zone, show a widespread distribution of

TABLE 13. Cationic content of the nodules and overlying and underlying pyroxenite pegmatoid layers.
(Calculated on the basis of 100 oxygens).

Sample Name	Fe++	Fe+++	Mn	Ti	Ca	K	P	Si	Al	Mg	Na	H	TOTAL
NOD 5	2,6	1,1	0,07	0,05	5,0	0,06	0,07	28,2	8,0	16,9	0,6	9,4	72,05
NOD 4	3,2	1,6	0,1	0,06	3,2	0,04	0,05	24,5	4,8	19,6	0,4	10,4	71,95
Pxmfw	3,0	2,0	0,1	0,1	4,5	0,02	0,03	30,4	5,2	18,2	0,6	3,8	67,95
Z 295 +	2,9	3,1	0,1	0,1	1,5	0,06	0,07	20,3	2,6	25,3	0,6	38,0	95,23
Mr IS	2,4	5,4	0,07	0,1	2,0	0,04	0,03	25,7	3,9	20,3	0,2	18,6	78,74
Mr284	2,6	3,6	0,07	0,25	2,8	0,1	0,03	28,4	5,1	19,8	0,8	8,4	71,75
Z1046	5,2	1,0	0,07	0,14	2,6	0,5	0,1	27,7	5,0	23,5	0,8	2,6	70,01
Z 280	3,3	1,4	0,1	0,2	3,3	1,2	0,06	30,8	5,0	19,4	0,7	0,6	66,36
PPug 4	3,8	1,7	0,1	0,2	3,4	0,2	0,02	30,2	2,8	20,2	0,4	8,8	71,82
Av 1	1,6	0,6	0,03	0,05	6,9	0,06	0,04	28,4	14,5	8,3	1,8	4,4	66,65
Av 2	0,6	0,1	-	0,01	9,1	0,15	0,05	27,5	20,1	1,8	2,7	3,0	65,16
Av 4	1,2	0,1	0,03	0,03	7,7	0,3	0,05	27,8	18,9	2,3	3,5	4,7	66,61

\+ plus 0,6 C

Av 1 Average noritic cumulate below the Merensky 'Reef'

Av 2 Average anorthositic cumulate below the Merensky 'Reef' - a.c.n.-

Av 4 Average anorthositic cumulate above the Merensky 'Reef'

Z 295 Pseudo-reef - S1046 Pegmatitic Reef - Z280 Merensky 'Reef'. Van Zyl (1969).

pegmatoid layers of pyroxenite composition, all of which show cumulate textures (e.g. the Merensky 'Reef' pegmatoid). Other pegmatoid pyroxenites show contrasting textures, very sparse occurrence and an intermittent lensoid character of reduced dimensions (Fig. 3). These pegmatoid pyroxenites are described under Lenses because their dimensions seldom exceed 1m in length, and 0,2m in thickness. Their shape is not accurately known, but may be irregular. Most of these lenses have a feldspathic pyroxenite composition, where the minerals present are orthopyroxene clinopyroxene plagioclase phlogopite and chlorite. Locally an unidentified green pleochroic amphibole replaces clinopyroxene and orthopyroxene.

Orthopyroxene composition is 2 per cent poorer in the En molecule than the cumulus orthopyroxene in the layer in which the lenses occur. This difference may be real or could be attributable to analytic error. In these lenses,clinopyroxene shows a composition of Ca 45, Mg 43, Fe 12.

In all cases observed orthopyroxene and clinopyroxene within the lenses, show an intergrowth texture (Photo 8) in which anhedral plates of both minerals cluster together. Orthopyroxene'rods' are found along cleavages in clinopyroxene, and both minerals include the other.

The textures and shape of the pyroxenes indicates their intercumulus nature.

III - LATE PEGMATOIDS

A. Ultramafic Pegmatoids

1. General. Under the general term ultramafic pegmatoids (Fig. 9), Willemse (1969a, p.11), includes the following:

(a) "Bronzitite pegmatoid, that forms pipe-like bodies in the Basal Zone, especially west of the Pilanesberg."

(b) "Hortonolite-dunite and dunite, which are closely associated in the well-known platiniferous pipes." (Onverwacht, Mooihoek, Driekop). Gradations in which the Fo content of the olivine increases outwards are known in Onverwacht and Mooihoek. Pipes which consist wholly of dunite or hortonolite-dunite are known to exist.

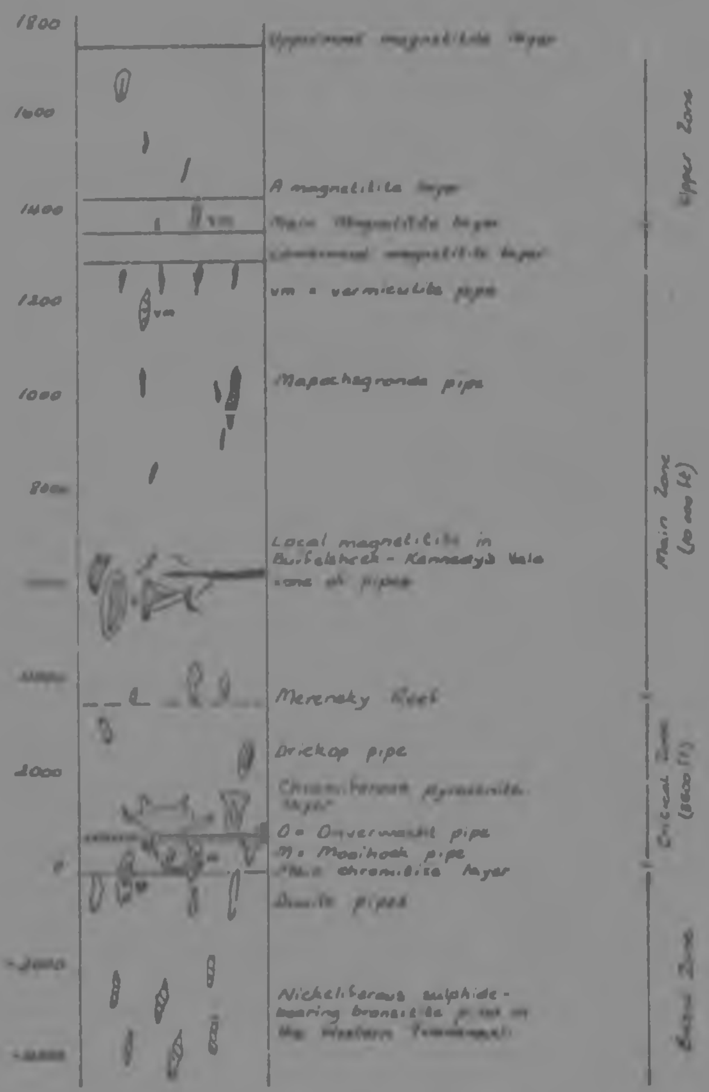
(c) Diallagite pegmatoid, formed essentially by diallage augite, olivine, plagioclase, hornblende, phlogopite, magnetite.

(d) Magnetitite pegmatoids, according to Willemse (op.cit.) "by a greater concentration of magnetite, the diallagite pegmatoid passes into massive magnetic iron ore." They are found above the Merensky 'Reef' in the Main Zone, continuing into the Upper Zone above the Main magnetite layer, in pipe-like bodies. Locally they also form sill-like bodies, both in the Eastern and Western Transvaal.

(e) Vermiculite pegmatoids: these bodies are found near the top of the Main and Upper Zones. Von Gruenewaldt (1964) has described them in the Roossenekal area. He found that they enclose angular fragments of country rock embedded in diallagite pegmatoid and are also associated with magnetite-rich phases.

The association of diallagite pegmatoids with dunites or hortonolite dunites has been stressed by Wagner (1973), Coertze (1960), Sohnge (1963), Cameron and Desborough (1964) and several other authors. Willemse (1969b, p.192) stresses the association between diallagite pegmatoids and magnetitite pipes, and between diallagite and vermiculite pegmatoids (1969a, p.11). Cameron and Desborough

FIG. 9. Schematic profile of the various pegmatoids in the layered rocks (olivine) diallagite pegmatoid - stippled; magnetitite - black (modified after Willemse, 1969a).



(Ibid, Fig. 21) show diallagite-hornblende-hortonolite to merge locally into hortonolite dunite. Intimate relationships between hortonolite dunite and magnetitite have been described by Coertze (1966, pp.17-20; 1969 p.15).

At Bafokeng, only types (b), (c) and (d) of Willemse (op.cit.) are present. Usually clinopyroxene (diallage), olivine and oxides form 96 per cent, by volume, of the ultramafic pegmatoids. Variation in clinopyroxene, olivine and magnetite produce all gradations between diallagite, dunite and magnetitite pegmatoids. Gradations in the composition of olivine make it difficult to define limits between hortonolite dunite and dunite pegmatoids. Therefore, the use of the general term 'ultramafic pegmatoids' is desirable.

In certain portions of ultramafic pegmatoids, plagioclase is an additional phase forming up to 25 weight per cent, producing feldspathic diallagites. Rare ultramafic pegmatoids composed of olivine and plagioclase or magnetite and plagioclase have been found. Accessory minerals are hornblende serpentine and occasionally micas. Hornblende rarely forms more than five per cent by volume of the ultramafic pegmatoids, although when these bodies come in contact with the Merensky 'Reef' the hornblende content locally increases to between 5 and 10 per cent by volume. Disseminated orthopyroxenes can be an additional phase in the ultramafic pegmatoids where they are juxtaposed with orthopyroxene cumulates.

Ultramafic pegmatoids, of dunitic composition (although in places they have irregular outlines), usually produce very rugged 20m (±) high, pipe-like outcrops. Diallage pegmatoids weather readily, so seldom outcrop, but several occur in road excavations; due to their iron content they are easily traced with a magnetometer. In places the diallage pegmatoids form discontinuous envelopes to dunitic pegmatoid outcrops, e.g. the dunitic pegmatoid between boreholes 510 and 506, but they also occur independent of dunite pegmatoids, e.g. the one on the western corner of the farm Vaalkop 275.

The outcrop over which No. 243 trigonometric beacon rests, on Vaalkop, is a magnetitite pegmatoid hill which protrudes through gabbroic rock types which belong to the Main Zone (Fig. 10). The relationship between this magnetitite pegmatoid and other rock types is obscure because of lack of exposure.

Conformable magnetitite pegmatoids have also been found above and below the chromitite layers of the Upper Group on the farm Doornspruit 106, being of small dimensions.

Magnetic surveys were carried out over some of the areas affected by ultramafic pegmatoids in an attempt to establish the magnetic response of the different bodies (Fig. 10). It was found that the magnetic profile is generally flat in the Bafokeng mining area, however, strong positive anomalies are associated with the ultramafic pegmatoids. A broad zone containing isolated positive magnetic anomalies strikes parallel to a shear zone at the northern boundary of the lease area. All surface boreholes drilled in this area, namely boreholes 510, 506

FIG. 10 Ultramafic pegmatoids and associated magnetic anomalies at the Bafokeng Leasehold.

- Ultramafic pegmatoid outcrops
- Ultramafic pegmatoid intersected by underground workings
- Granitic pegmatites
- Merensky 'Reef' outcrop
- Limits of magnetic anomaly
- Shafts
- Surface bor   es which intersected ultramafic pegmatoid
- Trig. beacon
- Farm boundaries
- Limit of the Bafokeng Leasehold

and 518 intersected thick bodies of ultramafic pegmatoid (Fig. 10). The magnetic method proved very helpful in the 5 Shaft area where shallow-lying (± 100m) bodies of ultramafic pegmatoid were predicted and their presence recently confirmed by mining operations. However, magnetic surveys carried out on the farm Wildebeestfontein 274, around borehole 639, which has a 55m thick intersection into ultramafic pegmatoid, at a depth of approximately 300m did not produce anomalous reading on surface.

Magnetic work has also been carried out by the Geological Survey (Von Backström et al., 1960), on the Bafokeng and adjoining areas during the compilation of the Rustenburg No. 4 Sheet. This work covered the farm Vaalkop 275 JQ to the East through the farm Kookfontein 265 JQ and the adjoining Boschfontein 268 JQ. These results show that the greater anomalies are associated with the dunite outcrops. They also found a magnetic anomaly above the Merensky 'Reef' connecting the dunite pipes on the farms Vaalkop and Kookfontein. They reported a similar type of anomaly further east and south above the Merensky 'Reef', and along the same elevation in the Rustenburg-Marikana area and at the Kroondal Platinum Mine area (Fig. 1). Their conclusion was that the magnetic anomaly was probably due to the presence of dunites, forming a continuous body over the Merensky 'Reef'. This anomaly was plotted in Figure 10, but mining operations in the 1 Shaft area have failed to prove any continuous body of ultramafic pegmatoid above the Merensky 'Reef'. In this area, intermittent, conformable and transgressive ultramafic pegmatoid bodies are found both above and below the Merensky 'Reef'.

2. The relationship of the ultramafic pegmatoids to the layered rocks.

a. Contacts.

i. General statement. - Contacts between ultramafic pegmatoids and the layered rocks have different characteristics depending upon the lithology of the layered rock. As an example contrasting contacts are produced when ultramafic pegmatoid intersect anorthositic or noritic cumulates (Photo 9). The majority of the contacts are sharp and undisturbed.

Ultramafic pegmatoids occasionally enclose layered rock (Photo 10). Gradational contacts with anorthositic cumulates may extend over 0,1 to 0,2m, however patchy development of ultramafic pegmatoid in the layered rock makes it difficult to be precise.

At Bafokeng, no true gradational contact between ultramafic pegmatoid and a noritic cumulate has been observed. Several particular examples of contact will be considered separately.

ii. Contacts with plagioclase and plagioclase-orthopyroxene cumulates. - Contacts of this type are sometimes sharp, but often there is a patchy development of clinopyroxene, olivine and oxides away from the ultramafic pegmatoid into the country-rock. (Photo 11). Locally diallage in the ultramafic pegmatoid is even more coarse grained at the contact than normal, and may extend into the layered rock giving the contact a serrated appearance (Photo 9). In this example the long axis of the diallage crystals measure 100mm.

In No. 3 cross-cut North, 5 Shaft, an ultramafic pegmatoid encloses the a.c.n. (Photo 10). The following structures were found in the a.c.n.:

- Patchy development of randomly orientated t[illegible]ular [illegible]uoite crystals which in places measure up to 0.3m (Photo 12).
- Intermittent layering, 3m long, composed of pegmatitic plagioclase and clinopyroxene (Photo 13). Within the latter layers macropegmatitic [illegible]opyroxenes have grown parallel to the plane of the layering. Their composition is similar to the clinopyroxene contained in ultramafic pegmatoids.

A different example of layering at the contact between ultramafic pegmatoid and country-rock was observed in 287 Stope, 5 Shaft. The Merensky 'Reef' is, on this raise, underlain by an anorthositic cumulate which grades downwards to an anorthositic-norite cumulate. The ultramafic pegmatoid is both conformable with and transgressive to the Merensky 'Reef' and has produced irregularly shaped layers parallel to the contact, immediately below the Merensky 'Reef' (Photo 14). These layers are composed mainly of pegmatitic plagioclase and magnetite with minor amounts of olivine and clinopyroxene. Either plagioclase or magnetite can be in direct contact with the chromite layer of the Merensky 'Reef', which in this area rests immediately upon the footwall rocks. In this raise, when the chromitite layer of the Merensky 'Reef' is underlain by pegmatitic plagioclase, the latter protrudes into the chromitite layer, producing displacement effects in the chromitite which shows an undulating outline (Photo 15).

A transition zone of pegmatitic feldspars and mafics between undisturbed layered anorthositic rock and ultramafic pegmatoid, which is devoid of plagioclase, was found in some borehole intersections. Coarse grained to pegmatitic plagioclase crystals develop within the ultramafic pegmatoid in the immediate vicinity of some contacts. The textures shown by these plagioclase crystals will be discussed later.

iii. Contacts with orthopyroxene-plagioclase cumulates. - These contacts are always sharp, and the crystal size of the ultramafic does not show increased pegmatoidal proportions similar to those described when they occur in some plagioclase-rich cumulates.

In the immediate vicinity of ultramafic pegmatoids in contact with orthopyroxene plagioclase cumulates, olivine is produced within the country-rock at the expense of cumulus orthopyroxene. Schwellnus (1956) found the same phenomena. Willemse (1964, p.118) notes that "a thin rim containing coarse-grained feldspar is a common feature of these pegmatoids where they occur in noritic rocks". At Bafokeng, this latter feature has been observed a few times. In 285 Travelling way in the 5 Shaft area, 0,1m wide symmetrically zoned apophyses protrude from an ultramafic pegmatoid (Photo 16). In some of these apophyses the core comprises unaltered country-rock followed by ultramafic pegmatoid which in turn is surrounded by pegmatitic plagioclase and having a margin of ultramafic pegmatoid.

iv. Contacts with orthopyroxene cumulates. - Contacts between ultramafic pegmatoids and orthopyroxene cumulates were studied at the B.M.R., Merensky 'Reef' and UG 2 pyroxenite elevations, but received special attention at the Merensky 'Reef' elevation. These contacts do not present a colour contrast, tend to be irregular and nearly always there is a development of a fine-grained portion within the ultramafic pegmatoid (Photo 17). Olivine is the main constituent of these fine-grained phases, however hornblende, clinopyroxene and to a minor extent, oxides may be present.

The contact between ultramafic pegmatoids and the Merensky 'Reef' show the cumulate textures of the latter almost obliterated by the development of the fine-grained ultramafic phases, which disrupt or react with orthopyroxene cumu[illegible]s (Photos 18 and 19). Occasionally ultramafic pegmatoids show transgressive relationships to the Merensky 'Reef', being mainly conformable. When ultramafic pegmatoids transgress the Merensky 'Reef' the development of ultramafic pegmatoid within the Merensky 'Reef' is patchy, and portions of Merensky

'Reef' are preserved within the ultramafic bodies. Borehole 647, shows that over the space of 0,5m the cumulate texture of the Merensky 'Reef', over- and underlain by ultramafic pegmatoid, is still recognizable. The ultramafic pegmatoid is a dunitic rock in which the size of the olivine is smaller than that of the orthopyroxene cumulus or the Merensky 'Reef'.

Contact relations showed relics of cumulus orthopyroxene within the ultramafic pegmatoid; a high degree of fracturing within the Merensky 'Reef' adjacent to the ultramafic pegmatoid, bending of orthopyroxenes grains within the Merensky 'Reef', and a high degree of alteration which produces serpentine, fibrous antigorite talc, amphiboles and chlorites, in both rock types. Veinlets of oxides, postdating olivine formation cut the ultramafic pegmatoid in two directions roughly perpendicular to each other.

When ultramafic pegmatoids conformably underlie the Merensky 'Reef', usually there is a conformable deposition of magnetitite pegmatoid immediately below the chromitite layer of the Merensky 'Reef', although in other cases no substantial amount of magnetitite pegmatoid has been deposited. The first case will be described in the following section because of the contact with a chromitite cumulate. The second case was studied in the second deflection of borehole 606. In this borehole the rock normally found below the Merensky 'Reef' is a plagioclase orthopyroxene cumulate, however, a troctolitic pegmatoid is found below the Merensky 'Reef' in the second deflection of borehole 606. One thin section of the chromitite layer of the Merensky 'Reef' shows undisturbed chromitite cumulus and variable amounts of hydrous alteration within the cumulus silicates. In a second section poikilitic olivine encloses the cumulus chromite (Photo 20), and magnetite serpentinite veins transect the rock perpendicularly to the chromitite layer. Above the chromitite layer olivine forms at the expense of orthopyroxene.

Generally when the Merensky 'Reef' is underlain by ultramafic pegmatoid olivine develops within the Merensky 'Reef' in the vicinity of the contact.

v. Contacts with chromitite cumulates. - At Bafokeng there are few underground intersections of the UG of chromitite layers, and most of the data at this stratigraphic level comes from borehole core. However, whenever observed the ultramafic pegmatoids conformably underlie the chromitite layers. From borehole intersections and outcrop exposures, it is evident that magnetitite pegmatoids readily develop when ultramafic pegmatoids immediately underlie chromitite layers including those of the Merensky 'Reef'. A maximum of 0,1m of magnetitite pegmatoid was observed below the UG 2 chromitite layer. As the thickness of this chromitite layer varies from place to place, it was impossible to judge if the position which magnetite now occupies was previously occupied by silicates or by chromite.

At Kroondal Mines, Tweedie (1969) observed that ultramafic pegmatoids frequently occur at the base of a pyroxenite separating two chromitite layers of the Lower Group. He noted that in places ultramafic pegmatoid may make up the total width of the parting and on occasions may transgress the underlying chromitite layer. Cousins (1964, p.195) states that "discordant bodies of pegmatitic pyroxenite have been observed in the vicinity of the chromite seams". He also notes that discordant iron-rich dunites occur on Groenfontein 138, Pilanesberg area, near the Middle Group of chromitite layers, and that elsewhere in the Western Transvaal, these bodies seem to favour the top of the Critical Zone near the Merensky 'Reef' in undisturbed areas.

The relationship between chromitite and underlying magnetitite pegmatoids was particularly studied at the Merensky 'Reef' elevation. Reflectivity and unit-cell measurements of opaque minerals were done across the chromitite-magnetitite pegmatoid contact. The reflectivity of chromite changes progressively from the top of the chromitite layer where the cumulate textures in chromite are in evidence, to a point below the contact zone, between lines in figure 11, where values become constant. At this point cumulate textures are almost non-existent. Unit-cell measurements show very little difference from chromite to magnetite.

Cameron and Desborough describe similar results (1964, pp.211 - 212) and conclude that reflectivity, hardness and unit-cell measurements are not fully satisfactory as a guide to changes in composition of chromite. Cousins and Feringa (1964) have shown that chromitite layers found near ultramafic pegmatoids show abnormally high Fe/Cr ratios (Table 14).

FIG. 11. Plots of reflectivities and unit-cell measurements of opaque minerals across a chromitite, magnetitite pegmatoid contact.

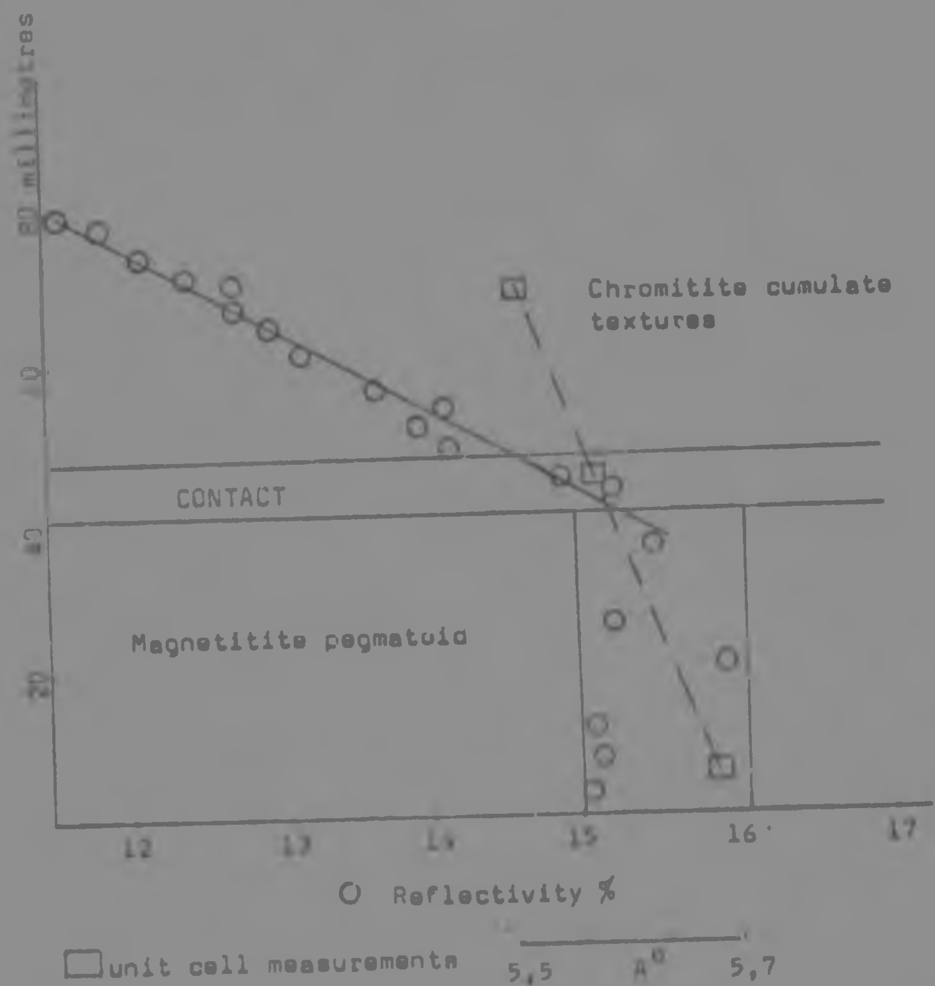


Table 14. Variation of the Cr/Fe ratio in the chromitite cumulates from the Critical Zone, compared to chromitites that have been effected by ultramafic pegmatoids occurring at the same height. Modified after Cousins and Feringa, 1964.

Affected iron-rich 'abnormal' chromitites Cr/Fe	Layered Chromitites	
	Cr/Fe	Position in the sequence
0,11	1,38	UG 2
	1,32	UG 1
	1,43	MG 4 (upper)
0,51	1,43	MG 4 (lower)
0,77	1,46	MG 3
0,22	1,66	MG 2
	1,45	MG 1

vi. Feldspathic pegmatoids. - Some ultramafic pegmatoids show the development of pegmatitic feldspathic-rich phases, often at the contacts with layered rocks. However transgressive feldspathic pegmatoids with no exposed connection with ultramafic pegmatoids have also been found.

In the 5 Shaft area, in 284 West Stope, a 3m thick feldspathic pegmatoid body transgresses the Merensky 'Reef', forming monomineralic margins of pegmatitic feldspar when in contact wi'.; the layered rock. This body is olivine- and clinopyroxene-bearing and occasionally shows the development of amphibole megacrysts, and on the whole it has a different mineralogy to the ultramafic pegmatoid in that almost 50 per cent by volume is composed of plagioclase feldspar. Portions of Merensky 'Reef' are also surrounded by feldspar mantles in the middle of the transgressive pegmatitic feldspar body (Photo 21). It is notable that the transgressive feldspathic pegmatoid is seen to grade laterally into an anorthosite cumulate, which in turn transgresses the layered rocks. The feldspathic pegmatoid is restricted to the transgressing 'mottled' anorthosite cumulate, and does not develop in the noritic cumulate (which forms the footwall of the Merensky 'Reef') nor in the Me.ensky 'Reef' itself. The nearest ultramafic pegmatoid intersected is 50m distant from this exposure but the relationships between both bodies if any are not known.

b. Form of the ultramafic pegmatoid bodies.

Transgressive ultramafic pegmatoids tend to be irregular and pipe-shaped. Ultramafic pegmatoids narrow where the layered rock is composed of noritic or pyroxenitic cumulates, and enlarge in anorthositic cumulates, with the result that locally they are mushroom shaped. Nearly always ultramafic pegmatoids which exhibited conformable relationships for distances of 30m or more, could be traced to places in which they transgress the layered rock. Tunnelling under ultramafic pegmatoid outcrops of known areal extent, intersected smaller ultramafic pegmatoid bodies than at surface. This seems to establish the possibility of alternative thickening and thinning of ultramafic pegmatoids.

c. The development of ultramafic pegmatoids in the different layered rock types.

From outcrop exposures it is evident that ultramafic pegmatoids occupy approximately 90 hectares, or 0,84 per cent of the total area of the Bafokeng Mining Lease.

Underground 20 raises were studied, all of them in the 5 Shaft area; the results of this study showed that ultramafic pegmatoid occupy 11,9 per cent by volume of the area with feldspathic portions occupying a further 1,1 per cent. Based on 24 surface boreholes an estimate (Appendix I) of the various rock types which act as hosts for ultramafic pegmatoids from 25m below the Merensky 'Reef' to 43m above it, is as follows:

- Plagioclase cumulates	60,9 per cent
- Plagioclase-orthopyroxene cumulates	21,7 per cent
- Orthopyroxene-plagioclase cumulates	10,9 per cent
- Orthopyroxene-chromite cumulates	6,5 per cent.

The preferential tendency for ultramafic pegmatoids to occur in plagioclase cumulates is confirmed in underground and surface exposures of the 5 Shaft area. Fourie (1959) in his map of the chromitite deposits near Rustenburg shows five hortonolite dunite outcrops in layered anorthosite, on the farm Doornspruit 106 (5 Shaft area). The relationship between ultramafic pegmatoids and layered rocks can be studied in figure 12.

In figure 12 the plagioclase cumulate indicated with the number 1, is the same cumulate, which forms a continuous layer below the Merensky 'Reef'. In 262 raise (Fig. 12, section A) an ultramafic pegmatoid locally transgresses the Merensky 'Reef', but it is mainly emplaced conformably down-dip at the expense of a plagioclase cumulate. In section B, the same ultramafic pegmatoid transgresses the plagioclase orthopyroxene layers and is conformably emplaced immediately below the Merensky 'Reef'. In figure 12, section C, the tendency to be emplaced conformably below the Merensky 'Reef' and at the expense of the plagioclase layer is further displayed.

When ultramafic pegmatoids develop conformably at the expense of the plagioclase layer depicted in figure 12, they do so for distances up to 30m. In these instances the plagioclse-orthopyroxene layers, above and below are completely unaffected by the ultramafic pegmatoid.

Figure 13 shows the distribution of ultramafic pegmatoid bodies in some of the studied boreholes as compared to one borehole undisturbed by ultramafic pegmatoid (Bh I.B.). The correlation of the boreholes shown in figure 13, was done on the bottom contact of the B.M.R. and can be considered accurate since this layer is normally

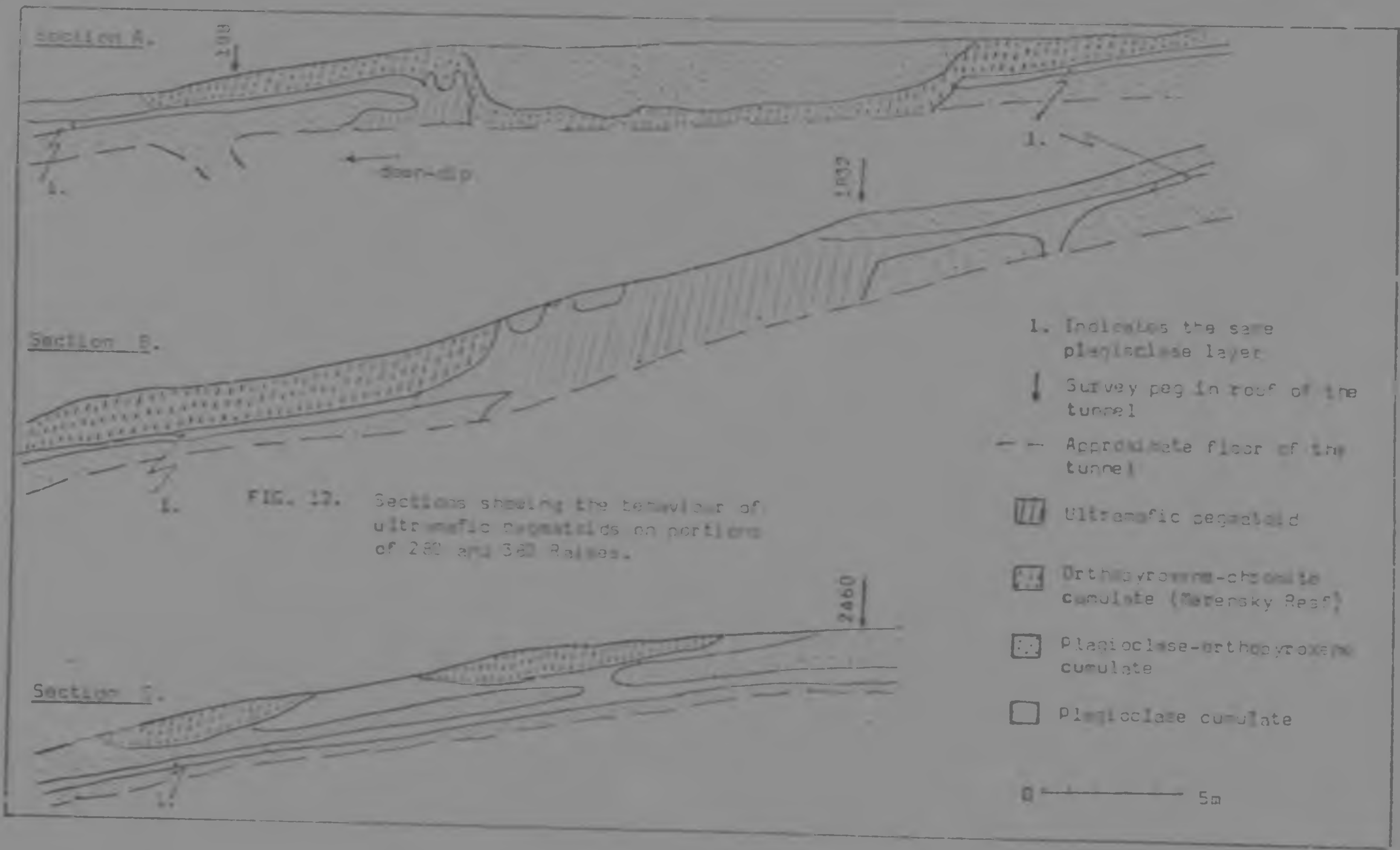
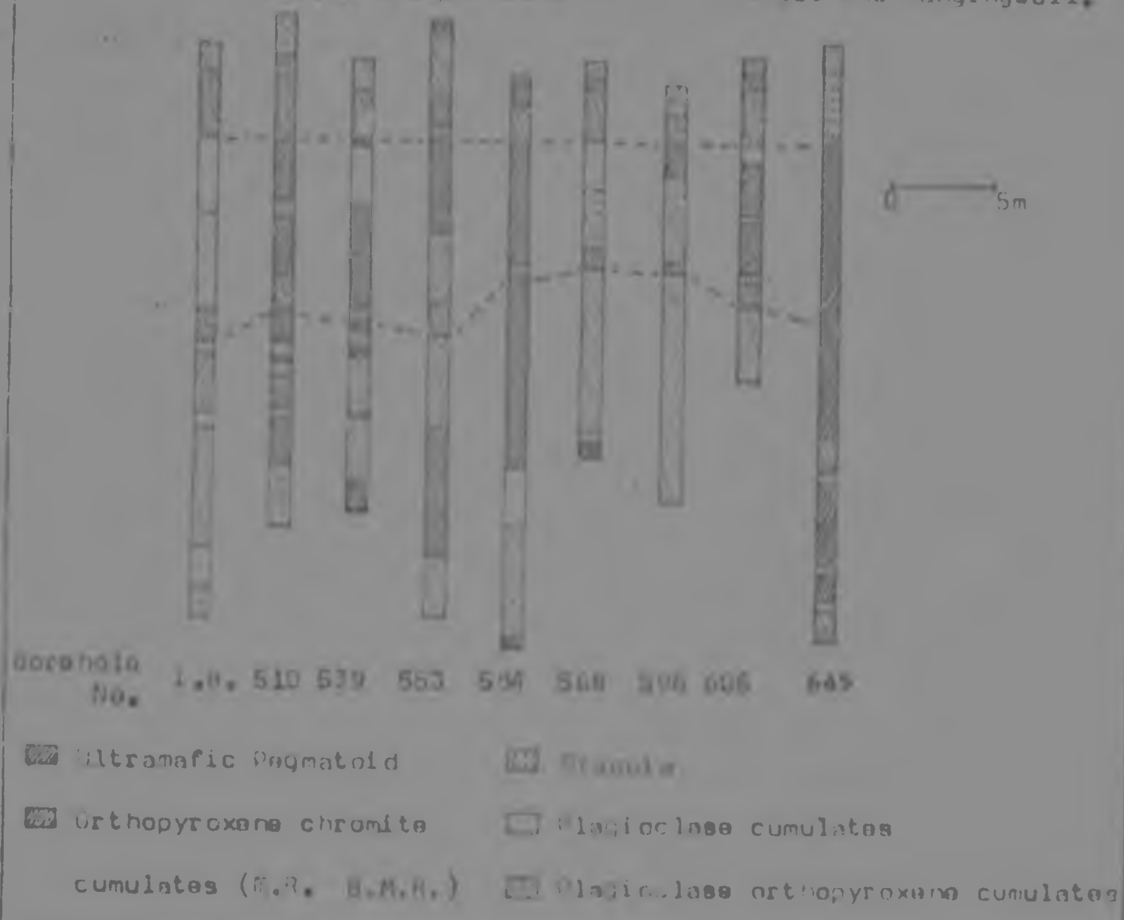


FIG. 12. Sections showing the behaviour of ultramafic pegmatoids on portions of 280 and 360 Raises.

FIG. 13. - Sections of borehole core showing occurrence of ultramafic pegmatoids within the Merensky 'Reef' M.R.U. and portions of its footwall and hangingwall.



very constant and varies in thickness between 2,2 and 3,1 metres. Variation in thickness of the B.M.R. like the one in borehole 553 are presumably due to the effect of ultramafic pegmatoids.

Comparisons between sections containing ultramafic pegmatoids and sections barren of these bodies (in I.B., Fig. 13) indicate that when ultramafic pegmatoids occur below the Merensky 'Reef' M.R.U., it is mostly at the expense of plagioclase cumulates.

Within the Merensky 'Reef' M.R.U. ultramafic pegmatoids develop both at the expense of plagioclase cumulates and plagioclase orthopyroxene cumulates, but the pyroxenitic portion remains mostly unaffected by them. Boreholes 510, 539, 553, 584, 596, 606 and 645 show extreme development of ultramafic pegmatoids in the anorthositic and noritic portions of the Merensky 'Reef' M.R.U., whereas the pyroxenitic portion and the overlying B.M.R. are virtually undisturbed.

In borehole 606 two widths of anorthosite showing effects of 'bleaching', fracturing and brecciation were intersected, marginally to an ultramafic pegmatoid, above the Merensky 'Reef'.

In borehole 639 ultramafic pegmatoid was intersected continuously from above the expected position of the B.M.R. to below the expected position of the Merensky 'Reef' both of these layers being absent. As this borehole could not be correlated it is not shown in figure 13.

When ultramafic pegmatoids develop above the Merensky 'Reef' M.R.U., the B.M.R. remains unaffected, e.g. boreholes 584, 588 and 606. On account of the diminished thickness of the B.M.R. in borehole 553, it is thought that the ultramafic pegmatoid intersected immediately above it could have formed partially at the expense of this layer.

d. Relationship of ultramafic pegmatoids with depressions. -

At the Bafokeng Mine two areas were selected to study a possible connection between ultramafic pegmatoids and depressions in the Merensky 'Reef'. The following observations were made. In the 5 Shaft area, 16 ultramafic pegmatoids conformably underlie areas where there are no depressions in the Merensky 'Reef'; two occurrences were found transgressing depressions approximately 3m deep, and three transgressing deeper seated depressions 10m ($\pm$). Two occurrences were found to conformably underlie small areas of undisturbed 'Reef' between depressions which are themselves free of ultramafic pegmatoids. Of the five exposures in which ultramafic pegmatoids were found transgressing depressions, two occur near the edge.

In the No. 1 Shaft area, the occurrence of ultramafic pegmatoid bodies is confined to three stopes in which these bodies transgress both areas where the Merensky 'Reef' is affected by depressions and undisturbed areas.

e. The relationship of ultramafic pegmatoids to joints and faulting.

In Rustenburg the joint systems have been described by Schmidt (1952, pp.236-7). At Bafokeng, in the 1 Shaft area, the direction of the main joint system strikes E-W approximately parallel to the strike of the Merensky 'Reef'. Joints are often occupied by ultramafic pegmatoids. This can be seen in Photo 22, where an ultramafic pegmatoid which occupies the place of an anorthositic layer can be seen filling a joint and expanding above it. Jointing often delimits one side of the ultramafic pegmatoid bodies when they transgress the layering.

Shearing which affects both ultramafic pegmatoids and layered rock occurs in several localities. In others neither shearing nor faulting is found in the vicinity of ultramafic pegmatoids. According to Coertze (1960) a zone of shear extends from SE of the Pilanesberg alkaline Complex to approximately the northwestern portion of the Bafokeng Lease area. In addition to shearing this zone is also characterized by the presence of:

- ultramafic pegmatoids;
- granitic pegmatites;
- dykes of Pilanesberg age.

According to Coertze (Ibid) the shear zone occurs mostly in anorthositic rock. This author suggests that ultramafic pegmatoids and granitic pegmatites were emplaced along shears, and that the anorthositic rock is a result of the heating and re-injecting of the layered rock. Outcrop exposures and all surface boreholes on the northern boundary of the Bafokeng Lease area were examined to test these observations. It was found that:

A [illegible] trending zone of sheared country rock occurs on the northern boundary of the Bafokeng Lease area (Fig. 10). Zones of intense shearing are intersected in most of the surface boreholes drilled in the vicinity of the shear zone.

All surface boreholes drilled on the northern boundary of the mine have intersected ultramafic pegmatoids; in some of them, i.e. borehole 50[illegible], 51[illegible] and 518 ultramafic pegmatoid is the predominant rock type throughout.

Within and outside the shear zone shown in Figure 10, steeply dipping granitic pegmatites form linear features, which strike NW, and transgresses both the layered rock and ultramafic pegmatoids.

Dykes of Pilanesberg age are of sparse occurrence and strike NW. The area on the northern boundaries of the Bafokeng Lease area has the characteristics observed by Coertze (Ibid).

The relationship of ultramafic pegmatoid and shears is made debatable by the fact that ultramafic pegmatoid bodies are almost unaffected by shearing in some boreholes, i.e. 506, whereas in others, i.e. 510, shearing which post-dates the emplacement of ultramafic pegmatoids has taken place.

At about 750 m above the Merensky 'Reef' several anorthosite cumulates could be correlated from borehole 506 to 520, 675 and 691 but are not present in borehole 510 which intersected ultramafic pegmatoid at this depth. In some of these boreholes several anorthosite cumulates occur below this depth (750m) and cannot be correlated from one borehole to another. No indication could be found that these anorthosite bodies were transgressive to the layered rocks.

Faults older than ultramafic pegmatoids have not been found at Bafokeng. The fault exposed in 2 West Drive, 5 Shaft, displaces an ultramafic pegmatoid, and is the single exposure in which displacement may be observed.

NW-SE trending, 0,5 to 1m thick micaceous carbonatites, which often occupy fault zones, transgress ultramafic pegmatoids.

3. Mineralogy

a. Plagioclase. - Within ultramafic pegmatoids plagioclase crystals of 50mm are not uncommon. Plagioclase is usually evenly distributed throughout the mass of ultramafic pegmatoid, forming 'pockets' which contrast with the dark colour of the rock.

Plagioclase are the first crystals to form in ultramafic pegmatoids, being replaced and fractured by clinopyroxene, oxides and olivines.

The following textures were found in plagioclase contained within ultramafic bodies and in contacts with layered rock:

- fracturing, Photo 23. Schwellnus (1956, p.128) noted that in peridotite pipes plagioclase is traversed by irregular cracks which are indicative of forcible disruption.
- bending of twin planes (Photo 23) and patchy extinction of plagioclase,
- alteration to penninite,
- interpenetration twinning (Photo 24) and irregular outlines between plagioclase crystals (Photo 25),
- granulation of plagioclase especially along zones of interpenetration twinning. (Photo 26).

Granulation also occurs along initial fractures and in the outer margins of plagioclase crystals. In the first case, a worm-like aggregate of small crystals, (Photo 27), occurs in pegmatitic plagioclase.

- small amounts of glide twinning especially in contacts with anorthositic country rock in which the lamellae pinch out in a concerted fashion (Photos 23 and 27)

Alteration products, especially chlorites, usually have a rosettely -

form habit and show characteristic anomalous blue interference colours. Occasionally the alteration takes the form of dark-brown staining, mantling magnetite.

Comparisons between plagioclases in the layered rock and plagioclases in ultramafic pegmatoid at the same elevation have been made by Coertze (1966, pp.40-41), Cameron and Desborough (1964, p.222) and Ferguson and McCarthy (1969, pp.76-78). Coertze (Ibid, p.40) quoting Van Zyl (1960, pp.66-70), describes a wehrlitic pegmatite part of "the ferrogabbro unit " (Upper Zone) in which the An content of plagioclase is 75 per cent, as compared to 48 to 50 per cent of plagioclase in the ferrogabbro. Coertze (1966) mentions that in the Western Transvaal plagioclase within an intrusive magnetite bearing mottled anorthosite, has 11 to 16 per cent more An than the plagioclase in the surrounding country rock. According to the same author (1966), An enrichment in plagioclase contained in ultramafic pegmatoids with respect to those contained in the juxtaposed layered rock, is also found in ultramafic pegmatoid pipes of the Leolo mountains. Cameron and Desborough (op.cit.) similarly show enrichment in the anorthite component in plagioclase from ultramafic pegmatoid as compared to plagioclase of the host rocks. Ferguson and McCarthy (1969), found that plagioclase in a transgressive ultramafic pegmatoid contained in mottled anorthosite, is ± 5 per cent richer in the An component than the co-existing plagioclase in the mottled anorthosite.

At Bafokeng comparisons between pegmatitic plagioclase within ultramafic pegmatoids and plagioclase from the layered rocks were done by four methods (Appendix I), and are shown in Table 11. Full chemical analysis gave approximately 4 per cent difference in the anorthite content of the plagioclase from the layered rock (An 79±) and that from the ultramafic pegmatoid (An 83±). The full analysis of PL2 and 180 are presented in Table 15. Analysis 180 is that of plagioclase within the a.c.n. and analysis PL2 is that of plagioclase within an ultramafic pegmatoid at the same height. The recalculation of Na, Ca and K to weight per cent in the respective albite anorthite and orthoclase molecules are also shown in Table 15. Differences between analysis 180 and PL2 are very slight but significant. Perhaps the main difference is given by the alkali content which has diminished from 180 to PL2 by fifty per cent of the total K_2O and fourteen per cent of the total Na_2O.

Comparisons are also made on the basis of 100 oxygens per unit

TABLE 15. Analysis of plagioclase [illegible] the a[illegible] 180), from an ultramafic pegmatoid (PL 2), and cat[illegible]contents on the basis of 100 oxygens.

	SPECIMEN No.	
	180	PL 2
SiO_2	46,50	47,27
TiO_2	0,03	0,02
Al_2O_3	33,17	33,01
Fe_2O_3	0,02	0,08
FeO	0,29	0,43
MnO	-	0,02
MgO	0,35	0,60
CaO	16,29	16,30
Na_2O	2,25	1,83
K_2O	0,44	0,21
P_2O_5	0,17	0,16
H_2O+	0,94	0,72
H_2O-	0,08	0,07
Total	100,53	100,73 weight per cent
CATIONIC CONTENT		
Si	26,4	26,9
Ti	0,01	0,005
Al	22,1	22,13
Fe_3	-	0,02
Fe_2	-	-
Mg	0,3	0,5
Ca	10,0	10,0
Na	2,44	2,04
K	0,2	0,06
P	0,08	0,07
H+	3,54	2,72
Total	65,17	64,445
Per cent		
Albite	18,62	15,88
Anorthite	78,83	82,89
Orthoclase	2,55	1,23

J. P. Jones Analyst.

cell, in this case we can see that both analyses have about the same silica, alumina and calcium contents. In this case the main differences are in the Na+ and K+ contents. Na+ has diminished nineteen per cent, and K+ seventy per cent, from analysis 180 to analysis PL2.

Results obtained by X-ray fluorescence, Na peak (Appendix I), show Table 16, that pegmatitic plagioclase within ultramafic pegmatoid bodies always contain a higher An content than the plagioclase in the layered rock in which the ultramafic pegmatoid is contained.

Plagioclase in transitional contacts show a tendency to approach the composition of plagioclase within the ultramafic pegmatoids rather than that of the layer in which they are contained (Table 16).

Data obtained by optical methods, (Appendix I), showed that when ultramafic pegmatoids are emplaced in the a.c.n., there is a difference of - 4 per cent An, between the plagioclase in the ultramafic pegmatoid which analyses An 60-82, and that of the a.c.n. at An 76 (Table 11).

Comparisons were attempted, using X-ray spectrography, but results were not satisfactory, (Appendix I). When results could be obtained, the composition of the feldspars within the ultramafic pegmatoids showed higher values than those of the country rock. This was the case of a sample from borehole 553 at a depth of 181m, which yielded a value of 80 per cent An, which is 6 per cent higher than the value obtained, by the same method, for plagioclase in anorthosite cumulates at the same elevation (Fig. 4).

Table 16. Variations in the An content of plagioclase across three different ultramafic pegmatoids, in transitional contacts and in the host layered rock (X-ray fluorescence method).

Rock Type	Plagioclase in the host layered rock	Plagioclase in the transitional contact	Plagioclase in ultramafic pegmatoid
	AN CONTENT		
a.c.n. (bottom)	80-81	-	85-85
noritic cumulates	80-81	89	90-90-90-92
a.c.n. (top)	77	87	89-90-90

Each An value represents 1 analysis.

b. Clinopyroxenes. - Ultramafic pegmatoids which develop in anorthositic cumulates show a tendency to contain more clinopyroxene than ultramafic pegmatoids developed in pyroxenitic cumulates. In ultramafic pegmatoids, olivine and oxides develop at the expense of clinopyroxene but clinopyroxenes always form later and at the expense of plagioclases.

Within ultramafic pegmatoids clinopyroxenes show interpenetration relationships (Photos 28 and 29), and occasionally when they come into contact with one another, narrow zones of decoloration develop. Clinopyroxenes in ultramafic pegmatoids show cleavages parallel to 100, characteristic of diallage. Some clinopyroxenes show the development of broad twin lamellae.

The formation of clinopyroxene at the expense of olivine as reported by Cameron and Desborough (1964, p.209), was not found at Bafokeng, where olivine usually forms after clinopyroxene. In dunitic pegmatoids clinopyroxene is sometimes interstitial to olivine.

At Bafokeng, clinopyroxene compositions in ultramafic pegmatoids, were studied in boreholes 553, 510 and in several underground exposures. Variations in 2V from 48-52^{o} and $n\beta$ from 1,675 to 1,699 (Appendix I), place the majority of the clinopyroxenes in the field of augite; however a minority plot in the endiopside field. Other data for clinopyroxenes in ultramafic pegmatoids is restricted to that presented by De Bruyn (1944). He gave the following compositions for the clinopyroxenes at Middellaagte (W.Bushveld): diopside-hedenbergite (2V = 60), and salite 2V (61).

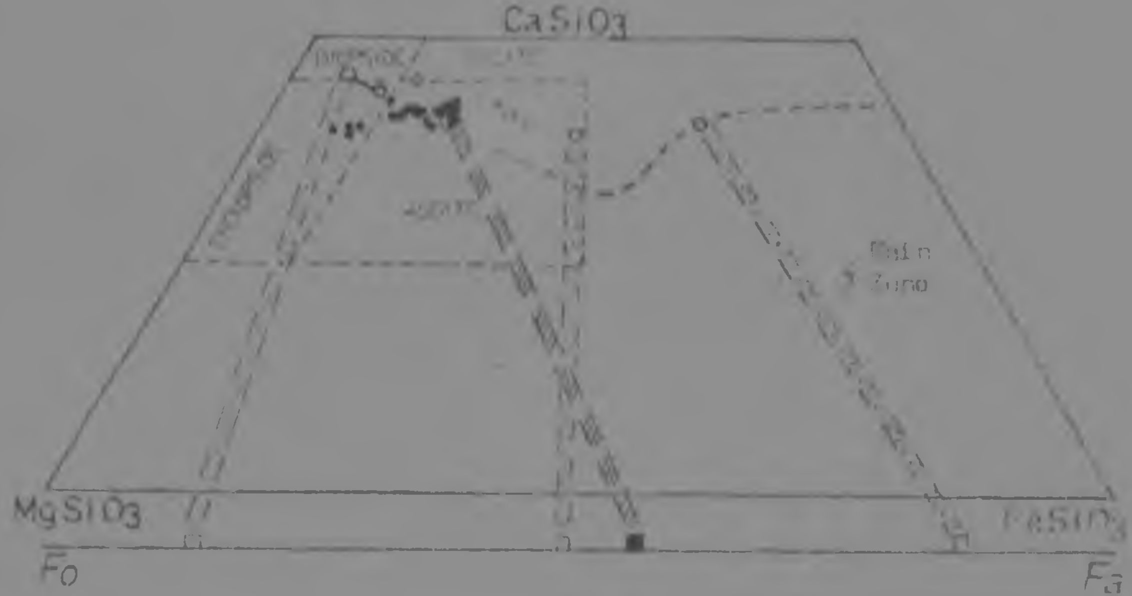
A chemical analysis of a pegmatitic clinopyroxene developed within the layered rock at the contact with an ultramafic pegmatoid in 3 Cross-cut North, 5 Shaft, was carried out (Table 17). Ca, Mg and Fe were re-calculated to weight per cent of the wollastonite, enstatite and ferrosilite molecules (Table 17) with the result that the analysis plots on the augite field, at the same place where the highest concentration of compositions from optical data was obtained (Fig. 14).

Olivines and clinopyroxenes co-existing in an ultramafic pegmatoid intersected by borehole 510 show the following values in weight per cent:

Ol: 44 Fo; Cpx: Ca 42 Mg 42 Fe 16.

In figure 14 clinopyroxenes in ultramafic pegmatoids are plotted against the trend of the Bushveld clinopyroxenes obtained from Atkins (1969), and a tie-line of co-existing clinopyroxene-olivine from ultramafic pegmatoids is plotted against tie-lines from the layered rocks. The clinopyroxene-olivine tie-lines from the layered rocks were obtained using data from Atkins (1969), and Wager and Brown (1968).

FIG. 14. Clinopyroxene composition and clinopyroxene-olivine tie-lines in layered rocks and ultramafic pegmatoids.



▭ Olivine composition in the layered rocks

○ Clinopyroxene composition in the layered rocks

■ Olivine composition in ultramafic pegmatoids

● Clinopyroxene composition in ultramafic pegmatoids

○ ▭ Clinopyroxene-olivine tie-line (layered sequence) data from Atkins ([illegible]) and Wager and Brown (1968)

● ■ Clinopyroxene-olivine tie-line (ultramafic pegmatoid, Bafokeng)

Trend of the Bushveld clinopyroxenes after Atkins ([illegible])

From Figure 14 several facts could be established, these are:

- the majority of the clinopyroxenes from ultramafic pegmatoids show the following composition: Ca 42, Mg 42, Fe 16,
- clinopyroxenes in ultramafic pegmatoids are enriched in Fe with respect to both cumulus and intercumulus pyroxenes at the top of the Critical and bottom of the Main Zone, which plot on the top left corner of figure 14,
- the average Fe content of clinopyroxene in ultramafic pegmatoids is intermediate between samples 7 and 8 of Atkins (1969, pp.230-231), which came from the Upper Zone,
- a clinopyroxene-olivine tie-line from an ultramafic pegmatoid shows a parallelism with a clinopyroxene-olivine tie-line from the layered rocks in the Main Zone.

Table 17. Analysis of clinopyroxene and cationic content on the basis of 100 oxygens.

	Weight per cent	100 0
SiO_2	57,14	31,0
Al_2O_3	2,89	2,0
Fe_2O_3	0,98	0,4
FeO	7,27	3,7
MgO	16,0	14,6
CaO	19,32	12,6
Na_2O	0,18	0,2
K_2O	-	-
Ti_2O_2	0,36	0,2
MnO_2	0,20	0,1
P_2O_5	0,20	0,1
H_2O-	0,10	-
H_2O+	1,31	5,3
Total	99,95	70,2
Rb	14 p.p.m.	
Sr	33 p.p.m.	
Rb/Sr	0,13	
$CaSiO_3$	42,2[illegible] per cent	Analyst:
$MgSiO_3$	41,99 per cent	J.P. Jones.
$FeSiO_3$	15,77 per cent	

c. Olivines. - In ultramafic pegmatoids at Bafokeng, olivine grows at the expense of pegmatitic plagioclase and clinopyroxene. Olivine often envelopes and isolates these minerals, and generally when included by them, the growth of the olivine crystal produces fractures in its host. Often olivines are interconnected by fractures between themselves across a single clinopyroxene crystal. Some of these fractures are intermittently filled by olivine. The deposition of oxides along cracks in olivine at the interface olivine-clinopyroxene is abundant. Olivine, in turn is fractured and enveloped by the growth of oxides which post-date the crystallization of the silicate phase.

In dunitic portions of ultramafic pegmatoids, some olivines show undulating patchy extinction (Photo 30). The inter-relationship between olivines in dunitic pegmatoids is variable. In places there is a tendency to subhedrality in olivine crystals, which co-exist with others showing highly irregular outlines. Olivine composition in ultramafic pegmatoids has been studied by several authors - i.e. Lombaard (1956), Schwellnus (1956). At the Onverwacht and Mooihoek pipes, Eastern Transvaal, Cameron and Desborough (op.cit.) found that olivine composition varies from Fo 33 to Fo 58 when the ultramafic pegmatoids occur in rocks of anorthositic and noritic compositions. At Onverwacht they also found that where the "replaced rocks were Mg-rich pyroxenites", the Fo content of olivine is 80-84 in the core of the pipe and Fo 88-92 on the margin. Coertze (1969) has compared the olivine in the upper part of the ferrogabbro (Main Zone) with that of dunitic pegmatoid pipes which occur in the Main Zone, and found that both are of the iron-rich variety hortonolite (Fo 50-40). At Bafokeng, olivine composition was studied in boreholes 553, 510, 606 and several underground exposures. The olivine in borehole 553 shows variable compositions from Fo 49 at 140m, increases to Fo 71 at 238m, and then decreases again to Fo 48 at 311m (Table 18). The olivine which gave the highest Fo content was contained in an ultramafic pegmatoid which has a troctolitic composition. Below this sample dunitic pegmatoids showing high degrees of serpentinization analysed Fo 63.

Olivine composition in borehole 510 shows very little variation from 35m to 850m (Fo 42 to 44). The olivine analysed between these depths comes from ultramafic pegmatoids where diallage is predominant. The layered rock during this interval is a gabbroic cumulate. The sample analysed at 850m comes from a portion where the layered rock is anorthositic. At the contact with the Merensky 'Reef', olivines in fine-grained ultramafic phases are separated from the cumulus orthopyroxene by continuous margins of hornblende and have a composition of Fo 73, which is 23% richer in the Fo component than the olivine analysed from 35 to 850m. Approximately 2m in the footwall of the Merensky 'Reef', olivine within a diallage-rich ultramafic pegmatoid gave a composition of Fo 52 (Table 18).

Analysis of olivine samples taken within ultramafic pegmatoids when anorthositic cumulates act as host rocks for ultramafic pegmatoids are shown in Table 19.

TABLE 18. Olivine composition in ultramafic pegmatoids intersected by surface boreholes 553 and 510.

BOREHOLE 553.

DEPTH	Fo Content Yoder-Sahama method (1957)	Fo Content Jambor-Smith method (1964)
140m	49	
156m	57	55
181m	57	-
238m	71	72
245m	63	-
275m	57	-
311m	48	-

BOREHOLE 510

DEPTH	Fo Content Yoder-Sahama Method (1964)
35m	42
512m	44
640m	44
850m	44
858m	73+
860m	52

\+ denotes fine-grained phase

Borehole 553 - Merensky 'Reef' at 303m

Borehole 510 - Merensky 'Reef' at 858m

TABLE 19. Olivine composition in ultramafic pegmatoids contained in anorthositic layers.

Sample No.	Locality	Fo Content	Description of layered rock
26	5 Shaft - 2 W.Drive - 281 line	38	Anorthositic cumulate
81	1 Shaft 345 Stope upper portion	42	Anorthositic cumulate
24	3 Shaft 377 Stope	59	Anorthositic cumulate (above M.'Reef')
33	Vaalkop hortonolite dunite pipe	34-35	-

i. Olivines within the Merensky 'Reef' in the vicinity of contacts with ultramafic pegmatoids.

The development of olivine within the Merensky 'Reef' when ultramafic pegmatoids are in contact with this layer was studied in 345 Stope and 3 W.Drive 1 Shaft, in 287 Stope and in borehole 606. Figure 15 shows 345 Stope and 3 W.Drive, 1 Shaft. West of the centre-gully line of 345 Stope, the footwall haulage intersected several transgressive ultramafic pegmatoid portions which form part of the same ultramafic pegmatoid intersected in 345 Stope (Fig. 15, Plan). Approximately 25m before the end of 3 West Drive, the Merensky 'Reef' plunges into a depression which was exposed by the haulage and is transgressed and over- and underlain by ultramafic pegmatoid (Fig. 15, section C). On the western portion of 345 Stope the same ultramafic body develops extensively below and also within the Merensky 'Reef' (Fig. 15, Sections A and B). In Section C the portion of Merensky 'Reef' contains olivine where it is exposed by the southern sidewall and where it is surrounded in the two exposed directions by ultramafic pegmatoid. In 287 Stope and borehole 606 ultramafic pegmatoids underlie the Merensky 'Reef'.

In the three examples studied, when ultramafic pegmatoids either surround or underlie the Merensky 'Reef', olivine is present within the Merensky 'Reef' at distances which vary between 0,1 and 2,0m from the ultramafic pegmatoid. Within this distance olivine occurs as follows:

- anhedral crystals enveloping or partially surrounding both cumulus orthopyroxene and intercumulus plagioclase,
- at the expense of orthopyroxene in a single cumulus grain, of which half is orthopyroxene and half olivine (Photo 31),
- included in interstitial feldspar. These olivines show 0,1mm appendixes protruding into the feldspar. Olivines included in feldspar occasionally show 0,2mm margins of orthopyroxene (Photo 32)
- included in orthopyroxene cumulus. Some of these olivines show subhedral to almost euhedral outlines. Brown staining probably produced by iron oxides was observed between the included olivine and the orthopyroxene. Fractures radiating from the included olivine into the orthopyroxene were also observed.

Usually olivines included in orthopyroxene or replacing orthopyroxene are the occurrences found farthest away from the contact with the ultramafic pegmatoid.

Olivine composition in 3 W.Drive 1 Shaft (Fig. 15, Section C southern sidewall) shows zonation. The composition of olivine in the ultramafic pegmatoid below the Merensky 'Reef' is Fo 38, within the Merensky 'Reef' Fo 82-85, and from 0,3 to 0,4m above it, where no cumulate textures are preserved Fo 71 to 48.

Olivines from fine-grained ultramafic phases found along sections A and B (Fig. 15) when ultramafic pogmatoids are in contact with the Merensky 'Reef' were analysed , giving a composition of Fo 57-58 (Table 20).

Differences in Fo content of olivine in fine-grained ultramafic phases and those included in the overlying Merensky 'Reef' were also found in 287 Raise, 5 Shaft. The olivine in fine-grained phases analysed Fo 56 and the olivine included in orthopyroxene Fo 79 (Table 20).

Variations in the Fo content of olivine were also found in borehole 606, from Fo 78-79 in a troctolitic pegmatoid underlying the Merensky 'Reef', to Fo 76-77 in olivines enclosing chromite cumulus, to olivine 68 within the overlying Merensky 'Reef' (Table 20).

d. Orthopyroxenes. - At the Merensky 'Reef' elevation orthopyroxene are often included by ultramafic pegmatoid. The occurrence of orthopyroxene grains in ultramafic pegmatoids away from the Merensky 'Reef' was observed only once in borehole 553, and several times in borehole 510. These crystals are always isolated and show signs of resorption to olivine and clinopyroxene. They may be included in clinopyroxene crystals in which case they are fractured perpendicularly to the clinopyroxene cleavages. Orthopyroxene may also be intermittently surrounded by hornblende. Olivine forms at the expense of these orthopyroxene relics, embaying and fracturing them. Compositional comparisons between these orthopyroxenes and those of the layered rocks at approximately the same elevation showed that both have the same En content (Table 21).

In 345 Stope, (Fig. 15, Section B), again orthopyroxene within an ultramafic pegmatoid showed resorbed edges to olivine and clinopyroxene. Four 2V readings could be obtained on orthopyroxene within the ultramafic pegmatoids in the places marked X, Y and Z in Fig. 15, Section B. The En contents of these pyroxenes En 76, 70 and 74 respectively. show the same variation as those contained in the adjoining Merensky 'Reef', plagioclase cumulate and plagioclase-orthopyroxene cumulate respectively.

TABLE 20. Variations in the Fo content of olivine when ultramafic pegmatoids occur in proximity of the Merensky 'Reef'

SAMPLE	LOCALITY	Fo content	Predominant minerals in the rock	From
204	1 Shaft,	48	olivine-cpx-oxides	0,3m above 205) ultramafic
205	3 West Drive	71	olivine-cpx-oxides	0,4m above 203) pegmatoid
202	" "	85	opx - very sparse olivine included in opx.	Merensky 'Reef'
203	" "	82-83	opx- (olivine included in opx)	Merensky 'Reef'
203	" "	82-83	opx- (olivine included in plagioclase)	Merensky 'Reef'
39	" "	38	olivine-cpx-oxides	ultramafic pegmatoid below the Merensky 'Reef'
56	345 Stope	57-58	fine-grained ultramafic phase	contact between ultramafic pegmatoid and Merensky 'Reef'
MR 1B	5 Shaft 287 Stope	79	olivine included in opx.	same place - overlying Merensky 'Reef'
MR 1A	5 Shaft 287 Stope	56-57	fine-grained ultramafic phase	contact between ultramafic pegmatoid and Merensky 'Reef'
277	Bh 606 - 2D	68	orthopyroxene-olivine	0,10m above 278) Merensky
278	Bh 606 - 2D	76-77	chromite-olivine	chromitite layer) 'Reef'
279	Bh 606 - 2D	78-79	olivine-plagioclase	troctolitic pegmatoid

FIG 15. Plan and sections showing behaviour of ultramafic pegmatoid in 345 stope and 33 Drive, 1 Shaft.

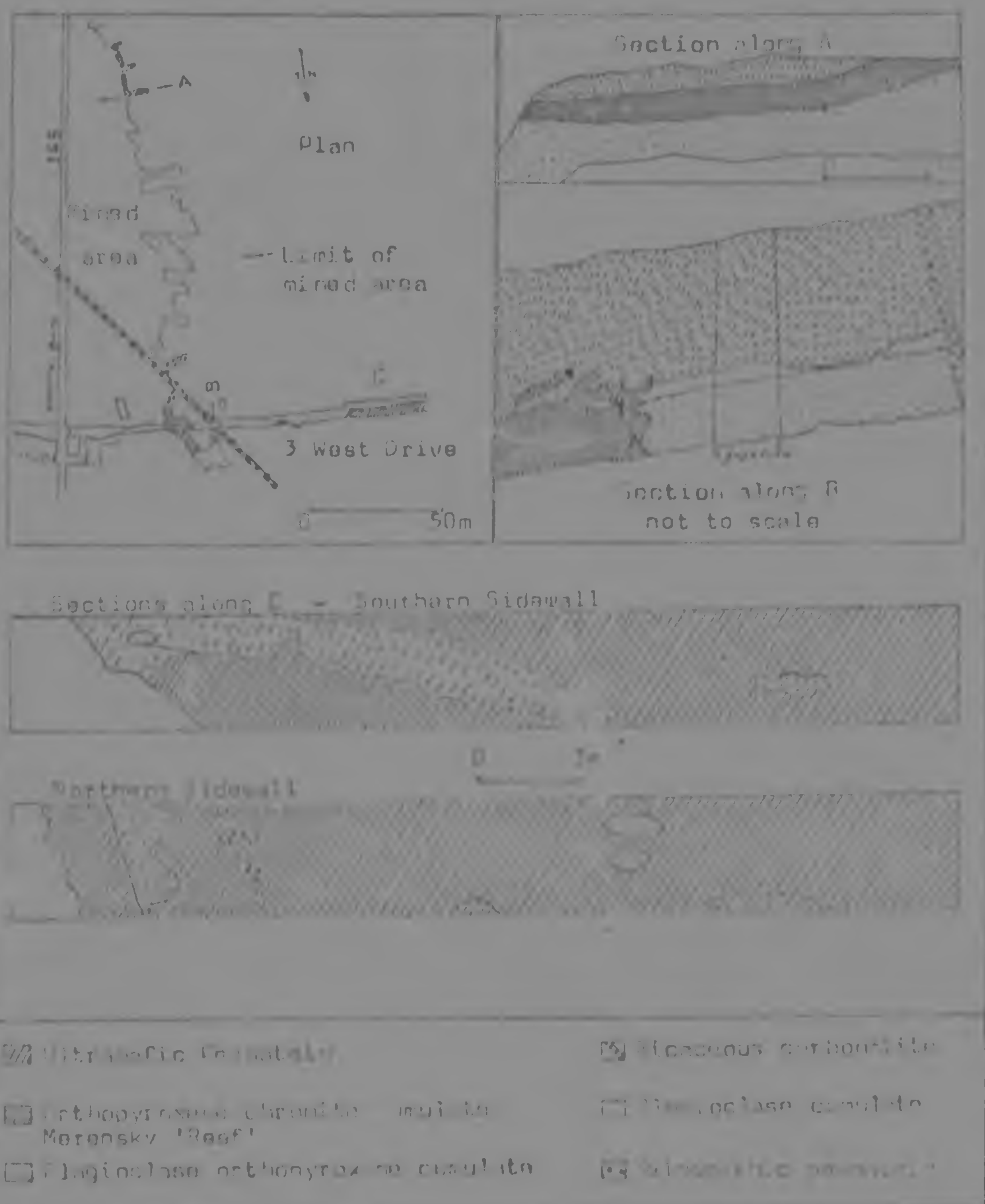


TABLE 21. Composition of orthopyroxenes found within ultramafic pegmatoids; and comparison with the orthopyroxene composition of the layered rocks at approximately the same height.

Bh No.	Depth above M.'Reef'	% En of Opx within U.P.	En of Opx (at approximately the same height in the layered rocks	
510	856m	68	834m	68
510	254m	72	255m	73
510	104m	73	114m	73
553	41m	71	-	-
510	1m	75	2m	75

M.'Reef' - Merensky 'Reef'

U.P. - Ultramafic pegmatoid

Opx - Orthopyroxene

e. Amphiboles and other silicate minerals. - Amphibole occurs widely in ultramafic pegmatoids. The amphibole is hornblende, and is normally found associated with olivine, oxides or clinopyroxenes. In ultramafic pegmatoids hornblende occurs as intermittent rims around oxides, and commonly forms at the expense of clinopyroxene, the latter controlling to a certain extent the crystallographic orientation of the former. Replacement occurs along cleavages, partings and also marginally. In ultramafic pegmatoids mica is sparsely distributed and is reported to be phlogopite (Willemse 1969a). Quartz was found together with ferrotschermakite in a contact between ultramafic pegmatoid and a tonalitic pegmatite. Furthermore one quartz crystal and biotite were found included in an ultramafic pegmatoid of the 5 Shaft area.

f. Oxides. - According to Deer et alii (1966, p.428) the magnetite minerals are composed of a continuous series in the spinel group. The oxide minerals found within the ultramafic pegmatoids belong to the magnetite series. "A considerable amount of Ti can enter the magnetite structure and there is a continuous relationship between magnetite and the ulvöspinel molecule Fe_2TiO_4." Deer et alii (Ibid, p.428) recommend that the term titanomagnetite be restricted to specimens where the presence of an ulvöspinel phase can be demonstrated.

Cameron and Desborough (1964, p.209) demonstrated the presence of fine ulvöspinel intergrowths in titanomagnetite pegmatoid phases of the Eastern Transvaal. At Bafokeng, magnetitite pegmatoids were studied mainly in the vicinity of the Merensky 'Reef', where they develop below chromitite layers. Magnetitite pegmatoids are composed essentially of a mineral which shows the following characteristics: a reflectivity between 15 and 16 per cent, a Vicker's hardness of 780-900 kg/cm^3, is light grey under polarized light, is anisotropic and has low birefringence. The reflectivity and birefringence are lower and much lower respectively, than those of ilmenite. The properties of this mineral as compared to those of ilmenite and magnetite are given in Table 22. The presence of ulvöspinel could not be demonstrated by X-ray techniques, therefore the term magnetite is retained for this mineral (Photo 33).

TABLE 22. Reflectivity and Vicker's microhardness of magnetite and ilmenite as compared with an oxide found within ultramafic pegmatoids at Bafokeng.

	Vicker's microhardness kg/cm^2	Reflectivity %
* Magnetite	480 - 740	20 - 21
* Ilmenite	520 - 730	17 - 22
Mineral at Bafokeng	780 - 900	15 - 16

* Data from McLeod and Chamberlain (1968).

Very thin lamellae of a highly anisotropic birefringent mineral, which could be hercynite, transects both magnetite and ilmenite in magnetitite pegmatoids.

Magnetite is predominant over ilmenite in both magnetitite pegmatoid bodies found below some chromitite layers and in interstitial late oxides within diallagite or olivine rich ultramafic pegmatoids. Locally, however, ilmenite rich phases may predominate (Photo 34).

Schwellnus and Willemse (1943, Plate V), have described "motheaten" patterns of titaniferous magnetite grading through magnetite into maghemite, from surface sampling of the magnetitite pegmatoid pipe found at Goedgedacht, Bafokeng Mine. Samples from underground exposures do not show these textures, which were presumably produced by oxidation.

Other textures within magnetitite pegmatoids, are those displayed by ilmenite in magnetite. Ilmenite occurs as:

- coarse exsolution lamellae ($\pm$ 8 mm),
- very thin ($\pm$ 1 mm) lamellae,
- individual grains,
- along partings in magnetite, and as coarse aggregates and rims in the limits of magnetite rich phases.

It is noticeable that exsolution of ilmenite from magnetite often takes place around sulphide grains.

Gangue bearing fractures some containing irregularly distributed oxides transect some magnetitite pegmatoids. Also within magnetitite pegmatoids skeletal blades of ilmenite are preserved in a mesh of ilmenite and silicate. The blades are evidently produced by exsolution of ilmenite in a mineral which is no longer present (Photo 35). Skeletal textures in magnetite are abundant when ultramafic pegmatoids are in contact with late granitic pegmatites, and are associated with intense amphibolization of the silicates within the ultramafic pegmatoid. Fractures filled by hematite cut through the magnetitite pegmatoids in some polished sections. When magnetitite pegmatoids come into contact with chromitite layers gradations in reflectivity and unit cell dimensions occur (Fig. 11). Within the chromitite layer where cumulate textures are preserved, the following textures were observed:

- veinlets of magnetitite transecting chromite cumulates,
- deposition of magnetite around the chromite crystals, from which veinlets of magnetitite transect the chromite (Photo 36).

g. Sulphides. - Volumetric studies of sulphides in ultramafic pegmatoids have been made by Liebenberg (1969, p.191). Van Rensburg (1962) studied the sulphides in the magnetitite pegmatoid at Kennedy's Vale, Eastern Transvaal and showed that the paragenetic sequence was pyrrhotite, pentlandite, chalcopyrite, cubanite. Stumpfl (1961) studied the sulphides present in a dunitic pegmatoid at Driekop using an electron microanalyser, and besides describing several new sulphides, found that platinum occurs as ferroplatinum.

When comparing the compositions of the sulphide phase of an ultramafic pegmatoid found at Middellaagte with that of the Merensky 'Reef' in the same locality (Table 23), it becomes apparent that:

- there is a decrease in the volume of pentlandite and chalcopyrite in the ultramafic pegmatoid,
- pyrrhotite is still the predominant sulphide by volume, but its volumetric proportions are higher in the ultramafic pegmatoid than

in the Merensky 'Reef',

- the presence of cubanite in the ultramafic pegmatoid suggests iron enrichment.

TABLE 23. Volumetric percentages of sulphides in the Merensky pegmatoid 'Reef' as compared with sulphides in ultramafic pegmatoids (after De Bruyn, 1944).

Sulphide	MIDDELLAAGTE (W. TVL)	
	Merensky Pegmatoid 'Reef' (De Bruyn, 1944)	Ultramafic pegmatoid (De Bruyn, 1944)
Pyrrhotite	45,1	85,6
Pentlandite	41,7	7,4
Chalcopyrite	16,1	1,1
Cubanite	-	5,8

In decreasing order of abundance the sulphides encountered in ultramafic pegmatoids at Bafokeng are: pyrrhotite, chalcopyrite, pentlandite, cubanite and pyrite. Liebenberg (op.cit.) reports also traces of mackinawite in these bodies and claims that sulphides found in the hortonolite dunites are dominantly pyrrhotite and cubanite, whereas the sulphides in the forsterite dunites of Onverwacht and Mooihoek contain mostly pentlandite. At Bafokeng either chalcopyrite or pentlandite may predominate over the other in different sections of an ultramafic pegmatoid. When these bodies occur in direct contact with the Merensky 'Reef' ~~larger~~ sulphides larger than usual develop within the ultramafic pegmatoid and pentlandite generally predominates over chalcopyrite.

At Bafokeng the distribution of sulphides in ultramafic pegmatoids varies from one body to the other; borehole sections of some ultramafic pegmatoids showed lengths of more than 100m, in which sulphides, mainly pyrrhotite and also pentlandite and chalcopyrite, were abundant. Other sections of the same borehole are barren of sulphides.

The textures and abundance of the different sulphides were studied across the pegmatoid layer of the Merensky 'Reef' when it is underlain by a magnetitite pegmatoid which in turn is underlain by an olivine diallagite pegmatoid.

Within the Merensky 'Reef' pegmatoid, pyrrhotite predominates over pentlandite and chalcopyrite, the relative percentage being given in Table 3. Pyrrhotite forms roughly 80% by volume of the sulphides present within the magnetitite and underlying olivine diallagite pegmatoid, the remaining 20% being mostly pentlandite and chalcopyrite with negligible amounts of cubanite and pyrite.

Within the magnetitite pegmatoid two sulphide generations are in evidence. The first generation forms roundish blebs and the second is filling cracks and fractures, being formed at least partially at the expense of the first generation. The first sulphide generation is composed mainly of pyrrhotite chalocpyrite and pentlandite. Pyrrhotite forms at the expense of chalcopyrite and pentlandite, and magnetite forms at the expense of all the sulphides, filling cracks within sulphides and being deposited in t[illegible] margin of sulphide blebs and along cleavages.

Fine dissemination of chalcopyrite and pentlandi[illegible]e in pyrrhotite or magnetite do occur. The texture termed 'birds [illegible]' (Stumpfl op.cit.) develops in pyrrhotite blebs, magnetitite being concentrically disposed within the pyrrhotite (Photo 37). S[illegible]me pyrrhotite blebs show disseminated magnetite. When seen un[illegible] [illegible]igh magnification it is evident that the magnetite within the pyrrhotite shows the beginning of a concentric alignment.

When magnetite comes into contact with the bleb[illegible] a migration of the sulphides to cracks and away from the magnetite is common (Photos 38 and 39). Cracks filled with pyrrhotite displace ilmenite exsolved from magnetite indicating movement of the second sulphide generation after oxide deposition.

Within skeletal textures in oxides small blebs of chalcopyrite are present which could represent a sulphide phase which crystallized at a different time from the ones described previously (Photo 35).

4. Chemistry.

It would appear that modal analysis of ultramafic pegmatoids differ considerably amongst themselves, and also compared with modes from ultramafic pegmatoids analysed in the Eastern and Western Transvaal by other authors. Differences in the major elements are reflected in the normative components. Variation in the proportions of plagioclase, ilmenite and diopside emphasise the different chemistry of the ultramafic pegmatoids. The presence of hyperstene as a normative mineral presents a further difference with the modal components. Ultramafic pegmatoids plot very near the MgO-FeO base line showing moderate spread but (Fig. 5) populating separately from the rocks of the layered rocks showing iron enrichment. In ultramafic pegmatoids there is a great variation in the normative components of different samples. Table 4.

a. Standard Cell calculations. - Standard cell calculations, on the basis of 100 oxygens, were carried out on rock analyses from Bafokeng and selected samples from the available literature. The aim was to compare ultramafic pegmatoids at Bafokeng with portions of the layered rocks and with ultramafic pegmatoids from the Western and Eastern Transvaal. Analysis of ultramafic pegmatoids by Liebenberg (1960), De Bruyn (1944), Schwellnus and Willemse (1943) and Van Zyl (1969), were recalculated to standard cell cationic per cent. Results are presented in Table 24. As all the analyses, other than those of Schwellnus and Willemse (Ibid) were taken from the compilation made by Visser (1964) the numbers used by this latter author are preferred over the original numbers.

The average ultramafic pegmatoid below the Merensky 'Reef' was compared with the average noritic, pyroxenitic and anorthositic cumulates below the Merensky 'Reef', Table 25. The most dramatic decrease from layered rock to ultramafic pegmatoids, is that of Al, but Na, K and Si always diminish from cumulates to ultramafic pegmatoids. Calcium is higher in ultramafic pegmatoids than in pyroxenitic and noritic cumulates, but a little is needed to reach the Ca content of anorthositic cumulates. Magnesium, is higher in pyroxenite cumulates than in ultramafics, but it is lower in anorthositic and noritic cumulates. Ultramafic pegmatoids are extremely enriched in total iron as compared with noritic, pyroxenitic and anorthositic cumulates.

Samples R22 and R15 taken by Schwellnus and Willemse (Ibid, Table I), from the magnetitite pegmatoid hill on farm Goedgedacht 114 (Fig. 18), were averaged. This composite sample shows the highest iron content, being 60 per cent of the cationic content.

Analysis 876 from the farm Vaalkop 275 represents the highest iron concentration in a hortonolite-dunite pegmatoid found at Bafokeng (34 per cent of the cationic content), and it is slightly greater than that of UPBMR, (30 per cent of the cationic content).

Comparing the iron content of ultramafic pegmatoids throughout the Critical Zone, it becomes apparent that of the rocks analysed

TABLE 24. Standard cell calculations on the basis of 100 oxygens for ultramafic rocks from Bafokeng and selected analyses from other zones of the Bushveld Complex. *Analyses from Bafokeng Mine.

	Fe++	Fe+++	Mn	Ti	Ca	K	P	Si	Al	Mg	Na	H	Total	Fe++ +Fe+++ / Mg++	Fe+++ / Fe+++ +Fe++
GBGF*	11,7	1,3	0,2	2,1	10,1	0,01	0,08	27,2	1,5	12,01	0,08	5,2	71,48	1,08	0,10
UPBMR*	21	1,5	0,3	2,7	5,5	-	0,04	23,6	1,0	14,0	0,01	5,2	74,85	1,61	0,07
553ba*	8,2	0,8	0,2	0,2	10,2	-	0,1	28,9	1,5	15,2	0,2	8,2	70,5	0,59	0,09
UPBMR*	12,7	1,5	0,3	2,7	5,5	-	0,04	23,6	1,0	14,0	0,01	5,2	74,85	1,01	0,11
UPMR*	18,1	2,0	0,2	0,6	6,4	-	0,04	25,8	1,0	15,8	0,04	4,6	75,58	1,27	0,10
553ab*	9,7	1,5	0,1	0,9	11,4	-	0,1	28,8	1,6	12,1	0,1	4,2	73,7	0,93	0,13
553*	9,2	1,4	0,15	0,2	6,1	0,02	0,06	25,1	6,0	16,0	0,6	12,2	77,03	0,66	0,13
822-15*	15,1	[illegible]	0,14	13,9	0,14	-	0,1	0,6	3,2	1,2	-	9,0	72,42	36,75	0,70
876*	22,1	4,0	-	1,7	1,0	-	-	23,4	0,8	14,0	0,1	6,8	75,83	1,86	0,15

TABLE 24. Continued.

	Fe++	Fe+++	Mn	Ti	Ca	K	P	Si	Al	Mg	Na	H	Total	Fe++ +Fe+++ / Mg++	Fe+++ / Fe+++ +Fe++
21060	13,1	6,1	0,2	1,9	6,7	0,2	0,08	23,6	0,9	15,0	0,3	3,2	71,80	1,28	0,32
892	20,2	1,9	0,2	0,7	4,8	-	-	26,05	1,5	15,5	0,9	-	71,75	1,43	0,09
875	26,8	5,4	-	2,3	0,7	0,008	-	20,85	1,2	15,0	0,08	2,6	74,94	2,14	0,19
877	23,4	2,6	0,2	0,5	1,5	-	-	23,45	3,53	16,7	1,8	-	73,68	1,56	0,10
871	22,1	-	0,6	-	0,4	-	-	25,7	1,0	23,3	0,4	-	73,5	0,95	-
872	21	1,5	0,2	0,02	1,8	-	0,03	24,4	1,2	23,5	0,2	2,6	76,5	0,96	0,07
865	20,8	5,6	-	1,5	0,3	0,08	-	19,05	3,06	20,06	0,08	8,8	79,33	1,32	0,21
866	13,6	2,5	-	0,01	6,3	0,01	-	26,7	1,6	18,1	0,1	4,6	73,52	0,89	0,15
867	23,4	3,9	-	0,7	0,3	0,01	-	23,1	-	20,4	0,1	4,4	76,34	1,34	0,14
								Average total					74,02		

Standard cell calculation

SAMPLE No.	ROCK TYPE	LOCALITY	REFERENCE
[illegible]22 + 15	Magnetitite Pegmatoid	Bafokeng *	Schwellnus Willemse (1943)
876	Hortonolite Dunite	Vaalkop (Bafokeng) *	Liebenberg (1961)
Z 1060	Wehrlite	Swartklip (W.Tvl)	Van Zyl (1969)
892	Hortonolite Wehrlite	Middellaagte (W.Tvl)	De Bruyn (1944)
875	Hortonolite Dunite	Buitfontein 259 JQ (W.Tvl)	Liebenberg (1960)
877	Hortonolite Dunite	Middellaagte	De Bruyn (1944)
871	Hortonolite Dunite	Mooihoek	De Bruyn (1944)
872	Hortonolite Dunite	Onverwacht	De Bruyn (1944)
865	Hortonolite Dunite	Onverwacht	Liebenberg (1960)
866	Hortonolite Dunite	Mooihoek	Liebenberg (1960)
867	Hortonolite Dunite	Mooihoek	Liebenberg (1960)

* = Analyses from Bafokeng Mine.

TABLE 25 . Average cationic contents in layered rocks and ultramafic pegmatoids at the same elevation calculated on the basis of 100 oxygens.

	Fe++	Fe+++	Mn	Ti	Ca	K	P	Si	Al	Mg	Na	H	TOTAL	(Fe++ +Fe+++) / Mg	Fe^{3} / (Fe++ +Fe+++)
AV1	1,8	0,6	0,03	0,05	6,9	0,06	0,04	28,4	14,5	8,3	1,8	4,4	66,64	0,26	0,273
AV2	0,6	0,1	-	0,01	9,1	0,15	0,05	27,7	20,1	1,85	2,7	3,0	65,16	0,37	0,143
AV3	13,6	1,2	0,2	1,6	8,6	0,003	0,07	26,5	1,3	13,7	0,09	6,2	73,06	1,08	0,081
AV5	3,4	1,8	0,1	0,1	3,9	0,1	0,02	30,1	4,0	19,2	0,5	6,3	69,52	0,27	0,3[illegible]
AV3-AV1	+12	+0,6	+0,17	+1,55	+1,7	-0,057	+0,03	-1,9	-13,2	+5,4	-1,71	+1,8	+6,42	-	-
AV3-AV2	+13	+1,1	+0,2	+1,59	-0,5	-0,147	+0,02	-1,0	-18,8	+11,85	-2,61	-2,61	+7,90	-	-
AV3-AV5	+10,2	-0,6	+0,1	+1,5	+4,7	-0,097	+0,05	-3,6	- 2,7	- 5,5	-0,4	-0,1	+3,54	-	-

AV1 average noritic cumulate below Merensky 'Reef'

AV2 average anorthositic cumulate below Merensky 'Reef'

AV3 average ultramafic pegmatoid below Merensky 'Reef' (in all samples the host rock is an anorthositic cumulate)

AV5 average pyroxenitic cumulate below Merensky 'Reef' this element does not show progressive enrichment upwards. Ultramafic pegmatoids from Onverwacht and Mooihoek, which are contained in earlier cumulates show a higher total iron content than some of the ultramafic pegmatoids of Bafokeng (Table 24).

Iron content in ultramafic pegmatoids does not seem to be connected with the type of host rock. Sample UPMR, where the host rock is a pyroxenite shows an iron content which is intermediate between those of samples GBGF and UPBMR where the host rock is an anorthosite. Both conformable and transgressive ultramafic pegmatoids show high iron contents, e.g. magnetitite pegmatoids below chromitite layers, and samples R22 and 15 respectively.

In an attempt to elucidate comparable trends in ultramafic pegmatoids, total cationic iron (Fe^{++} + Fe^{+++}), was plotted against the remaining cations (Fig. 16). The plots of iron against Ca and against Si reveal a covariance. As the iron content increases the calcium and silica contents decrease. Plots of total iron against Al^{+++} and Mg^{++} show a scatter of points.

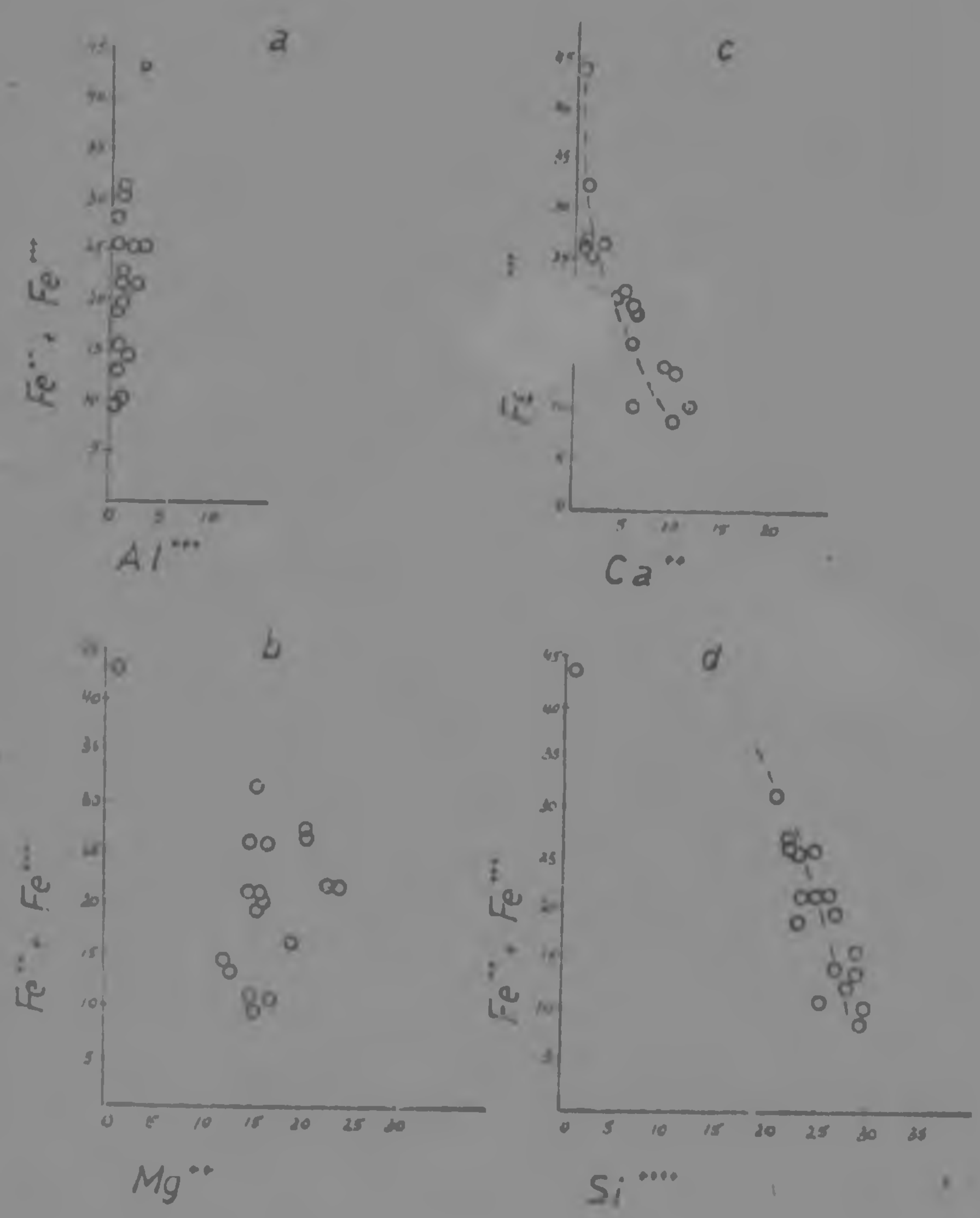
The Mg content in samples, other than the titano-magnetitite pipe (Sample R22 + 15), is very regular in ultramafic pegmatoids analysed at Bafokeng. The Mg^{++} content of ultramafic pegmatoids from Onverwacht (samples 872-865) and Mooihoek (samples 871-366-867) where the host rocks were Mg-rich pyroxenites, is variable, but is higher than that of ultramafic pegmatoids at Bafokeng. However, Mg^{++} in sample UPMR, where the host rock is the Merensky 'Reef' shows very little difference with the Mg^{++} content of other ultramafic pegmatoids (Table 24), and is lower than that of sample 553 where the host rock is a gabbro.

Alkali distribution throughout ultramafic pegmatoids is very low, especially that of K+, which is below the detection limits in some cases. The highest K+ content observed, is that of a wehrlite (Z1060, Van Zyl, 1969), which shows 1,67 per cent normative orthoclase.

The Ca++ content of ultramafic pegmatoids at Bafokeng is very variable, from 5,5 to 11,4, Table 24, and is generally very much higher than that of ultramafic pegmatoids from Onverwacht and Mooihoek. An average of three ultramafic pegmatoids emplaced in anorthositic rocks (Table 25) gave a Ca++ content of 8,6, as compared with Ca 6,4 per cent of the ultramafic pegmatoid within the Merensky 'Reef'(UPMR).

Alumina in ultramafic pegmatoids other than 553, which includes

FIG. 16. Plots of $Fe^{++} + Fe^{+++}$ against other cations in ultramafic pegmatoids.



troctolitic pegmatoid phases, shows little variation.

b. Trace elements. - Ultramafic pegmatoids were analysed for Zn, Cu, Ni (Table 5 and 6), S (Table 7) and Rb-Sr (Tables 8 to 10). See Appendix I.

Wager and Mitchell (1951, p.158), showed that zinc tends to replace Fe when in fourfold co-ordination. They conclude: "The presence of Zn in magnetite in which Fe has a fourfold co-ordination and its virtual absence in ilmenite in which the Fe has a sixfold co-ordination is in harmony with Neumann's conclusions". Wager and Brown (1968, p.200) quoting Woode (1961) suggest the same possibility. In ultramafic pegmatoids at Bafokeng Zn increases with total iron content (Fig. 17). From Table 5 it is also evident that Zn is enriched in ultramafic pegmatoids with respect to the layered rocks. Pyroxenites show the highest Zn contents of the layered rocks analysed: sample UPMR taken when the host rock is a pyroxenite shows the highest Zn content of all the ultramafic pegmatoids analysed.

The average Cu and Ni contents of ultramafic pegmatoids are 248 and 435 p.p.m. respectively. Liebenberg (1960, Table 21D) has found the following Cu values in ultramafic pegmatoids of Onverwacht and Mooihoek: 162, 6 and 36 p.p.m. In the same samples Ni was 540, 320 and 350 p.p.m. respectively. These values show that ultramafic pegmatoids at Bafokeng are generally enriched in Cu and have approximately the same Ni content as those analysed by Liebenberg (op.cit.), lower down in the Critical Zone.

The average Cu content of the average dunitic rocks is, according to Goles (1967) 30 p.p.m., and the Ni content reaches 1770 p.p.m. These values do not approximate the average values obtained in ultramafic pegmatoids at Bafokeng. The relative abundance of Cu and Ni in ultramafic pegmatoids is subject to variations in different parts of the same body because of variations in the abundance of Cu Ni sulphides. Partial sampling by the Assay Department of Bafokeng Mine, of borehole 553 showed that, from 93m above the Merensky 'Reef', to 156m above it, Cu almost always exceeds Ni content. Within this stratigraphic interval Ni averages 292 p.p.m., whereas Cu averages 415 p.p.m., and the Ni/Cu ratio is 0,7. However, a sample taken below this depth, 553, shows that nickel is predominant. Sample 553, which is a composite from 40 to 66m above the Merensky 'Reef', is composed mainly of dunitic and troctolitic phases.

Variations in the Ni/Cu proportions apparently occur in several ultramafic pegmatoids. De Bruyn (1944) showed that at Middellaagte Ni varies between 0,33 to 0,62 per cent and Cu from 0,40 to 0,54 per cent.

The factors which may affect the Cu Ni distribution in ultramafic pegmatoids will be examined briefly. The higher Cu content of an ultramafic pegmatoid, that of sample UPBMR, coincides with the higher total iron content; however in ultramafic pegmatoid from Bafokeng there is no apparent covariance between Cu and total iron content (Fig. 17), even though Cu is known to replace ferrous iron in ferromagnesian minerals and iron ores (Wager and Mitchell, 1951, p.190). In ultramafic pegmatoids plots of Ni against MgO (Fig. 17) show that there is a covariance between both. Evidently upon discussing the Ni content of ultramafic pegmatoids it is of utmost importance to determine how nickel would behave in an environment which is being enriched in iron. Wager and Brown (1968, p.168) have shown that nickel readily enters ilmenite and magnetite; however, when plotting Ni against total iron in ultramafic pegmatoids analysed at Bafokeng, these elements do not show a covariance. Comparisons between the Cu and Ni contents in ultramafic pegmatoids and the layered rocks, were made to try to establish if fractionation had taken place in ultramafic pegmatoids. Ultramafic pegmatoids at Bafokeng have 2,1 times less Cu and 5,6 times less Ni than ultramafic rocks from the Western Transvaal, Liebenberg (1969, Table 30). [illegible] ultramafic pegmatoids of Bafokeng are compared to the avera[illegible] given by Liebenberg (Ibid, Table 29) for ultramafic rocks of the Bushveld Complex, the following data is obtained: ultramafic pegmatoids have 7 times more Cu and 1,6 times less Ni. The Cu content of ultramafic pegmatoids at Bafokeng is higher than that of all the analysed layered rocks but the Merensky 'Reef'. If we compare the Ni content of ultramafic pegmatoids with that of the layered rocks at Bafokeng, it is found that: the Ni content of the ultramafic pegmatoids is similar to that of the noritic cumulates of the footwall of the Merensky 'Reef'; is higher than that of the anorthositic cumulates, but lower than that of the pyroxenitic and pegmatoid pyroxenite cumulates. In the ultramafic pegmatoids at Bafokeng, the Ni content is lower than that of the magnetites and magnetite gabbros of the Upper Zone as given by Liebenberg (1969), which is 600 p.p.m.

From figures given by the Assay Department of Bafokeng, it was

FIG. 17. Plots of Cu/FeO- Ni/FeO- Ni/MgO, and Zn/FeO in ultramafic pegmatoids from Bafokeng.

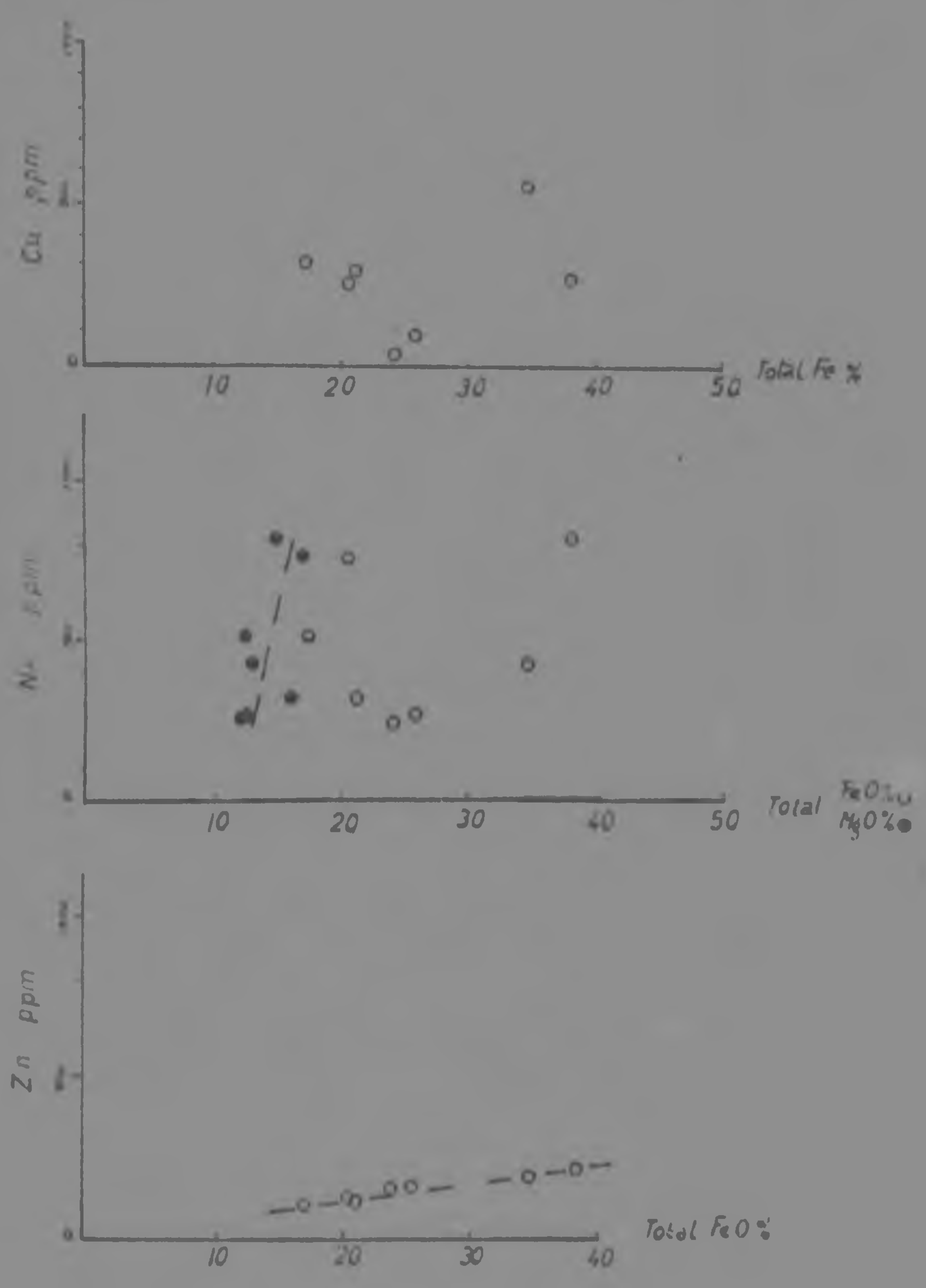


FIG. 18. Cu-Ni content of ultramafic pegmatoids in the vicinity of the Merensky 'Reef'.

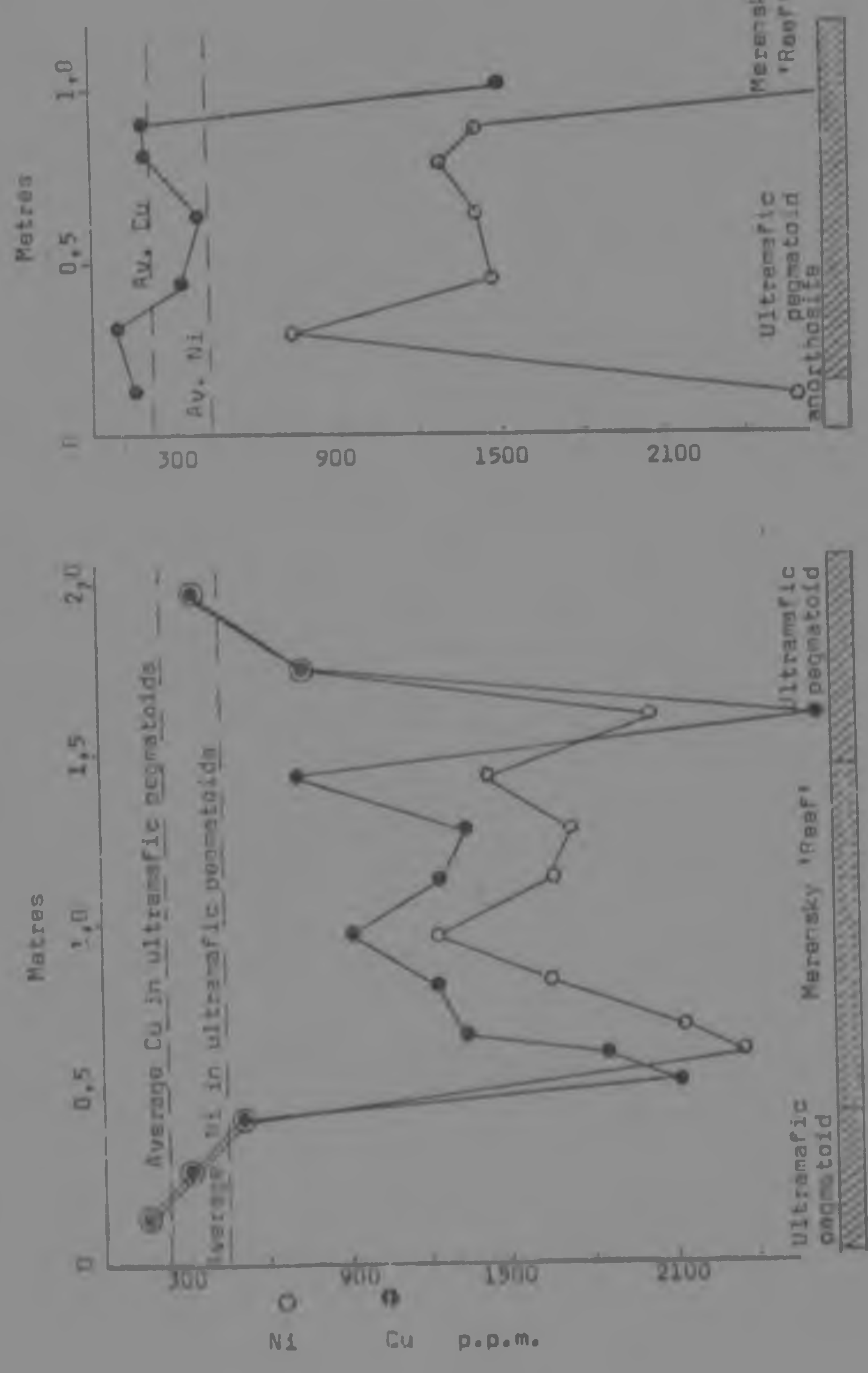
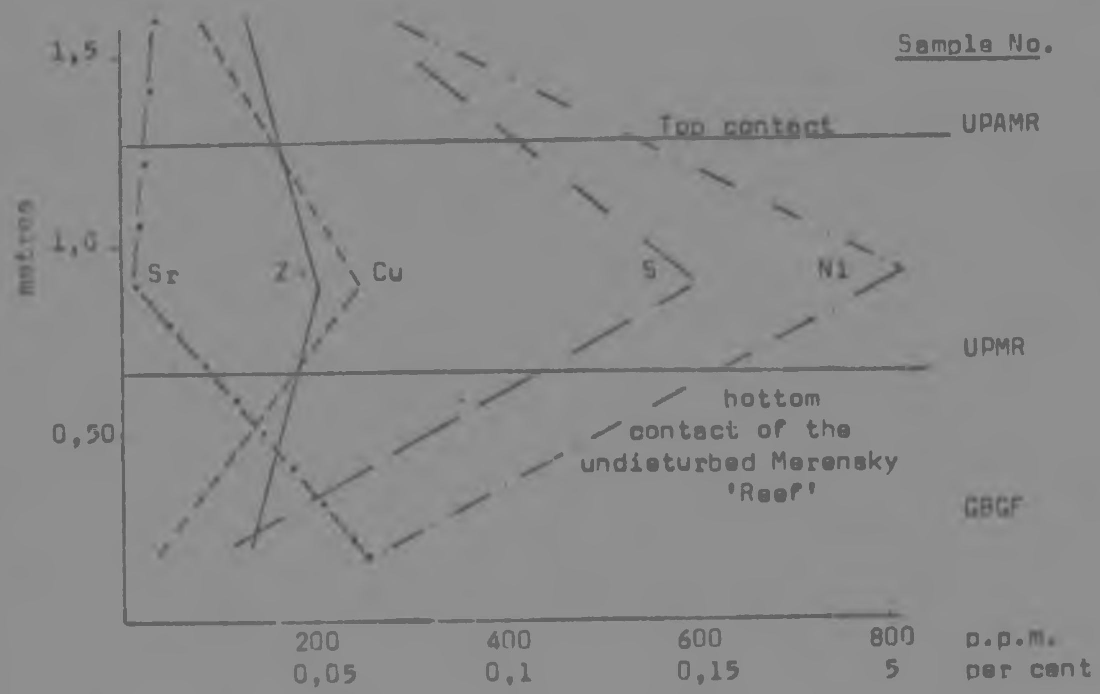


FIG. 19. Variation of Cu, Ni, Zn, Sr and S in ultramafic pegmatoids taken above, within and below the Merensky 'Reef'.



found that when the Merensky 'Reef' is underlain and/or transgressed by ultramafic pegmatoids, it generally shows a depletion in PGM, Cu and Ni. The ultramafic pegmatoids which overlie and underlie the Merensky 'Reef' are usually enriched in PGM, Cu and Ni. These same facts were described in the Rustenburg district by Wagner (1973). A compari on between the Ni and Cu content of the Merensky 'Reef' and the ultramafic pegmatoids in its vicinity, is given in figure 18. From figure 18 it can be seen that ultramafic pegmatoids show Cu Ni values above average in the area next to the contact with the Merensky 'Reef'.

Samples GBGF-UPMR-UPAMR, which are from a sequence of ultramafic pegmatoids taken immediately below, within and above the Merensky 'reef'; show a nickel and S peak coincident with the Merensky 'Reef' position. This is more noticeable because the nickel content of both the sample taken below, GBGF, and the one taken above, UPAMR, which show 267 and 276 p.p.m. Ni respectively, are less than half the Ni content of UPMR. Figure 19 shows the behaviour of the different trace elements in the above described samples.

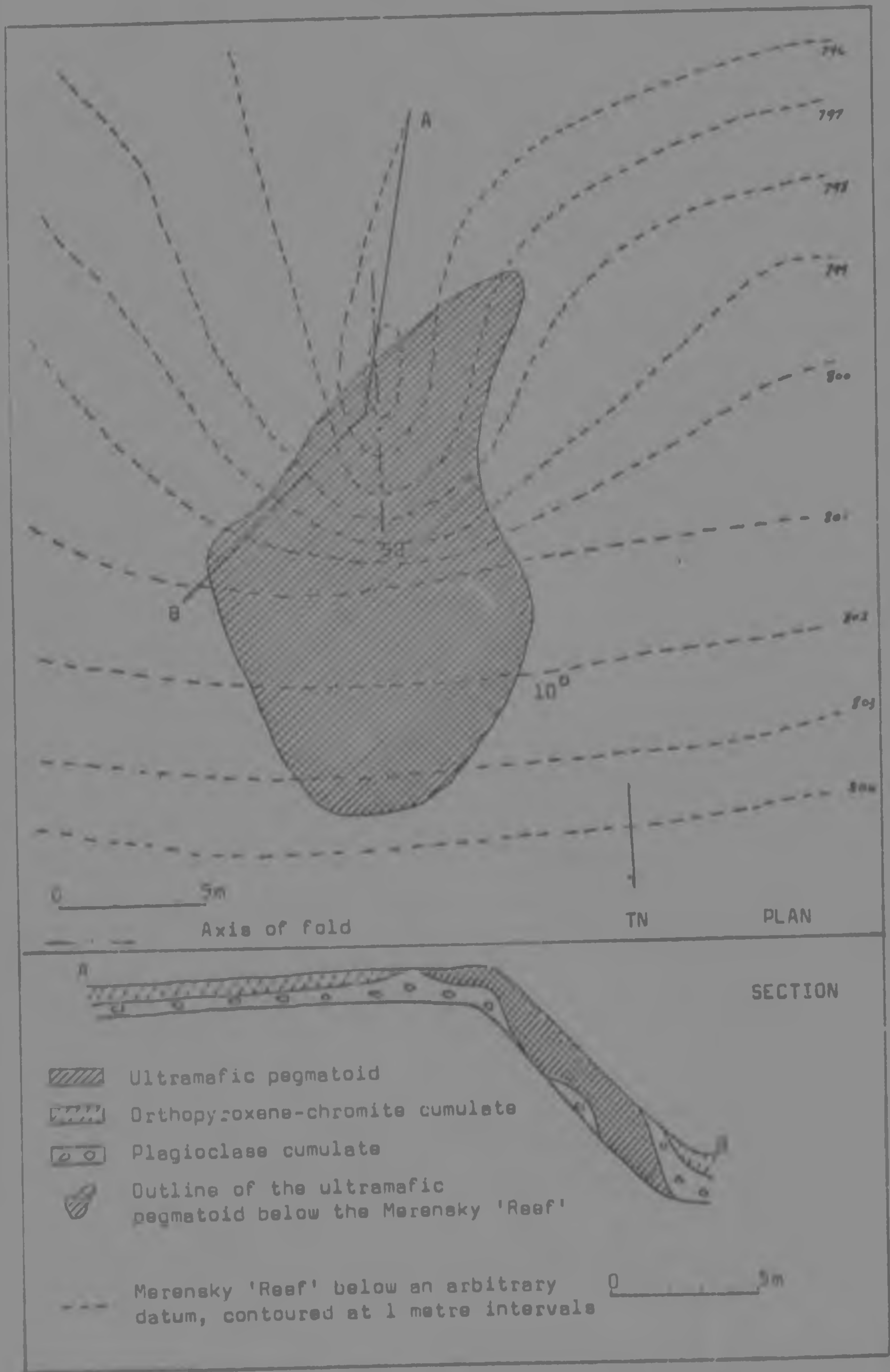
The ultramafic pegmatoids which show the highest sulphur content (Appendix I) (Table 7) are both in the footwall of the Merensky 'Reef', samples 553be and UP8MR, and both of them show higher S concentrations than the ultramafic pegmatoid sample taken at the Merensky 'Reef' elevation (UPMR). Average S in ultramafic pegmatoids (1750 p.p.m.) seems to be higher than that of the Bushveld Magma, which, according to Liebenberg (1969, p.200) who accepted the S content of the Hendriksplaas norite as representative of the magma, is 228 p.p.m. S content in ultramafic pegmatoids is also higher than the average value of 150 p.p.m. for the Complex as a whole.

Compared to the layered rocks analysed at Bafokeng, Rb is at its lowest concentration in ultramafic pegmatoids, however, Sr is also low in ultramafic pegmatoids, almost three times less than in pegmatoidal pyroxenite cumulates and 19 times less than in anorthositic cumulates, (Table 9), with the result that Rb/Sr ratios are higher in ultramafic pegmatoids than in most of the layered rocks. The Sr content in layered rocks and ultramafic pegmatoids, is clearly affected by the plagioclase content, as shown by sample 553 with 144 p.p.m. Sr, which was not taken into account in the averages (Table 8). The factors controlling the Rb content in ultramafic pegmatoids could be the presence of amphibole and mica. Wyllie (1967, p.75) has shown that in ultramafic rocks the Rb content is very sensitive to the distribution of small amounts of amphibole. Comparisons between the Rb/Sr data obtained at Bafokeng and data from Davies et alia (1969) and Liebenberg (1960) are given in Table 10, Appendix I.

5. Description of structures in the layered rocks which were studied in connection with late ultramafic pegmatoids.

a. 344 East Stope, Figure 20. - In most of this stope the footwall of the Merensky 'Reef' is formed by anorthositic heteradcumulate. In a portion of this stope the Merensky 'Reef' and its immediate footwall are folded (see Fig. 20). At the apex of the fold the Merensky 'Reef' is at 795m below datum. The Merensky 'Reef' plunges to 801m below datum, dipping at 50^{o}N over 6 metres, before returning to the average dip of 10^{o} below contour 801. An ultramafic pegmatoid is partially juxtaposed with this fold, being emplaced conformably in the anorthosite heteradcumulate. The ultramafic pegmatoid shows both fine-grained transitional and sharp contacts with the anorthosite. Both the anorthosite and ultramafic pegmatoid show extensive fracturing in the con-

FIG. 20. Plan and section showing behaviour of the layering on 344 east stope, and intersection by an ultramafic pegmatoid.



tact zone. Between contours 802 and 804 a normal Merensky 'Reef' is underlain by ultramafic pegmatoid. Within the Merensky 'Reef' above the apex of the fold, cumulus orthopyroxenes are completely deformed and bent, however there is no disruption of the overlying Merensky 'Reef' by the ultramafic pegmatoid which has a conformable contact. Gently folded structures in the layered rocks occur in the same stope, and in other portions of the mine, without any obvious connection to ultramafic pegmatoids.

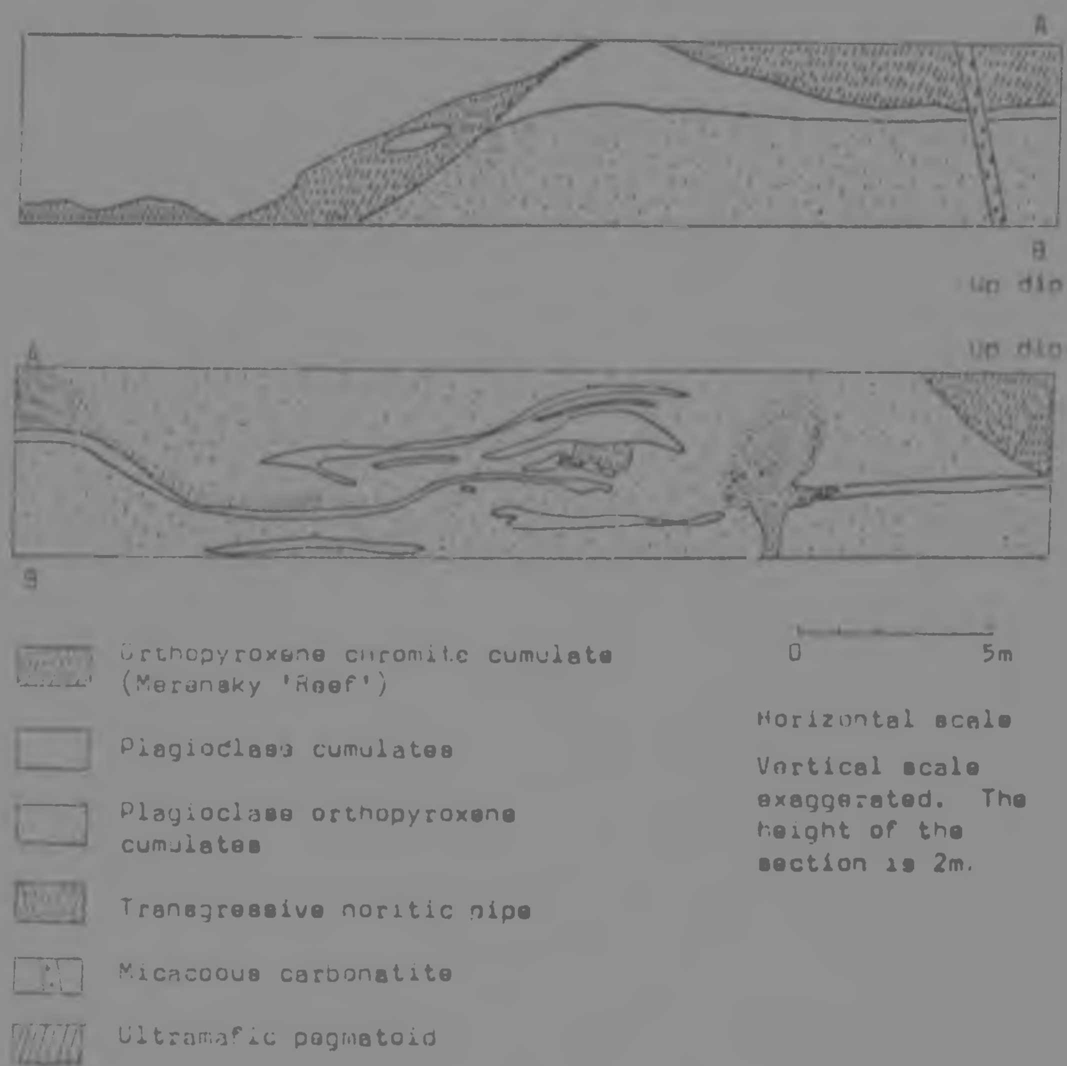
b. 377 Raise. Fig. 21. - As we progress up dip on this Raise, the Merensky 'Reef' is seen emerging from a depression, which is also occupied by a poorly exposed ultramafic pegmatoid which contaminates the overlying plagioclase cumulate with olivine (Fo. 59). After a brief disappearance in the hangingwall of the tunnel the Merensky 'Reef' is seen again resting on a plagioclase cumulate which is part of the normal layered rocks. Both are transected by a micaceous carbonatite. Further up dip, (see lower part of figure 21), both the Merensky 'Reef' and the plagioclase cumulate immediately underlying it, form a depression and the Merensky 'Reef' grades laterally to a plagioclase-orthopyroxene cumulate.

Within this depression, the following features were observed

- A 1,8m well developed orthopyroxene-chromite 'lense'. The En content of the orthopyroxenes of this 'lense' is En 80, which is similar to that of the orthopyroxenes of the Merensky 'Reef' in the same Raise line.
- Plagioclase cumulates form intermittent layers which show rapid lensing.
- Locally, 'pockets' of massive sulphides are trapped between the intermittent plagioclase cumulates.
- Over a distance of 0,4m the chromitite layer underlying the Merensky 'Reef' splits to form four thin separate chromite layers.

On the up dip side of these features a small pipe-like structure, 1 to 3m wide, transgresses the plagioclase-orthopyroxene cumulate which forms the immediate footwall of the Merensky 'Reef'. This pipe was investigated because of a possible genetic connection with the ultramafic pegmatoid intersected 35m down dip. The mineralogy of the transgressive pipe is completely different to that of ultramafic pegmatoids, being of noritic composition. It consists of orthopyroxene and plagioclase, the former becomes more abundant towards the upper portion of the pipe. The orthopyroxene forms clusters in

FIG. 21. Sections showing structures in 377 Raise
(drawings based on photographs).



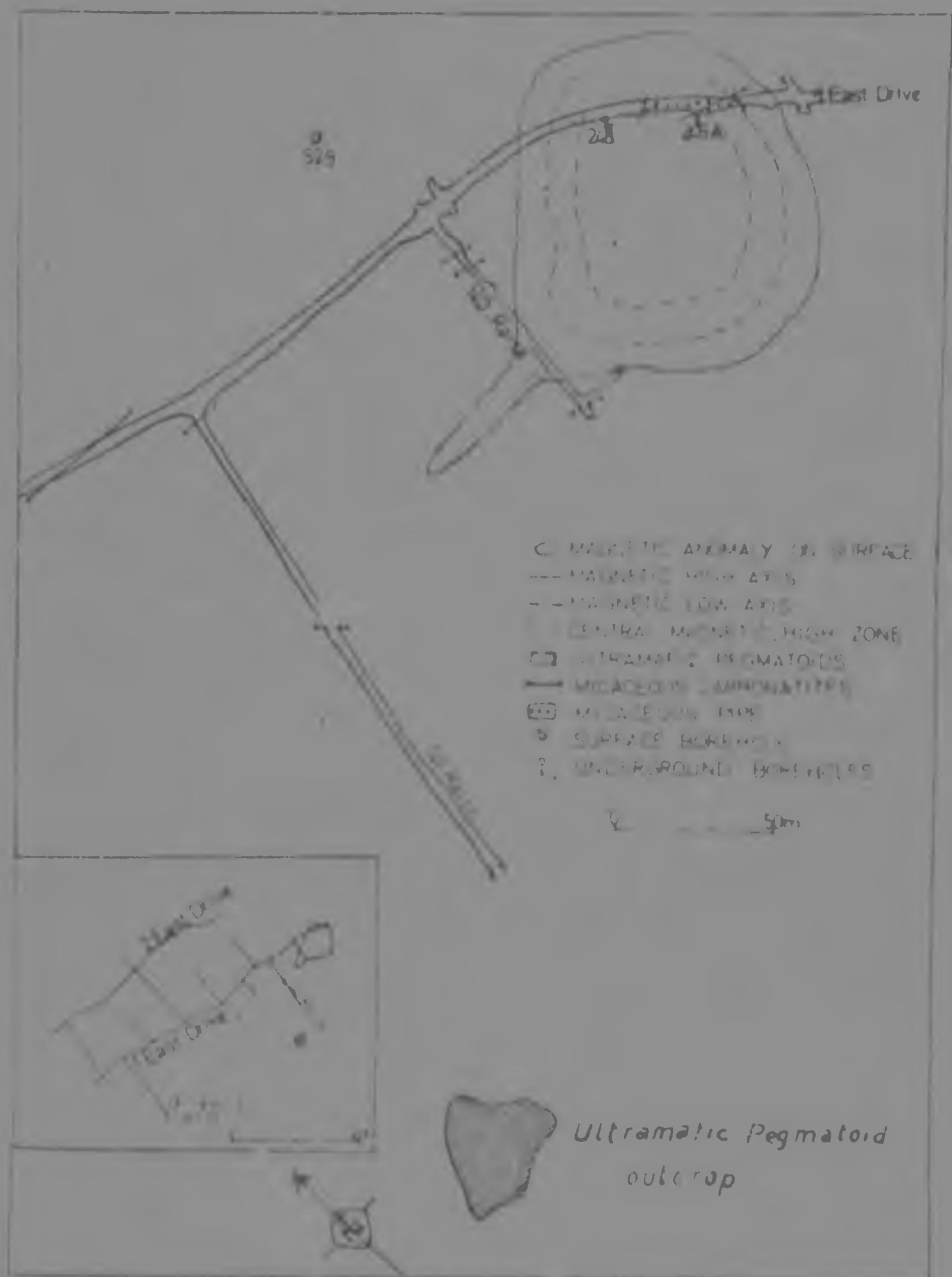
which platinum, copper and nickel sulphides co-exist with chromite crystals. The En content of this orthopyroxene is 80 to 82 per cent, which is higher than that of the orthopyroxenes of the footwall of the Merensky 'Reef', En 76, but similar to the En content of orthopyroxenes within the Merensky 'Reef', En 80-82.

c. No. 1 Shaft, 1 East Drive. Fig. 22 . - Mining operations intersected a micaceous pipe in the East Drive of the 1 Shaft, SE of borehole 529, which was originally thought to be an intrusive breccia. At the position of intersection by the tunnelling, the pipe has a diameter of 30m, and is intersected by a micaceous carbonatite dyke, which strikes approximately east-west. Preliminary studies on this pipe, showed it to be composed of fragments of layered rock in a highly altered matrix. A magnetic survey over the zone occupied by the pipe was done by Mr. A. Linde (1968-9) who found the following magnetic anomalies, starting from the outside:

- a remarkably symmetric high magnetic anomaly, which ranges from 300 to 480 γ and can be correlated with the pipe,
- Immediately inside this a zone of low magnetic intensity, and
- Further there is a zone in which the magnetic intensity is again high (400 γ).
- A zone of high magnetic intensity protrudes towards the west in the direction of 141 Raise.

According to Mr. A. Linde (1969), who interpreted these features, "the intrusive body widens from 1 East Drive towards surface and narrows with depth. From a crude separation it appears that most of the magnetic fraction is pyrrhotite with smaller amounts of magnetite". The author's attention was attracted by the fact that the protruberance of the magnetic anomaly points to 141 Raise towards a 5m wide, ultramafic pegmatoid which transgresses the layering on this raise. This is the closest observed ultramafic pegmatoid to this micaceous pipe. Figure 22 shows an ultramafic pegmatoid outcrop which occurs up dip from the micaceous pipe, and furthermore surface drilling in the No. 1 Shaft area has proved the existence of various ultramafic pegmatoid bodies. In an attempt to investigate the possibility of a connection between the micaceous pipe intersected in 1 East Drive and ultramafic pegmatoids, one underground borehole was started at position 246A (Fig. 22), but it had to be abandoned due to poor hangingwall conditions. The drill was moved to position 248,

FIG. 22. Magnetic anomalies produced above a micaceous pipe.



where a second borehole was drilled to intersect the Merensky 'Reef' and see how it was affected by the micaceous pipe. The shape of the pipe could not be established from these underground boreholes or from the drive intersection, however, several facts became apparent: The matrix of the pipe completely or partially surrounds the country rock fragments in situ, and there seems to be no displacement or transport from one layer to another. The Merensky 'Reef' is affected in the same way by sparse zones with a brown micaceous matrix which becomes still less abundant below the Merensky 'Reef'. Brown mica is present as rod-shaped crystals, which locally show stronger pleochroism on the outlines of the crystal. Portions of the matrix show interconnected veinlets of calcite, which form networks, which are of later formation than the matrix.

Alteration of plagioclase and orthopyroxene cumulates in country rock fragments seems to have proceeded from the periphery inwards, producing resorbed margins. Opaque minerals and sericite, which are alteration products, form halos which are concentrically distributed around plagioclase remnants. Optical data of the minerals in the layered rock and included country rock fragments at the Drive intersection gave the following compositions: orthopyroxene En 72, plagioclase An 73. Locally a mineral of acicular habit, probably a zeolite (?) has grown concentrically around plagioclase. The elongated direction of the zeolite fibres are perpendicularly orientated to the surrounding plagioclase. X-ray photography failed to identify this mineral due to masking by biotite lines. Networks of magnetite and pyrrhotite grains were also found in thin section.

i. Chemistry. - Analyses of the matrix were made by crushing the rock, followed by hand picking of fragments apparently free of country rock and late calcite veinlets. The intimate relationship of matrix and country rock made a complete separation impossible. It was estimated (Appendix I) that 15% of country rock fragments were included in the original analysis of the micaceous pipe. Using the values of En 72 and An 73, which are the compositions of the orthopyroxene and plagioclase respectively, the composition of the 15% country rock fragments was calculated. The object of this calculation being to obtain a more accurate analysis of the matrix of this pipe. Fifteen per cent of layered rock was subtracted from the original analysis. Results are presented in Table 26.

TABLE 26. Analysis of the micaceous pipe (P) intersected by 1 East Drive, 1 Shaft.

	P (Original Analysis) weight per cent	P minus 15% country rock. Recalculated to 100 per cent
SiO_2	44,04	42,83
TiO_2	0,75	0,88
Al_2O_3	10,72	7,96
Fe_2O_3	2,39	2,81
FeO	4,79	5,14
MnO	0,12	0,14
MgO	10,99	11,99
CaO	10,62	12,48
Na_2O	1,20	0,94
K_2O	2,97	3,49
P_2O_5	[illegible]44	0,51
H_2O+	[illegible]7	8,66
H_2O-	1.31	2,12
TOTAL	100,02	99,95

	p.p.m.
Zn	53
Cu	41
Ni	508
Ni/Cu	12,4
Rb	74
Sr	579
S	570
Rb/Sr	0,127
FeO/MgO	0,63
FeO/Mg	0,64

Analyst: J. P. Jones.

ii. Differences between the micaceous pipe and ultramafic pegmatoids.

The analysis of the micaceous rock shows 7,37 per cent H_2O+ which is probably due to abundance of mica and zeolites. A plot of this rock in the FeO-MgO-alkalis diagram shows that there is a complete break in chemistry between the pipe and the field of the ultramafic pegmatoids (Fig. 5). The main difference is given by an Fe/Mg ratio being less than one, for the pipe, compared with that of the ultramafic pegmatoids, having a ratio greater than one.

The Cu and Ni contents of the pipe (41 and 508 respectively) are similar to those of the ultramafic pegmatoids. Zn is very much lower. S is 0,05 per cent (Table 7). Rb and Sr are 18 and 36 times higher in the micaceous pipe than in ultramafic pegmatoids.

IV - SALIC PEGMATITES

A. Tonalitic-pegmatites

At Bafokeng tonalitic pegmatite veins cross-cut the layered rocks at steep angles. Rice (1963, p.419) defines tonalite as "a quartz-diorite containing hornblende and biotite as the chief mafic minerals". The leucocratic veins found at Bafokeng, are of pegmatitic habit, quartz-plagioclase-mica-bearing, and can be classified as tonalitic-pegmatites. Tonaltic-pegmatites are mainly confined to individual layers (Fig. 23 i), rarely transgressing the layer above. Their age relation to Late ultramafic pegmatoids is uncertain. In 3a5 Stope a tonalitic-pegmatite has developed at the contact between an ultramafic pegmatoid and layered rock. Thin sections of the contact showed quartz and the development of ferrotschermakite, partially transgressed by the ultramafic pegmatoid.

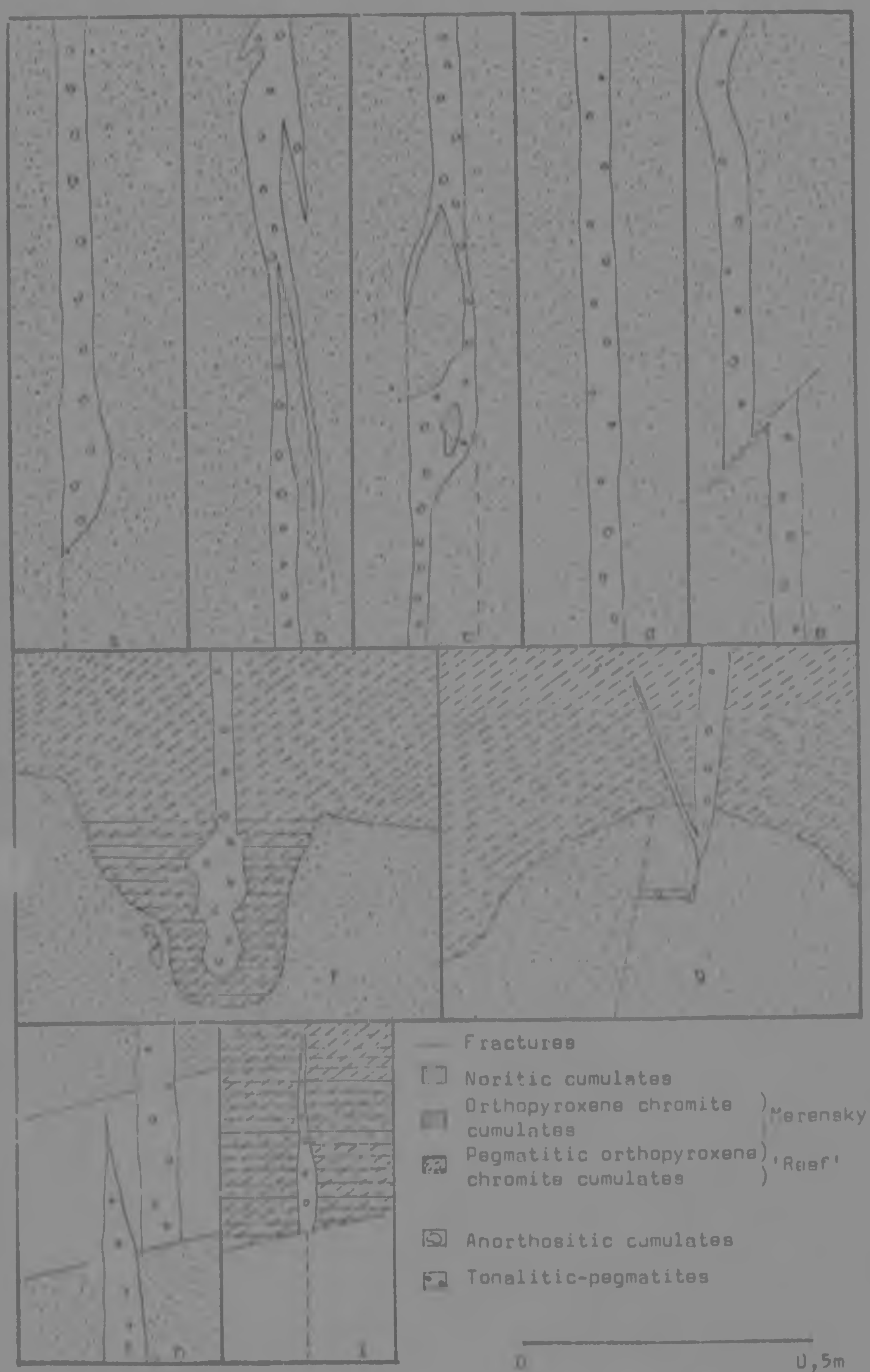
Tonalitic-pegmatites are nearly always filling fractures (Fig. 9a) which pinch-out within individual layers (Photo 40), or continue over short distances (e.g. 0,2m) in the overlying or underlying layers (Fig. 23 i, Schmidt 1952, p.247). At other times tonalitic-pegmatites extend from the bottom of a noritic layer without continuing into its immediate footwall.

Fourie (1959, pp.6-7) shows that in the Lower Group of Chromitite layers in an inclined shaft at Bultfontein 259 JQ "pegmatite veins chiefly composed of quartz, alkali feldspar and mica cut both the chromitite and the country-rock, but they tend to become wider in the latter and peter out in the former, so that in some cases only a very narrow crack or joint in the chromitite indicates the continuation of these veins. They are presumably later than the faulting".

The same behaviour has been observed in tonalitic-pegmatites at Bafokeng. Tonalitic-pegmatites have been observed in order of decreasing abundance, transgressing pyroxenitic, noritic and rarely (Fig. 23 h) in anorthositic cumulates. Their preponderance in pyroxenitic cumulates is well demonstrated when noritic layers grade laterally into pyroxenitic layers.

Tonalitic-pegmatite veins generally have a width which varies between 20 and 150 mm. The maximum vertical length observed was three metres in a footwall haulage, but it must be pointed out that the vein was continuing into the footwall and hangingwall of the tunnel.

FIG. 23. Form of tonalitic-pegmatites



From observations in the 1 and 2 Shaft areas it is apparent that they roughly follow the local strike of the Merensky 'Reef', which in these shafts is parallel to the main fracturing direction of the region, however their strike length is very variable, being at times up to 30m. Their lengths along strike are 100 times that of their widths. Very rarely upon reaching a contact between layers do they extend conformably for a distance no greater than 200mm.

The contacts of the veins with the country rock are very sharp, often, when the host rock is an anorthositic-norite cumulate, the orthopyroxenes in this rock show a darker coloration due to tremolite-actinolite alteration. When the host rock is the Merensky 'Reef', chlorization and amphibolization usually develop at the expense of the pyroxenes. The pegmatoid layer of the Merensky 'Reef' has a greater percentage of biotite in the vicinity of tonalitic-pegmatites.

Tonalitic-pegmatites have greater concentration within depressions of the Merensky Reef (Fig. 23 f) where no obvious feeders are observed, although they are more abundant in the more leucocratic portions of the pegmatoid layer of the Merensky 'Reef'.

Zoning is present in some veins, especially the thickest ones. A coarse zoning is produced by the deposition of mica, on the sides of the vein and/or in the middle of it. These mica plates often form a 'book' structure', Schmidt (1952), or grow with the basal cleavage at a high angle to the margins of the vein.

Tonalitic-pegmatites show characteristic 'swellings' which normally occur above a barren fracture or near the contact between two layers. Sometimes the 'swelling' occurs and then the vein thins to a constant thickness (Fig. 23 a). In other exposures, especially in smaller veins, the thickness tends to remain constant through the exposed length (Fig. 29 d). Occasionally the veins send off small apophyses (Fig. 23 b and g). Offsetting is occasionally observed in tonalitic-pegmatites. The mode of emplacement of offset tonalitic-pegmatites (Fig. 23 c), seems to be similar to that described by Currie and Ferguson (1971, pp.530-531) for horn-style type of offsetting, in that two closely spaced parallel fractures may have initially produced the offset. However no 'horns' were found across an offset plane at Bafokeng. Accounts of the offsetting phenomenon are given by Keitare (1953), Ramsay and Sturt (1970) and Currie and Ferguson (1970). Microfaulting and duplication over short distances (Fig. 23 e) is also present.

The behaviour of these veins in the different footwalls of the Merensky 'Reef' can be seen in (Fig. 23 f g i). If the Merensky 'Reef' is underlain by anorthosite as is the case in some depressions, the vein stops abruptly at the Merensky 'Reef' bottom contact, and the barren feature can be seen to continue in the footwall. If the Merensky 'Reef' is underlain by anorthositic-norite cumulate, the pegmatitic vein either fills the fracture in the footwall for about 100mm, or else stops abruptly at the Merensky 'Reef' bottom contact, while only the barren fracture continues into the footwall.

a. Mineralogy. - Plagioclase shows characteristic thin albite lamellae and compositions between An 46-48. Zonation is present in some of the plagioclase crystals. Quartz shows patchy extinction and is intergrown with plagioclase feldspar (Photo 41). Plagioclase, quartz and biotite are the predominant minerals, however, in the vicinity of the UG 2 chromitite layer these veins may incorporate diallage to its composition. This occurs when they transgress a porphyritic pyroxenite. Occasionally when they transgress the UG 2 chromitite layer they incorporate chromite crystals. Schmidt (1952) reported An contents between 50-54 for the plagioclase in these veins.

b. Chemistry. - One chemical analysis (FVM 1, Table 27) was made of a vein which starts on the Merensky 'Reef' pegmatoid and pinches out on its hanging wall. The norm of this analysis contrasts with the mode in that a high proportion of orthoclase is present. This probably results from K present in biotite being calculated as orthoclase.

Plots of these veins in a triangular diagram FeO-MgO-Na_2O+K_2O showed that Mg predominates over total Fe and that alkalis are the lowest of the three components. Their proportions are FeO 46,4 per cent - MgO 31,6 per cent and alkalis 22 per cent as compared to FeO 3[illegible].4 per cent - MgO 49,7 per cent - alkalis 15,9 per cent for the later granitic pegmatites. Tonalitic-pegmatites show alkali enrichment with respect to the pegmatoid layer of the Merensky 'Reef'. The Ni content is 333 p.p.m., the Cu content is 93 p.p.m., Zn being 11 p.p.m. The Rb content is 12 p.p.m. as compared to 7 p.p.m. for the host rock. The Sr content is 148 p.p.m. as compared to 80 p.p.m. for the host rock.

TABLE 27. Analysis of a tonalitic-pegmatite and C.I.P.W. Norm.

	FVMR		
SiO_2	67,07		
Al_2O_3	13,78		
Fe_2O_3	0,06		
FeO	2,51	Zn	11 ppm
MgO	3,75	Cu	93 ppm
CaO	8,22	Ni	333 ppm
Na_2O	1,49	Ni/Cu	3,58
K_2O	0,29	Rb	12 ppm
TiO_2	0,52	Sr	148 ppm
MnO_2	0,05	Rb/Sr	0,07
P_2O_5	0,16		
H_2O	0,09		
H_2O+	2,96		
Total	100,95 weight per cent		

C.I.P.W. Norm	
Quartz	35,67
Or	15,95
Albite	3,50
Anorthite	15,55
Di	7,96
Hy	9,58
Fe_3O_4	0,09
Ilmenite	1,01
Apatite	0,39

Analyst J. P. Jones.

B. Granitic pegmatites

1. Introduction. - In the Bushveld Complex a number of salic pegmatites are present. Mr. J. Barry has shown the author pegmatites consisting essentially of K-feldspar and quartz outcropping approximately 500 and 1 600m above the Merensky 'Reef' in the adjoining Rustenburg Platinum Mine. He stresses that these pegmatites also occur below the Merensky 'Reef' and in the marginal areas of the Bushveld basin. In the explanation of the Rustenburg No. 4 sheet, (Von Backström et al, 1960), on the farm Beestkraal 290, pegmatites in mafic rocks, are described that are composed of green hornblende with a centre of white feldspar. Further south they occur near hortonolite dunite pipes. Mention is also made of pegmatites composed of different coloured feldspar, quartz, tourmaline and sulphides. Hiemstra and Van Biljon (1959) have described microline-perthite-quartz-muscovite-tourmaline pegmatites from the Eastern Bushveld. They remark that they occur in rocks of both igneous and sedimentary orig. .

At Bafokeng late pegmatites of granitic composition have been found to transgress both the layered rocks and the ultramafic pegmatoids of the Plutonic phase. They are essentially quartz-potassic-feldspar-amphibole-mica bearing.

2. Occurrences. - At Bafokeng outcrops of late granitic pegmatites are sparse and poorly exposed. They are obscured by weathering and soil, and their relationship with the country rock is difficult to see. The majority of the outcrops, which have linear characteristics and seem to be connected with fracture systems, are at the northern boundary of the mine area. On the farm Klein Doornspruit 108 they seem to be associated with the same area in which the magnetic anomalies are prominent further to the east (Fig. 10). Several small outcrops between boreholes 510, 506 and the margins of a tributary of the Magatespruit, and intersections by boreholes 510 and 518, seem to prove that they are abundant around ultramafic pegmatoids. A second line of intermittent outcrops and abundant float was found to occur south of the previous mentioned area, starting on the farm Goedgedacht 110 and progressing in an approximate NW-SE direction. The outcrops behind 4 Shaft are mostly related to this second line. Granitic pegmatites also outcrop on the farm Kookfontein (Fig. 10).

On outcrop exposures it was seen that granitic pegmatites generally tend to occur in dyke-like bodies which do not exceed two metres in thickness. In some of them, the central part of the pegmatite is coarser than the rest, and quartz attains 0,04 to 0,08m in diameter, with occasional epidote crystals slightly smaller.

A particular and consistent characteristic of the granitic pegmatites is that they are very often found in the immediate vicinity of ultramafic pegmatoid outcrops. Their relationship to these bodies is further stressed by the fact that in numerous surface boreholes, i.e. 510, 518, 645, among others, they occur transecting ultramafic pegmatoid bodies. Mr. J. Barry (personal comm.) has also noted the presence of quartz-k-feldspar float in the vicinity of ultramafic pegmatoid outcrops. Granitic pegmatites are younger than ultramafic pegmatoids, but older than micaceous carbonatites which transect them. Some of the granitic pegmatites intersected by borehole 510 cross-cut the layered gabbro of the Main Zone. Sometimes along the contact between the granitic pegmatite and the gabbro 0,05 to 0,12m long crystals of amphibole co-exist with four to eight mm plate-like individuals of mica and amphibole set in plagioclase feldspar. In borehole 510 granitic pegmatite dykelets form macroscopically poorly defined contacts with ultramafic pegmatoids, mainly due to an irregular development of amphibole in the ultramafic pegmatoids. Veinlets of amphibole develop across contacts, and also irregular masses of amphibole mica and perthite occasionally transect the ultramafic pegmatoid. Locally oxides in the ultramafic pegmatoid were resorbed with biotite forming a reaction product. Microscopically these contacts are very altered, clinopyroxene assumes a spotted appearance due to the development of patchily disposed portions of amphibole. Chloritization, and amphibolization also affect plagioclase and olivines in the ultramafic pegmatoids. Underground at Bafokeng granitic pegmatites have seldom been recorded; the only exposure available for study was that in 380 Stope, 5 Shaft, from which samples for mineralogical and chemical analysis were obtained.

3. Granitic pegmatite in 380 Stope. - A granitic pegmatite, approximately one metre thick, cross-cuts both the footwall of the Merensky 'Reef' and the 'Reef' itself, but locally upon reaching this contact, has sill-like extensions. Quartz breccias of reduced dimensions, less than 1m wide, form in the overlying Merensky 'Reef' (Photo 42). Where vertical, the granitic pegmatite has a definite assymetric zoned structure with quartz forming the central part.

On one side, a K-feldspar zone comes directly in contact with the layered rock, an anorthositic cumulate, but on the other a thick zone of amphibole is developed. The side on which amphiboles are present, is in contact with a plunging edge of a depression of the Merensky 'Reef'.

a. Mineralogy. - Quartz and K-feldspar form individual pegmatitic crystals, and they also show a widespread tendency to form micropegmatitic intergrowths. In Stope 380 micropegmatitic intergrowths develop in the conformable portion of the granitic pegmatite below the Merensky 'Reef'. The K-feldspar is usually very cloudy. Occasionally quartz, when in contact with amphibole crystals, shows undulatory extinction. The amphibole occurs in the marginal contact with the Merensky 'Reef' as pegmatitic, poorly defined crystals, and also in the micropegmatitic portion as euhedral isolated crystals. Its optical properties are $2V_x$ 81, $2V_z$ 95, γ ^ c [illegible]. Its colour shows the following pleochroism: x yellowish green, y green, z dark green. Some of these properties approach those of kaersutite, others however, are those of cummingtonite. X-ray powder diffractometry showed that there is more similarity with the d-spacings of kaersutite than with those of cummingtonite (Table 28).

TABLE 28. D spacings of kaersutite, cummingtonite, and the amphibole analysed. D spacings listed in order of decreasing I.

KAERSUTITE	AMPHIBOLE A		CUMMINGTONITE
d	d		d
2,69	2,71	strongest	8,33
3,11	3,13	very strong	3,06
8,38	8,40	very strong	2,76
2,548	2,549	regularly strong	2,19
3,36	2,599	regularly strong	4,13
2,589	3,27	very weak	3,26
1,44	2,164	weak	2,63
3,26	1,442	weak	2,50
2 153	4,12	weak	

In view of the vague definition of the composition of this amphibole, a chemical analysis of one of the isolated crystals set in micropegmatite was made. Results are presented in Table 29. Calculation of the formulae on the basis of 24 oxygens were made and are presented

TABLE [illegible]. Analyses of a Calcium amphibole (Anf A) and a granitic pegmatite (380) from Stope No. 380.

	Weight per cent		380	
	Anf. A	380	C.I.P.W. Norm	
SiO_2	40,44	57,40		
Al_2O_3	10,77	9,22		
Fe_2O_3	5,62	1,31	Quartz	12,12
FeO	15,54	9,16	Or	15,95
MgO	9,55	7,37	Albite	3,59
CaO	10,13	10,78	An	15,55
Na_2O	1,24	0,42	Di	30,97
K_2O	1,19	2,67	Hy	19,03
TiO_2	2,53	0,29	Fe_3O_4	1,92
MnO_2	0,22	0,17	Ilm	0,56
P_2O_5	0,11	0,13	Apatite	0,31
H_2O-	0.14	0,04		
H_2O+	2,53	1,29		
Total	100,11	100,25	Total	100,00
Zn ppm.	-	55		
Cu ppm.	-	56		
Ni ppm.	-	159		
Ni/Cu	-	2,85		
Rb ppm.	18	59		
Sr ppm.	77	77		
Rb/Sr	0,24	0,76		
Na_2O/K_2O	1,04	0,25		

Analyst J. P. Jones.

in Table 30.

TABLE 30. Cationic percentage of Amphibole A calculated on the basis of 24 oxygens.

						Cationic per cent
SiO_2	40,44	60	0,674	1,348	12,208	6,104
Al_2O_3	10,77	51	0,211	0,317	2,871	1,914
Fe_2O_3	5,62	80	0,070	0,105	0,951	0,63
FeO	15,64	72	0,217	0,217	1,965	0,03
MnO	0,22	71	0,003	0,003	0,027	0,03
MgO	9,55	40	0,239	0,239	2,164	2,16
CaO	10,13	56	0,181	0,181	1,639	1,639
Na_2O	1,24	31	0,040	0,020	0,181	0,362
H_2O	2,53	9	0,281	0,140	1,268	2,536
K_2O	1,19	47	0,025	0,0125	0,113	0,226
P_2O_5	0,11	71	0,001	0,003	0,027	0,010
TiO_2	2,53	80	0,032	0,064	0,579	0,290

Analyst: J.P. Jones.

Phillips (1963) suggested that without fluorine and chlorine values the method of 24 anions would give erroneous results. These two elements were not analysed. However, according to Leake (1968, pp. 33-34) the analysis of Anf. A fulfills the requirements of a good analysis in that:

- the analysis total is between 99,40 and 100,60 weight per cent,
- Si in half of the unit-cell does not exceed 8,08,
- Si + Al in half of the unit-cell is not less than 7,92,
- the sum of Ca+Na+K is between 1,75 and 3,05 (2,73),
- the sum of Al^6+Fe^3+Fe^2+Mn+Mg+Cr+Ni (the last two not determined) lies between 4,75 and 5,25, is 4,80, and adding Ti is 5,09.
- OH is equal to H_2O weight per cent.

An objection to the analysis could be that OH + F + Cl (the last two not determined) in ferriamphiboles and kaersutites often do not exceed 2,00. Here OH is 2,53. However this is not a rule. Leake (op.cit.) stresses the necessity of the material to be pure, since as an example one per cent of ilmenite is sufficient to add 0,5 per cent titania to the analysis. It is noticeable that Na_2O/K_2O of Anf. A is higher than that of the granitic pegmatite (analysis 380, Table 29) being 1,04 to 0,25 respectively, minimizing in this way the possibilities of K-contamination in the analysis of this mineral. According to this if the amphibole is classified under the subdivisions given by Leake in Table II, it is ferrotschermakite. According to Leake (op.cit.) the term tschermakite gives rise to acute difficulties, especially provoked by Al^{6+}. The ideal formulae of tschermakite $Ca_2Mg_2Al^{VI}Si_6Al_2^{IV}O_{22}(OH_2)$, is not electrostatically balanced and a theoretical end member for an amphibole which has Si 6,25, Ca+Na+K 2,50, Ca 1,00 and Al^{IV} 1,00 as the one with which we are dealing has not yet been defined. The paragenesis of tschermakite seems to be wider than that of the kaersutite members which are present mainly in alkaline rocks. Mica is found as individual crystals and also as intermittent rims around calcium amphibole. From a thin section of a pegmatitic amphibole in the sill-like portion of the granite pegmatite, it was found that magnetite had crystallized within the amphibole. Magnetite is present in blades along the amphibole cleavages and also rounded crystals within the amphibole. In places ilmenite has exsolved from magnetite. Some of the magnetite seems to grow at the expense of the amphibole. Sulphides occur later than the oxides ? are also found within the amphiboles.

In some places above the sill-like portion of the granitic pegmatite, iron sulphides and oxides are enriched within the Merensky 'Reef'. In one polished section investigated, sulphides are present as pentlandite and bornite.

b. Chemistry. - A channel sample of the dyke-like portion of the granitic pegmatite was cut in Stope 380. Results of the analyses are presented in Table 29. Plots of analysis 380 in the MgO-total FeO-alkalis diagram show that the granitic pegmatites are displaced more towards the MgO-FeO base line than analysis 93 and 94 taken from Visser (1964), which are from other granitic rocks in the Western Transvaal (Fig. 5).

IV - DISCUSSION OF RESULTS

A - Nodules and Lenses

1. The formation of nodules.

The origin of the nodules in the layered rocks of the Bushveld Complex has not yet been thoroughly discussed in the literature. However, Ferguson and Botha (1963) have suggested the possibility of inclusions growing in situ as a result of diffusion or secretion. Another theory considered feasible to account for the formation of the nodules is that of Van Reysen (1971) who proposed that the nodules formed through the break-up of a pyroxenite layer with subsequent sinking of the fragments; an event occurring penecontemporaneously with the formation of the layered rocks.

The theory of diffusion or secretion would require a chemical gradient penecontemporaneous with the formation of the layered rocks towards centres of nucleation of one of the phases crystallizing at the moment, namely pyroxenes. During the growth of a nodules the ions of the required material would migrate to a nucleating centre depleting the surrounding material of these constituents. The fact that some of the nodules show a bleached zone poor in mafics around them suggests some degree of diffusion. Diffusion may have operated during the concentration of the intercumulus material in 'mottles', however there are differences between the proportions of clino- and orthopyroxene in the intercumulus material ('mottles') of the a.c.n. as compared to the nodules. Analysis of the a.c.n., numbers 126 and 163, Table 4 and also Figure 8, showed that within the a.c.n. intercumulus clinopyroxenes is either equal or predominant over orthopyroxene; whereas in the nodules clinopyroxene is subordinate to orthopyroxene. Further differences are:

- the En content of orthopyroxenes which is En 76 in intercumulus phases within the a.c.n., and En 81-82 in the nodules,
- the presence of olivine and chromite in the nodu[illegible] which are not intercumulus crystals in the a.c.n.,
- the cumulus character of orthopyroxenes in intermittent noritic and pyroxenitic layers within the a.c.n. is difficult to reconcile with diffusion alone.

At this point it seems justified to discuss the origin of the of the pyroxenitic lenses because of their possible bearing upon the theory of the nodules growing in situ. Textures like the ones found in lenses of pyroxenite could represent the crystallization of intercumulus liquid in zones of high concentration of pyroxene component. This high concentration could be produced or helped by diffusion. However, the fact that the lenses are mineralogically and texturally different from the nodules could suggest a different genetic origin for the nodules.

The second theory has several points in its favour. The break-up of a pyroxenitic layer would explain:

- the presence of medium grained pyroxenite nodules and pegmatoid ones, because the Merensky 'Reef' of the Main Zone and layered pyroxenites at the top of the Critical Zone, usually develop pegmatoid pyroxenite layers.
- The fact that some nodules are mineralized and that some have a chromite stringer, which is usually found at the bottom contact, and others do not.
- The presence of olivine in the nodules.
- The shape of the nodules. If a downward movement (like sinking) was operative, it would tend to give the nodules a spherical shape on the leading face in order to offer less resistance.
- The absence of a pyroxenite layer such as the Pseudo 'Reef' between the Merensky 'Reef' and the UG 2 chromitite, could be explained by the break-up of this layer to produce the nodules.

On the farm "Swartklip 988", Van Zyl (1969) describes a "three metre thick pseudo-reef which is seventeen metres below the Merensky horizon". Feringa (1959) describes a pegmatoidal pyroxenite Pseudo 'Reef', which has been intersected at the farm "Zwartklip 988", north-eastern Bushveld Complex (Fig. 1); it occurs at varying distances between the UG 2 chromitite layer and the Merensky 'Reef'. In both cases the nodules within the a.c.n. are not described. It seems that the thickness of the layering between the Merensky 'Reef' and the UG 2 chromitite is less at Zwartklip 988 than it is at Bafokeng, but a correlation between the Pseudo 'Reef' and the nodules seems possible. Cousins (1964), states that on the Rustenburg Platinum Mines, "the nearest similar pyroxenites to the 'boulders' are those of the Merensky Reef and those overlying the top Chromite Seam."

If we compare the pyroxenitic nodules with the overlying Merensky

'Reef' and underlying pegmatoid pyroxenite associated with the UG 2 it is found that they are similar in:

- their mineralogy. Orthopyroxenes show similar (80-82) En contents. The presence of mica and hydrous minerals like amphibole and chlorites. The UG 2 pegmatoid pyroxenite is however more altered than nodules or the pegmatoid layer of the Merensky 'Reef'. This fact could be due to its position below a thick chromitite layer which may have favoured the concentration of volatiles and water with the resultant hydrous alteration of minerals.
- their chemistry. Nodules and UG 2 pegmatoid layer show a similar position in the differentiation trend (Fig. 5). The analysis of pegmatoid layer of the Merensky 'Reef' are displaced towards the FeO corner of the diagram probably due to the presence of an iron-rich sulphide phase.

Similarities between pyroxenite nodules and over- and underlying pyroxenite could weigh in favour of the nodules being a pyroxenite layer which broke up. The features present in the nodules, like their sphericity in plan, a more regular outline at the bottom surface which is also concave upwards, seem to point to a sinking of the nodules. That the nodules did sink to their actual position in the a.c.n. is strongly supported by the evidence shown in Photo 43 , where a pegmatitic pyroxenite nodule of large dimensions can be seen breaking two intermittent noritic layers found towards the bottom of the a.c.n. in the No. 5 Shaft area. A similar exposure is present in the No. 6 Shaft area. On two exposures, 3 East Drive 5 Shaft, and 3 East Drive 1 Shaft, intermittent pyroxenite layers found towards the bottom contact of the a.c.n. were found to be breaking off producing nodules (Photo 44 and 45). Factors which could have influenced the velocity of sinking could be the difference in density between the nodules and the anorthosite, and the amount of consolidation of the a.c.n. The noritic cumulate which underlies the a.c.n. was probably in a consolidated condition as no nodules are found to be included in it.

Van Reysen (op.cit.) proposes the break-up of the pyroxenite layer which is found in the 5 Shaft area together with the 0,1m pyroxenite which is found overlying the a.c.n. in the same area. Nodules are present between both pyroxenites. Further evidence (Photo 4) shows that at least one noritic layer which is found towards the bottom contact of the a.c.n. could have contributed to the formation of some nodules. The position of this noritic layer near the bottom of the a.c.n. may indicate that it is an uplifted portion of the footwall noritic cumulate which started to break. The uplifting could be due to the same movements which produced the break-up of the pyroxenites which formed the nodules. If pyroxenitic and uplifted noritic layers had contributed to the formation of the nodules, the presence of pyroxenitic and noritic nodules could be easily explained by the break-up of these layers as a result of some disturbance in the magma chamber. These disturbances may include earthquakes, fracturing of the roof, the emplacement of a new magma addition, resulting in increased current action. If current action caused the break-up of a pyroxenite layer, the nodules may be equated to an intraformational breccia.

According to the separate injection theory (e.g. Schwellnus, 1956; Coertze, 1958) the anorthosite layer which contains the nodules could be a new magma addition. Acontentions to this possibility are given by Ferguson and Botha (1963, pp.274-275), Hess (1960, pp. 53 and 156), Willemse (1964, p.117) and Wager and Brown (1968, p.345), who showed that the mafic rocks of the Bushveld Complex are more likely to be a product of crystal accumulation.

The Merensky 'Reef' has been regarded as one of the typical examples where a new pulse of magma was added to the differentiating sequence (Wager and Brown, 1968). The reasons for this interpretation are phase layering and marked change in composition of the cumulus phases across this contact. The nodules show Mg-rich olivine and an En content of orthopyroxenes similar to that of the orthopyroxene within the Merensky 'Reef', cumulus orthopyroxene in the nodules shows a marked compositional change with respect to the surrounding orthopyroxene cumulus which suggests the hypothetical pyroxene which formed the nodules could have originated from a new magma pulse before breaking up.

The site of crystallization may have influenced the formation of the nodules. The pyroxenite which is supposed to have formed the nodules may have formed as a raft of crystal mush in the magma chamber. Lauder (197[illegible] is of the opinion that mats of pyroxenite can form at a relatively early stage in the crystallization of a layered intrusion with magma above and below them. If at this point the magma chamber was disturbed by some exterior force, for example a tremor, an early formed pyroxenite could have broken and be taken as fragments by magma currents, to form nodules. On the other hand currents may have broken and transported semi-consolidated pyroxenite on the floor of the intrusion. If we consider a M.R.U. to have formed by accumulation of crystals at the bottom of the magma chamber, we could envisage the following process:

After the norite underlying the a.c.n. finished accumulating this anorthosite began to accumulate. The crytallization of anorthosite was finally interrupted and a new M.R.U. was initiated with the precipitation of chromite followed by pyroxene. At this point the magma chamber was disturbed which increased magma current activity or produced load-casting effects, and the partially consolidated dense pyroxenite started sinking in the underlying and loosely packed lighter anorthosite, producing an intraformational breccia. The bleached zones around the nodules could be explained by diffusion of the pyroxene enriched liquids towards nucleating centres like the nodules. This bleaching phenomena is also observed around the bottom contact of the Merensky 'Reef' and around some chromitite layers of the Upper Group.

If the theory of formation of the nodules by breaking off of several layers is accepted, it would appear that accumulation in the middle and upper stages of the Critical Zone progressed under violent movements in the magma chamber. This is borne out by the fact that depressions, which are thought to have been produced by current action (Ferguson and Botha, 1963), are known above and below the layer containing the nodules, and the fact that Cameron (1971) suggested violent movements of the magma within the chamber to explain the jumbled layering of the 'K unit' approximately in the middle of the Critical Zone. Furthermore it has been shown (Wager and Brown, 1968, p.543) that the earlier part of the crystallization history of the Bushveld progressed under unstable conditions. This comprises the "the integration stage, Basal and Critical Series", and suggests the possibility of several additions of magma to the differentiating sequence.

8. - Tonalitic pegmatites

There are several problems related to the genesis of tonalitic pegmatites. These are: the time, and conditions influencing their emplacement; their association to layers of pyroxenitic and noritic composition with preference to anorthositic layers; and the contrast of their mineralogy with that of the layered host rock.

The field relationships show that tonalitic pegmatites are younger than the layers which contain them and possibly older than ultramafic pegmatoids. The fact that tonalitic pegmatites pinch out in the thick chromitite layers, where only a barren crack continues through the chromitite, and transgress thin chromitite layers immediately above may indicate a moderate amount of pressure, enough to expand the fissure in one case but not in the other. The lengths of tonalitic pegmatites are 1 000 times their widths, a fact which could point to the possibility that tonalitic pegmatites contributed to some extent to the opening of fractures during emplacement. The fact that lengths are 1 000 times the widths in lamprophyre dykes caused Currie and Ferguson (1970) to postulate an initial mobile gaseous phase, which could enlarge fissures, as the percursor of emplacement. Successive 'builds-up' in pressure would off-set the volatiles to other fissures. Ramsay and Sturt (1970) consider that thin hair-like and curved apophyses may have been formed by filling of fractures produced by the intruded magma. This would be facilitated by a highly mobile fluid under hydrostatic pressure. Feringa and Cousins (1963, p.280) note that "gash veins filled with pegmatite are common around the rims of potholes" and conclude that they are almost certainly tension cracks. Ferguson and Botha (1963, p.280) remark that they may be indeed a tensional feature but their presence is by no means confined to the rims of depressions.

The association of tonalitic pegmatites with pyroxenitic and noritic layers may be related with the characteristics of the residual liquids in these layers. The pegmatoid pyroxenite layers associated with the Merensky 'Reef' and with the UG 2 M.R.U. could be well described as mesocumulates, in which part of the intercumulus liquid was not expelled. It has been shown that normative quartz is present in most of the pyroxenitic and some of the noritic cumulates analysed. Wagner (1973) points out that quartz is present in the Merensky 'Reef'. Wager and Brown (1968, p.384) stated that occasional small patches of quartz are found in a few olivine-free cumulates from the lower zones of the Bushveld Complex, suggesting that mesocumulates, with a small amount of pore material, occur inter-layered with adcumulates and heteradcumulates. On the other hand, micas are also present in noritic and pyroxenitic layers of the Critical and Main Zones, therefore it would appear that in these layers a different quartz-alkali-rich liquid would not be so difficult to obtain. The presence of biotite in tonalitic pegmatites and hydrous alteration products in their immediate vicinity suggests that the role of water was important in the development of this rock type. The highest concentration of tonalitic pegmatites inside depressions remains to be explained.

One possible explanation for the contrasting chemistry of tonalitic pegmatites and host rock could be obtained, if tonalitic pegmatite represented the residual intercumulate liquid of pyroxenitic and noritic layers which was emplaced into fractures. Schmidt (1952) effectively indicates a mode of origin by referring to tonalitic pegmatites as segreagational veins, and (op.cit. p.247) concludes that "the veins obviously represent the residual fraction of the magma which invaded the cracks in the Merensky Reef".

C - Granitic pegmatites

Hiemstra and Van Biljon (1959) propose that microcline-perthite-quartz-muscovite-tourmaline pegmatites of the Eastern Bushveld are "secretion pegmatites which have grown at the expense of the wall rock".

Willemse (1969a, pp. 10-11) states that "granite pegmatite occurs sporadically and cannot generally be referred to a granite intrusion. As rheomorphism and feldspathization of arenaceous inclusions are known to have occurred, the granite pegmatite evidently owes its origin to local anatexis and granitization of sedimentary material".

It is felt that at this stage very little can be said about the origin of the granitic pegmatites found at Bafokeng. Further data are required before serious conclusions may be drawn. However several points are noteworthy, namely:

- They are related to the main fracturing system of the area,
- They are younger than all the rest of the pegmatites and pegmatoids studied.
- They seem to be abundant within ultramafic pegmatoids.

Their chemistry should be studied further to ascertain whether amphibole-rich phases are merely a reaction phenomena, or are primary crystals. In this respect euhedral pegmatitic ferro-tschermakites with associated sulphides and oxides represent a puzzling problem.

A localization of granitic pegmatites in ultramafic pegmatoids, could be related to the elastic properties of the latter. In this respect Middlemost (1965, p.59) records graphic granites mainly localized in hornblendites of the Kheis system. Quoting Anderson (1931), he suggests that: "the elastic properties, the facility with which they fracture and the larger thermal contraction, are some of the factors which may have influenced the localization of granitic pegmatites in amphibolitic country rock in preference to other country rock types". However contemporaneous co-existence of mafic and granitic magmas produced by sluggish mixing rates, could also explain the field relationship. (Yoder, 1973).

D - Late ultramafic pegmatoids

1. Mineralogy.

Several of the features present in pegmatitic plagioclases within ultramafic pegmatoids could have been produced by the effects of pressure. These features are fractures, glide twinning and granulation. Schwellnus (1956) attributed fracturing in plagioclases within ultramafic pegmatoids to pressure. Glide twinning could be attributed to bending. Vance (1961, p.108) notes that "even more commonly secondary lamellae are genetically related to an evident bending or twisting of the crystal such that the lamellae are localised and most broadly developed in the areas of greatest strain". As noted by Vance (1961, p.112) the most significant single process in the formation of glide twinning is deformation of the plagioclase by forces external to the rock, but several other processes have been postulated to account for its formation. Among others, stresses caused by mutual interference of grains during crystal growth, stresses set up within crystals upon heating or cooling, etcetera. The process of granulation in plagioclase has been described by Kaye (1965) in the titaniferous magnetite deposits of Sandford Hill. Kaye (Ibid, p.1286) found that granulation and development of mafic silicate minerals seems to be closely related, and that in this case granulation would not only be explained by distributive shear. "Geothermal gradients produced by shear favoured the emplacement of the oxide phase".

According to Kays (op.cit.), another process which could produce cataclastic textures are movements during crystallization and filter-press action.

The composition of the plagioclase in ultramafic pegmatoids, as obtained by chemistry, X-ray fluorescence and optical methods, is between 4 and 5 per cent richer in the An component than the plagioclase in the layered rocks at the same height (Tables 11, 15 and 16). If plagioclase from the layered rock is assimilated into the composition of ultramafic pegmatoids, the water-rich fluids in the latter magma could account for the enlargement of plagioclase from the layered rock. Subsequently the included plagioclase develops glide twinning and fractures, which become filled with mafic material, as a result of pressure exerted by the crystallizing mafic crystals.

The higher An content of plagioclase within ultramafic pegmatoids as compared to plagioclase in the layered rocks at the same height, could be produced by it recrystallizing under conditions of increased pressure, which is in accordance to the findings of Yoder (1954).

It is also possible that the plagioclase found in ultramafic pegmatoids has crystallized directly from the ultramafic pegmatoid magma. It is interesting to note however that while clinopyroxene (Fe 16) and olivine (Fo 38-57) in ultramafic pegmatoids, show enrichment in low T end members with respect to clinopyroxene (Fe 9) and olivine Fo 82-85 in the adjacent rock, plagioclase shows enrichment in high T end members. Clinopyroxenes are more abundant when ultramafic pegmatoids are developed in anorthositic cumulates, whereas they are subordinate to olivine and amphibole when ultramafic pegmatoids develop in pyroxenitic cumulates. The fact that Ca-rich minerals, plagioclase and augite, develop within ultramafic pegmatoids emplaced in anorthositic cumulates could point to incorporation of layered anorthositic rock into ultramafic pegmatoid magma. This possibility is supported by the fact that the average Ca content in ultramafic pegmatoids emplaced in anorthositic cumulates (Av5 Table 20) is 8,6 which is higher than the Ca content of the ultramafic pegmatoid analysed within the Merensky 'Reef' which is 6,4, Table 20.

One relationship which has been reported but not yet found at Bafokeng, is the formation of clinopyroxene at the expense of olivine (Schwellnus, 1956, p.145, among others). According to Ruckmick and Noble (1959), quoting Clayton (1955), olivine can be converted to magnetite and pyroxene according to the reaction:

$3Fe_2SiO_4 + 3Mg_2SiO_4 + 2H_2O = 2Fe_3O_4 + 2H_2 + 6MgSiO_3$, which is possible if water circulates through an alteady formed ultramafic pegmatoid.

On studying the mineralogy of olivines one of the main problems was to estahlish its origin in the Merensky 'Reef'. Within the Merensky 'Reef' crystals of olivine included in feldspar or orthopyroxene could be primary in the sense that they were deposited contemporaneously with the other cumulates or alternatively could have a secondary origin. A point in favour of the first alternative is:

- the subhedral to euhedral habit of these olivines, which is difficult to explain if a replacement process is to be accepted.

Points in favour of the second alternative are:

- the fact that the included olivines were only found when the Merensky 'Reef' is in contact with or surrounded by ultramafic pegmatoids,
- the non-cumulative nature of these olivines,
- the composition of the olivine included in the Merensky 'Reef' (Fo 85), which differs from that reported by Coertze (1969) for olivines within the Merensky 'Reef' in the Western Bushveld which are Fo 78-80.

Because of these points and the fact that in the same exposure anhedral olivine from the ultramafic pegmatoid, shows reaction against orthopyroxene cumulus, and replaces orthopyroxene (Photo 33) it seems possible that the included olivines were formed as a result of the juxtaposition with the ultramafic pegmatoid. Schwellnus (1956, pp.106-107) stresses the fact that marginal norite adjacent to dunite is impregnated with olivine, and that pyroxenite layered rock, next to chrysolite dunite pipes is olivine-bearing. Heckroodt (1959, p.67) found that the norite which surrounds the Driekop dunite pipe is olivine-bearing. He attributes the formation of this olivine "to liquids, undersaturated in silica and derived from the dunitic "magma", which penetrated the surrounding noritic rocks forming olivine at the expense of the pyroxene". The olivine within the Merensky 'Reef', marginal to ultramafic pegmatoids averages Fo 85 compared to an average of Fo 56 in fine-grained ultramafic phases at the contact between ultramafic pegmatoid and Merensky 'Reef' and an average of Fo 38 of olivines within the underlying ultramafic pegmatoid. In this case the olivines further away from the ultramafic pegmatoids show the highest Fo contents.

In borehole 553 the Fo content of olivine in a troctolitic pegmatoid is Fo 71 which is higher than that of olivine in adjoining ultramafic pegmatoid being Fo 57 to 63 respectively. In borehole 553 the layered rock, host of the troctolitic pegmatoid is a gabbroic cumulate.

Van Rensburg (1962, p.30) notes that a troctolitic character is imparted to ultramafic pegmatoids, where the disintegration of noritic inclusions has reached an advanced stage. Schwellnus (1956, p.127) has noted that "troctolitic rocks, olivine, plagioclase bearing have been produced by noritic country rock being included in dunite pipes". In the case of borehole 606 and borehole 553, if a gabbroic rock has produced the troctolitic pegmatoid, on the margins of the ultramafic pegmatoids we would have a condition in which the Fo content of olivine within the ultramafic pegmatoid increases outwards, and is highest at the contacts. Steyn (1955, p.61) states that dunites are not in direct contact with gabbroic rocks but separated from them by a zone of decomposed gabbro pegmatite. Steyn (op.cit., Table IX) shows that the olivines in this gabbro pegmatite has a Fo content 2-6 per cent higher than the olivine in dunite.

The question arising is why olivine marginal to ultramafic pegmatoid bodies is richer in Fo than the olivine found within these bodies? We shall consider two alternatives, assuming that ultramafic pegmatoids produced these olivines:

the marginal olivine is a late product
the marginal olivine is an early product.

In the first alternative, the marginal olivines could be a late product of the ultramafic pegmatoid magma. If so the olivine composition should be richer in iron than those occurring within the ultramafic pegmatoid, especially because the latest minerals within the ultramafic pegmatoid are iron rich.

If the marginal olivines are produced early during the crystallization of an ultramafic pegmatoid they could be richer in Mg than the later olivines crystallizing more centrally within the ultramafic pegmatoids. If undersaturated water-rich fluids are in equilibrium with the ultramafic pegmatoid magma it could be expected that marginally to ultramafic pegmatoids, olivine would form at the expense of orthopyroxene producing Fo-rich olivines.

Magnetite is of special importance since it represents the product of final enrichment in iron and titanium within ultramafic pegmatoids.

Regarding the relationship between marginal ilmenite and magnetite found in some magnetitite pegmatoids, Edwards (1964, p.64) notes that unmixing takes place rapidly at high T when diffusion is high, but if cooling is slow ilmenite tends to diffuse to the margins of the magnetite crystals so that the final product may be granular.

The relationship between the layered chromitites and magnetitite pegmatoids was studied by several authors. Frankel (1941) reported transitions between magnetite and chromite. Coertze (1958) notes that when pipe-like dunite bodies with magnetite cores "occur within the chromitite zones, the magnetite continues outwards from the pipe-like bodies into the country-rock and follows the chromitite seams in sheet-like fashion, transgressing it in places and enclosing chromitite fragments". Cameron and Desborough (1964, pp.210-211) reported that when magnetite-rich facies of ultramafic pegmatoids are in contact with chromitite layers "instead of a contact, there is an unbroken transition from chromite to titanomagnetite".

At Bafokeng, ultramafic pegmatoids develop magnetite-rich phases below chromitite layers. According to Cameron and Desborough (1964) the gradations in reflectivity and unit cell measurements found between chromitite layers and underlying magnetitite pegmatoids do not prove changes in composition therefore they are not per se evidence for a replacement origin for the magnetitite pegmatoids.

e. Sulphides. - Relative to the sulphides in the layered rocks those in the ultramafic pegmatoids show Fe enrichment. This is especially true of sulphides contained in magnetitite pegmatoids, where Cu and Ni sulphides are replaced and mobilized by magnetite.

2. <u>Contacts</u>.

Upon studying the contacts between ultramafic pegmatoids and layered rocks it was noticed that the composition of ultramafic pegmatoids becomes more feldspathic along some contacts. Van Rensburg (1962, p.30) and Willemse (1964), attributed the same fact to the incorporation of norite from the adjacent country rock to the ultramafic pegmatoids. Infrequent inclusions of layered rock in ultramafic pegmatoids were found at Bafokeng (Photo 12). In Fig. 15

section B, projecting the position of the layering through the ultramafic pegmatoids it is found that the orthopyroxenes in ultramafic pegmatoids have the same composition as those of the different projected layers. This feature which is also evident from Table 21, and the fact that the orthopyroxenes in ultramafic pegmatoids show resorbed margins suggests that orthopyroxenes in ultramafic pegmatoids represent remnants of incorporated host rock.

3. Emplacement of ultramafic pegmatoids.

At Bafokeng the undisturbed character of the Merensky 'Reef' and B.M.R. with development of ultramafic pegmatoids argue for a passive type of emplacement for these bodies. Usually ultramafic pegmatoids display evidence of passive emplacement (Cameron and Desborough, 1964; Willemse, 1964, p.118) however a few occurrences of forceful emplacement have been reported (Schwellnus, 1956; Willemse, op.cit.; Ferguson and McCarthy, 1969).

The relationship between the emplacement of ultramafic pegmatoids and faults have been discussed by several authors. Wagner (1973) suggested a potential line of weakness in the underlying rocks to explain that the pipes of Onverwacht, Mooihoek and Driekop were confined to a straight line about ten miles in length which strikes N 53 W. Cousins (1962, p.261) suggests that ultramafic pegmatoids are related to zones of disturbance in the Bushveld rocks, and later Cousins and Feringa (1964, p.195) state that discordant bodies of pegmatitic pyroxenite have been described in the vicinity of the chromitite layers. "They are related to faulting and zones of disturbance, grade into normal Bushveld rocks and are more likely metasomatic than intrusive". Coertze (1962) postulates that in the Western Bushveld, the Rustenburg fault controlled the emplacement of the ultramafic pegmatoids. Several authors have disagreed with this interpretation, among others Liebenberg (1969, p.167), who points to the fact that the Rustenburg fault does not pass through Vlakfontein. Willemse (1969b, pp.188-189) states that "the suggestion by Coertze (1962, p.253) that the dunite and diallagite pegmatoid in the Rustenburg district, Western Transvaal, are related to faults is not borne out by the evidence of the occurrence in the Critical Zone in the Eastern Transvaal". However, Willemse (1964 and 1969b) states that the magnetitite pegmatoid of Kennedy's Vale, Eastern Transvaal could be related to a faulting system. Willemse

(1969b, p.192) states "No direct relationship with the faults in the Buffelshoek-Kennedy's Vale area is, however, apparent - the faults are younger - unless a vaguely defined weak zone is indicated along which pegmatoids concentrated and faulting occurred at a later date". Cameron and Desborough (1964, p.213) found that fracture control is evident in some ultramafic pegmatoids of the Eastern Transvaal. From Ferguson and McCarthy's (1969, p.75) data, and the author's own observations around Tweefontein in the Eastern Transvaal, it is evident that joint control is an important controlling factor in the emplacement of ultramafic pegmatoids in this area. Fault control was not proved at Bafokeng. There is however some evidence of joint control and bedding plane control, which seems to indicate a certain degree of cooling of the layered rock prior to their emplacement. The fact that certain ultramafic pegmatoids have exceeded the lithostatic pressure, and have been emplaced by forceful injection points to the same possibility (Ferguson and McCarthy, 1969). The fact that ultramafic pegmatoids are emplaced conformably below layered rocks, could indicate certain characteristics of the fluids which produced the ultramafic pegmatoids. Ramberg (1970, p.285) concludes that different types of structures develop depending upon differences in viscosity between the moving material and the surrounding 'crust'. "If the viscosity contrast is large the flow pattern is strongly controlled by the structures of the surrounding "crust", the "magma" following layering and other zones of weakness in layered models. With smaller viscosity contrast between the moving material and the surroundings, the shape and path of the rising perturbations are little affected by the structure of the surroundings".

The presence of intermittent layers of ultramafic pegmatoids (Photos 13 and 14) in the vicinity of ultramafic pegmatoid contacts with country rock, was seldom observed. A suggestion as to their origin is difficult to make but intermittent layers were only found when ultramafic pegmatoids are emplaced in anorthositic rocks. Loomis (1963, p.66) has reported "combed layers" along intrusive contacts and around inclusions, and stressed that "the combed structure suggests but does not prove rapid crystallization on solid surfaces. Opening of fractures in wall rocks during rapid emplacement of wet magmas from a lower level is the type of structural control envisioned".

Among the methods of emplacement of ultramafic pegmatoids replacement has been suggested by Cameron and Desborough (1964). At Bafokeng reaction relationships, and hence lack of equilibrium conditions, were found in narrow (0,1-0,5m) zones at the immediate contact of ultramafic pegmatoids with the host rock. The formation of olivine and hornblende in fine-grained ultramafic phases at the expense of orthopyroxene cumulus could be viewed as a replacement reaction. However, the majority of the contacts lack a reaction zone between ultramafic pegmatoids and layered rock. There are differences in SG between ultramafic pegmatoids (3,97) and the layered rock, anorthosites (2,77) norites (2,98). These differences could suggest that if ultramafic pegmatoids are penecontemporaneous with the layered rock, for the ultramafic pegmatoids to be emplaced in fractures and following layered contacts, they would have had to have a solidus temperature lower than that of the layered rock. Von Seifert and Schreyer (1966) have indicated that "amounts of potassium as low as 1 per cent may already convert solid ultramafic materials, with predominantly forsterite, into crystal mushes that remain mobile and thus able to intrude other rocks down to temperatures of about 700°C". In ultramafic pegmatoids some K is present in micas and plagioclase, the highest K+ content reported being 1,67 weight per cent (Van Zyl, 1969). There is then the possibility that the liquids which produced the host rock reached solidus temperature while the liquids which produced the ultramafic pegmatoids were above it. If that was the case then they would have been out of equilibrium and minor reaction phenomena along contacts could have occurred.

4. Other features.

A possible genetic connection between ultramafic pegmatoids and depressions in the Merensky 'Reef' has been suggested by Feringa and Cousins (1963, p.280). In the subsequent discussion Ferguson and Botha (1963, p.281) state that "The fruquent association of cross-cutting feldspathic pyroxenitic pegmatites and depressions is not surprising in view of the ubiquitous development of the former bodies throughout the Critical Zone". At Bafokeng no evidence was found to support a genetic connection between late ultramafic pegmatoids and depressions.

Localization of ultramafic pegmatoids in certain layered rocks has been found by Coertze (1969, p.15) who notes that in the area north of the Pilanesberg alkaline Complex most of the ultramafic pegmatoids occur in the ferrogabbro of the Upper Zone (Fig. 1). It is of note that the projection of the trace of the gabbro unit (Main Zone) through the transgressive portion of the ferrogabbro (Upper Zone) results in most of the ultramafic pegmatoids north of the Pilanesberg falling within the limits of the transgressed portion.

South and SE of Pilanesberg ultramafic pegmatoids are emplaced mainly within the gabbro unit of the Main Zone. At Bafokeng ultramafic pegmatoids are emplaced and expand more readily in rocks of anorthositic composition than in those of pyroxenitic composition.

5. <u>Chemistry</u>.

It is interesting to compare ultramafic pegmatoids with ultramafic rocks of complexes like Duke Island and others which show high iron contents. Table 31 shows analyses taken from Tables 2 and 3 of Taylor and Noble (1969) and an average of three analyses from Bafokeng (Av5).

TABLE 31. Comparisons between ultramafic pegmatoid analyses from Bafokeng (Av5), and other ultramafic rocks.

	1	3	5	Av.5	4
SiO_2	38,3	39,5	40,0	39,69	50,7
Al_2O_3	7,2	-	10,6	1,86	1,6
Fe_2O_3	13,3	-	-	2,87	1,6
FeO	9,7	-	-	24,96	3,9
Tot. Fe	16,8	17,4	14,5	27,54	-
MgO	11,7	-	-	12,6	20,2
CaO	16,7	-	13,8	12,72	20,9
Na_2O	0,9	-	-	0,05	-
K_2O	0,2	-	-	0,01	-
TiO_2	1,8	2,1	1,9	3,76	0,3
MnO	0,1	-	-	0,36	0,1
P_2O_5	-	0,2	0,5	0,13	-
H_2O+	0,2	-	-	1,12	0,3
H_2O-	-	-	-	0,04	0,2

- = not given in original.

1. Duke Island) Magnetitite-hornblende pyroxenites
3. Klukwan) from Table 3 - Taylor and Noble (1969)
5. Percy Islands)

Av.5 Bafokeng. Average of CBGF, UPMR and 553 Be

4. Kanjakovski-Kamen, Olivine pyroxenite. From Table 2,

Taylor and Noble (1969).

Analysis 4 has 0,5 per cent Cr_2O_3.

From a comparison of the modes it appears evident that the iron content of ultramafic pegmatoids at Bafokeng is higher than that of iron-rich ultramafic rocks. Contact phenomena do not rule out the possibility that ultramafic pegmatoids would have been 'contaminated' by the incorporation of layered rock so it is pertinent to look at the feasibility of this process. Given an ultramafic pegmatoid of a known composition the questions arising are: How to get this composition by mixing layered rock and an unknown 'magma' and in what proportions? An addition and subtraction diagram of the type used by Bowen (1956) was constructed (Fig. 24) to try to answer these questions. (The chemical compositions used in the construction of figure 24 are given in Table 32.)

In Fig. 24, the average ultramafic pegmatoid below the Merensky 'Reef' and the average noritic cumulate, which is thought to represent the average magma composition, at the same elevation, are plotted on a base line of silica content. Lines A and S are the limiting compositions determined by FeO and Al_2O_3 respectively. It is of note that TiO_2 limits the composition more than FeO, but as in the layered rock Ti is an accessory element, it was not considered as accurate as iron. The same is the case of Na_2O and K_2O, which limit the composition more than Al_2O_3, see inset in Fig. 24, but have a very low concentration in ultramafic pegmatoids. To get a magma with the composition of the average ultramafic pegmatoid as found below the Merensky 'Reef' we must mix 8 per cent of the average noritic cumulate with 92 per cent of a magma of composition A. The modal and normative components the Limiting Composition A are given in Table 32. If either Na_2O or K_2O were chosen as limiting compositions the amount of normative anorthite in composition A would be zero. The importance of this diagram is shown by the fact that to explain contaminations higher than 8 per cent of ultramafic pegmatoid magma by layered rock, migration of elements like Na and K becomes necessary, because more extreme compositions of ultramafic pegmatoids are not obtainable since Na_2O and K_2O are already zero in the ultramafic of composition A. If we plot ultramafic pegmatoids against anorthositic cumulates, the limiting compositions are almost equal to those of the analysis compared.

In ultramafic pegmatoids at Bafokeng the average Ni content is

FIG. 24. Addition-Subtraction diagram.

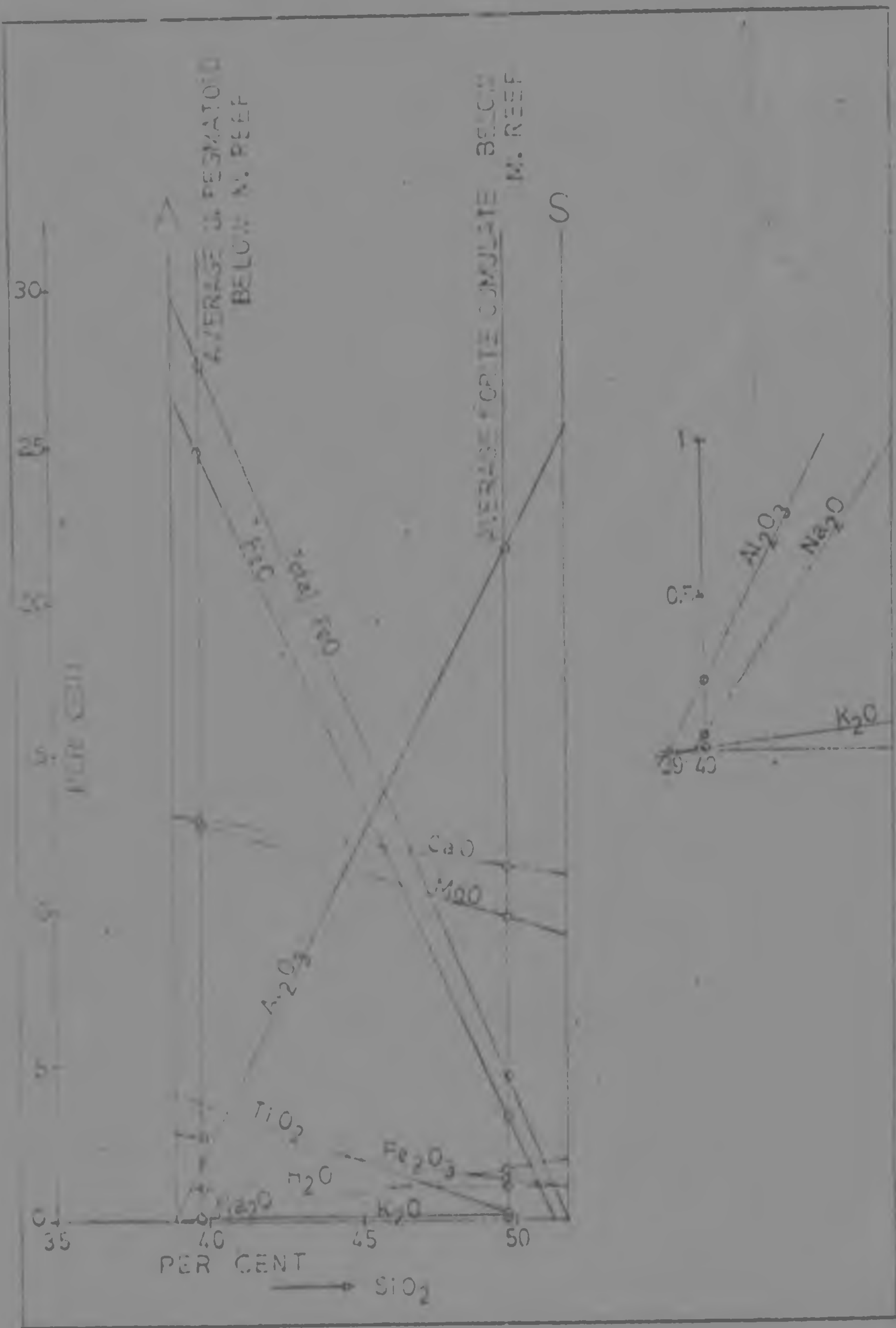


TABLE 32. Chemical compositions used in the construction of the addition-subtraction diagram of Fig. 24.

	Average ultramafic pegmatoid below the M. 'Reef'	Av. norite cumulate below the M. 'Reef'	Limiting composition A	Normative components of composition A	
SiO_2	39,69	49,38	38,85		
Al_2O_3	1,86	21,50	0,1	An	0,27
Fe_2O_3	2,87	1,46	-	$CaSiO_4$	0,67
FeO	24,96	3,28	-	Magnetite	4,09
Total FeO	27,54	4,60	29,80	Ilm	9,18
MgO	12,60	9,59	12,9	Olivine	34,18
CaO	12,72	11,31	12,9	Diopside	51,61
Na_2O	0,05	1,54	-		
K_2O	0,01	0,13	-		
TiO_2	3,76	0,12	4,2		
MnO	0,36	0,08			
P_2O_5	0,13	0,14			
H_2O+	1,12	1,23	1,1		
H_2O-	0,04	0,06			

H_2O- not plotted in Fig. 24.

similar and the average Cu content generally higher than that of ultramafic pegmatoids analysed by Liebenberg (1960, Table 210) at Onverwacht and Mooihoek, lower down in the Critical Zone. Furthermore as the distribution of Ni and Cu in ultramafic pegmatoids at the top of the Critical and bottom of the Main Zones may have been influenced by the incorporation of Ni and Cu-rich sulphides from the layered rocks, therefore no evidence of fractionation in the fluids which produced the ultramafic pegmatoids can be based solely on the Ni and Cu results. The same applies to Rb and Sr, and in addition the Rb and Sr contents of Basal Zone and chill phase are not accurately known.

6. Composition of the intercumulus liquids in the Critical Zone.

One of the main problems of the investigation was to answer the following question: can intercumulus liquid produce ultramafic pegmatoids?

The requirements necessary to answer this question are:

- an accurate knowledge of the composition of the evolved magma at any one stage, (1)
- an accurate knowledge of the phases which crystallized from the trapped intercumulus liquid (2).

As the trapped material represents the composition of the magma

- subtracting (2) from (1), the material which had to be added or subtracted from the trapped magma considered, to produce intercumulus crystals of the composition observed, could be obtained.

At Bafokeng, (2) could be calculated from direct observation. The composition of the magma approximately 20m below the Merensky 'Reef' was thought to be represented by the average noritic cumulate below the Merensky 'Reef'. The reason for this assumption is that this noritic cumulate shows approximately the same proportions of the two cumulus minerals crystallizing at the top of the Critical Zone, namely orthopyroxene and plagioclase.

Analyses 1637 and 722, both of noritic cumulates below the Merensky 'Reef' were averaged. It is then assumed that the composition of the trapped material equal to that of the contemporary magma, can be estimated from the average of these two analyses (Table 33).

In the portion of the Critical Zone which was studied, anorthositic cumulates are the more frequent hosts to ultramafic pegmatoids, therefore the path of crystallization of intercumulus material in one of these anorthosites was considered. From a modal count, Fig. 8, an average anorthosite is seen to be composed of 91 per cent plagioclase and nine per cent pyroxenes, of which:

26 per cent is zoned plagioclase, which probably represents intercumulus growth,

5 per cent is orthopyroxene, of which 0,9 per cent is zoned,

4 per cent is orthopyroxene, of which 0,8 per cent is zoned.

The following objections can be made to these figures:

- the proportion of intercumulus material (35%) is in accordance with the figures given by Wager and Brown (1968, p.554) under normal packing conditions. However, Wager and Brown (op.cit. p.66) remark that "A rock containing 80 per cent of plagioclase is likely to have been produced by loose packing of 50% of plagioclase tablets, followed by adcumulus growth giving about 20% more plagioclase of the same composition and, finally, by the deposition from the trapped liquid of about 10% of lower tempasrature, more sodic plagioclase".

It was determined that the composition of the zoned plagioclase is An 80, as compared to An 76 of the cumulus. No complex zoning of the type described by Ferguson and Wright (1969) was found.

Taking into account zonation, the pyroxenes gave an average composition of En 76 and clinopyroxene Ca 44 Mg 45 Fe 11.

The volumetric proportions of zoned plagioclase, clinopyroxene and orthopyroxene were recalculated to weight per cent (Table 33). The 34,99 was recalculated to 97,9 per cent and named (Avincr). Comparison with the magma composition, as represented by the average rock (Av.mgm) was then made (Table 33).

Theoretically, if during the process of postcumulus growth there had not been exchange of material between the trapped liquid and the overlying magma, the composition of the products of crystallization of the intercumulus liquid should be equal to the composition of the magma trapped. Since analyses Av mgm and Av incr are different, material must have been exchanged between the magma and the trapped liquid. By subtracting Av mgm from Av incr the material exchanged during intercumulus growth becomes apparent (Table 33). The material 'extracted' from the average magma to produce the observed intercumulus minerals is mainly MgO and FeO in a ratio FeO/MgO 0,386.

TABLE 33. Calculations of the composition of the trapped magma approximately 50m below the Merensky 'Reef'.

	Average magma Average of analyses 1637 and 722	Average of ultramafic pegmatoid below the Merensky 'Reef'	Average intercumulus liquid in an anorthosite cumulate (Av incr) 35% intercumulus plagioclase + opx + cpx	 35% recalculated to 97,92%	Av. mgm minus Av. incr
SiO_2	49,34	49,38	17,44	48,81	- 0,54)
MgO	9,60	12,60	2,12	5,93	- 3,67) 6,52
Total FeO	4,60	27,50	0,82	2,29	- 2,31)
CaO	11,32	12,72	5,28	14,78	+ 3,46)
Na_2O	1,55	0,05	0,62	1,74	+ 0,19) 6,51
Al_2O_3	21,51	1,86	8,71	24,37	+ 2,86)
Total	97,92		34,99	97,92	

TiO_2, MnO_2, H_2O+, H_2O- not included.

mgm = magma

Av = average

Av.mgm = Average magma

Av.incr = Average intercumulus liquid in an anorthosite cumulate

\- extracted from the Av mgm to produce Av incr.

\+ added to Av mgm to produce Av incr.

The material 'added' is mainly CaO, Al_2O_3 and Na_2O. Supposing that the material 'extracted' instead of migrating to the overlying magma had migrated laterally within the anorthosite considered, could it have produced ultramafic pegmatoids?

If we compare the FeO/MgO ratio of the 'extracted' material with that of the ultramafic pegmatoids, the latter varies from 2,89 in sample UPBMR, to 1,06 in sample 553, differing considerably from the value of 0,386 of FeO/MgO of the 'extracted' material. Therefore it seems that if instead of migrating to the overlying magma, the 'subtracted' material had done so laterally, the ultramafic pegmatoids would be more enriched in magnesium than in iron.

7. Comparison of the average magma (Av mgm) with a rock obtained by mixing the average anorthositic layered rock and ultramafic pegmatoids. All these rocks below the Merensky 'Reef'.

It was thought interesting to compare the average magma below the Merensky 'Reef', represented by Av mgm, with a rock obtained by mixing the average layered anorthosite below the Merensky 'Reef' with the average ultramafic pegmatoid below the Merensky 'Reef'. The reason for this exercise was the localization of ultramafic pegmatoids in anorthositic layered rock and the possibility that ultramafic pegmatoids could represent the 'unwanted' intercumulate material of the anorthositic layers (Table 34).

TABLE 34. Comparison of the average magma (Av mgm) with a rock obtained by mixing the average anorthositic layered rock and the average ultramafic pegmatoid. All these rocks below the Merensky 'Reef'.

	Av UP	Av. An a.c.n.	10 weight per cent of ultra-mafic pegmatoid	+	90 weight per cent of anor-thosite a.c.n.	=	100%	Noritic cumulate (Av mgm)
FeO	24,96	1,31	2,49		1,18		3,67	3,28
Fe_2O_3	2,87	0,20	0,29		0,18		0,47	1,46
MnO	0,36	0,04	0,03		0,03		0,06	0,08
TiO_2	3,76	0,05	0,37		0,05		0,375	0,12
CaO	12,72	14,82	1,27		13,34		14,61	11,31
K_2O	0,01	0,20	0,001		0,18		0,181	0,13
P_2O_5	0,13	0,16	0,013		0,14		0,153	0,14
SiO_2	39,69	48,31	3,96		43,47		47,43	49,38
Al_2O_3	1,86	29,86	0,18		26,87		27,05	21,50
MgO	12,60	2,17	1,26		1,95		3,21	9,59
NaO	0,05	2,44	0,005		2,19		2,195	1,54
H_2O+	0,04	0,06	0,004		0,05		0,054	0,06
H_2O-	1,12	0,79	0,11		0,71		0,82	1,17

Av UP = Average ultramafic pegmatoid below the Merensky 'Reef'
Av An = Average anorthosite cumulate below the Merensky 'Reef'
Av mgm = Average magma

Although no true estimate was made throughout the mine, it was estimated that in the 5 Shaft area ultramafic pegmatoids occupy 10 per cent by volume of the anorthositic layers found between the Merensky 'Reef' and the bottom contact of the a.c.n. Based on this estimation 10 per cent of ultramafic pegmatoid was added to 90 per cent of anorthositic rock and compared with the average magma represented by the average noritic cumulate. The results are given in Table 34.

This comparison is hampered by the fact that weight per cent of oxides are compared, and the percentage of ultramafic pegmatoids in anorthositic cumulates was obtained by volume.

8. Origin of structures studied in connection with ultramafic pegmatoids.

The structures described in 344 Stope, 377 Raise and 1 East Drive 1 Shaft, do not seem to be connected with the emplacement of ultramafic pegmatoids. The folded structure in 344 Stope (Fig. 20) was produced in the same stope without connection with ultramafic pegmatoids, and furthermore no transgression of the layering was observed at the apex of the fold.

Regarding the exposure in 377 Raise (Fig. 21), several facts have to be considered. The mineralogy of the cross-cutting pipe shows a noritic composition in which the En content of orthopyroxenes is similar to the orthopyroxenes within the Merensky 'Reef' (i.e. En 80). This, together with the fact that orthopyroxenes are not considered to be primary minerals in late ultramafic pegmatoids could suggest that there is no genetic connection between the cross-cutting pipe and the ultramafic pegmatoid intersected down dip. If there is no genetic connection between the two, another origin must be postulated for the cross-cutting pipe. Down dip from the pipe, the Merensky 'Reef' and its immediate anorthositic cumulate footwall show features which may have been the product of slumping. These features are intermittent layering, branching of the chromitite layer of the Merensky 'Reef', pyroxenite interlayered with anorthosite with the pyroxenite showing Pt, Cu and Ni mineralization, and the 'absence' of the Merensky 'Reef' in the area affected by these features. If these features were produced by slumping the fact that the vertical distance affected by the slump is approximately 3m, is consistent with several studies concerning the depth of unconsolidated mush on the floor of an intrusion. According to Hess (1960, Chap. XIII) slumping affects only the top six to ten feet of the crystal mush. He suggests that the reason is that at greater depths there has been sufficient crystallization of the intercumulus liquid to bind the crystals together and prevent slumping. Displacements in contemporaneous faults, in the Critical Zone of the Bushveld Complex, do not exceed 3m, (Ferguson and Botha, 1963 p.271), which agrees with the figures given by Hess. If slumping of the Merensky 'Reef' and immediate footwall had occurred, it seems reasonable to expect that, on the edges of the slumped area, a re-injection of material of similar composition to that of the rocks affected by slumping had occurred. If this is so the pipe would be a penecontemporaneous event genetically related to the layered rocks and not to ultramafic pegmatoids.

Finally, regarding the micaceous pipe intersected by 1 East Drive 1 Shaft (Fig. 22), the scarcity of the data obtained does not warrant extensive conclusions but that water has been added to the country rock seems evident. The pipe shows closer microscopic and chemical affinities to the micaceous carbonatite dyke, which intersects the pipe itself than to the ultramafic pegmatoids. It is possible that this pipe and dyke are much later Pilanesberg age (Ferguson, 1973). Even if a zoned arrangement of oxides and silicates is sometimes present on a microscopic s le, both borehole intersections failed to prove any large scale ing in the pipe, therefore it is possible that the concentric magnetic anomaly is due to weathering near surface. No ultramafic pegmatoid was intersected in contact with the micaceous pipe and even if a superimposition of both bodies occur near surface, it is doubtful whether their origins could be genetically related.

9. <u>Origin</u>.

a. Previous theories. - Wagner (1973) studied the ultramafic pegmatoids in the Rustenburg district, and concluded that some bodies were developed by replacement processes but others were definitely intrusive. Since then several authors have proposed different theories to account for the origin of ultramafic pegmatoids. Lombaard (1956, p.69) suggested that the Bushveld dunites resulted from the fractionation of an interstratified magma. "Thus at Mooihoek there are three phases emplaced in the sequence: chrysolite dunite, hortonolite dunite and hornblende pegmatite. The dominant silicates of the three phases conform to the calc-alkali trend of differentiation, being from anhydrous, iron-poor varieties towards alkali-bearing, hydrous and relatively iron-rich types, typical products of crystal fractionation". "Seeing that the dunite bodies are small and scattered somewhat arbitrarily although occurring mostly in the Critical Zone, their likely seats of origin are local reservoirs or an extensive (interstratified ?) chamber,......"

Schwellnus (1956, pp.167-169) found that the co-occurrence of hortonolite dunite and chrysolite dunite in composite pipes at Onverwacht, Mooihoek and Driekop is the exception and not the rule. He postulated that "the chrysolite dunite and hortonolite dunite represent separate magmatic entities". Since then the origin of the 'magma' which produced the ultramafic pegmatoids has been thoroughly discussed. Liebenberg (1960, p.67) remarks the chemical differences between hortonolite dunites and the layered rocks and concludes that "The hortonolite dunites are the differentiation product either from another magma than that from which the other rocks are formed or from the same magma after it has first undergone a partial change".

Coertze (1960) postulates remelting of country rock and injection of dunitic magma. This same author later describes magnetitite layers and associated magnetitite pipes. To account for the apparent connection between both he proposes "a process of spreading-out and injection" with the magnetitite pipes acting as feeders.

Since Lombaard (op.cit.) suggested the idea of an interstratified magma which has undergone fractionation several authors have endorsed his views.

Liebenberg (1969, p.192) claims that the ultramafic pegmatoid pipes of the Critical Zone crystallized from a pegmatoid fluid which originated in the intercumulus spaces of the rocks of the Critical Zone. And also that "the pegmatoidal fluid is a differentiation of the pyroxenites and norites of the Critical Zone".

Willemse (1969b) suggests that certain magnetitite plugs with associated diallage pegmatoid occurring in the central and upper portion of the Main Zone are of local origin. Quoting Molyneux he stressed, (Ibid, p.205), that there is a clear relationship between the magnetitite plugs and the layers at a given elevation. As the magnetitite plugs have a slightly lower content of vanadium they "are of local origin and represent pegmatoidal segregations in their environment". Willemse had stated previously (1964, p.118): "The magma could have originated almost in place by any process such as filter-pressing or lateral secretion leading to a concentration of iron-rich fluids".

Söhnge (1963, pp.xlvi - xlvii) postulated that "pockets of hydrous femic residium were segregated in the most highly differentiated layers of the gabbro sill". According to Söhnge, injection, lateral and upward diffusion of iron and magnesium towards hydrous centres, and metasomatic reaction are some of the processes which may have contributed towards the formation of the different ultramafic pegmatoid types.

Metasomatism of the layered Bushveld rocks as a process leading to the formation of ultramafic pegmatoids has also been postulated by Cousins (1960, p.83) and more recently by McTaggart (1971, p.38) who proposes that in the pipes of the Bushveld Complex, "if H_2O and other volatiles were fed continuously from underlying sedimentary rocks to high points in the base of the crystallizing magma, they could form "gas chimneys" (Waters 1960, p.358), that although small in cross section, might open during crystallization of the Bushveld magma and provide a passageway for metasomatizing fluids. It is suggested that metasomatizing fluids were able to replace the walls of the gas chimneys with olivine, pyroxene, hornblende, sulphides, and so on, and deposit iron-rich hortonolite along the axis of the pipe". According to Cameron and Desborough (1964) replacement of layered rocks by water-rich undersaturated fluids best explains the features observed at Onverwacht and Mooihoek. They suggest that as the layered rocks in the Critical Zone contain elements like Fe, Ti and in which the ultramafic pegmatoids are enriched with respect to layered rock, then all that is needed to produce the ultramafic pegmatoids is a "hydrothermal (pneumatolitic) re-arrangement of material within a mass of rock". Other processes leading to the formation of ultramafic pegmatoids have been described by Ferguson and McCarthy (1969, p.79) who attributed the formation of an ultramafic pegmatoid product of violent emplacement to "an aggregation of volatile fluids, rich in ultramafic components in the mafic Bushveld magma". In the subsequent discussion with Cameron (1969, p.79), this author mentions a small ultramafic pegmatoid body which appears to have formed largely by the filling of dilatant fractures.

b. Iron enrichment. - At Rafokeng the extreme iron enrichment of some ultramafic pegmatoids poses two evidently related questions: where did all the iron present in ultramafic pegmatoids come from, and is there a penecontemporaneous relationship between ultramafic pegmatoids and their host rock, or are we dealing with different time scales?

At the moment three different origins for the iron can be postulated. It can be suggested that it originates from:

- intercumulus differentiated liquids,
- that it has been selectively remobilized from the layered rocks by later fluids,
- that it comes from an underlying magma reservoir in which iron enrichment was taking place. We shall examine these possibilities.

i. Intercumulus liquids. - The process of late iron enrichment in layered complexes has been attributed by several authors to late-stage liquids. In Alaska, pyroxenite-magnetite layers are found below the presumably earlier differentiates (Taylor and Noble, 1969). To explain these layers, Taylor and Noble (op.cit.) suggested migration of dense, late-stage liquids to the bottom of the basin along the margins of the intrusive.

Rucknick and Noble (1959) discussing "magnetite bands" of the Union Bay Complex, have proposed that "at a late stage in crystallization of the pyroxenite, when most of the diopside but little of the magnetite had crystallized, the whole may have had enough rigidity to respond to stress as a solid. In this case, stress created by subsequent intrusion may have caused the almost wholly crystalline mass to fail along regular fractures. Following local pressure gradients created by fracturing, the still-liquid portion of the magma (mostly magnetite) would then have accumulated along the fractures".

Bateman (1951, p.422) proposed the theory of "a late gravitative liquid accumulation, which in this case became subjected to pressure and was squirted elsewhere ..." to explain hortonolite dunite and dunite pipe at Mooihoek Platinum Mine, Eastern Bushveld.

Within the mafic rocks of the Bushveld Complex, iron enrichment took place continuously with differentiation and culminated in the magnetitite layers of the Upper Zone, therefore it could be argued that as differentiation progressed the trapped intercumulus liquids became more enriched in iron. We must therefore examine if ultramafic pegmatoids show an iron enrichment from the Basal to the Upper Zone, comparable to that of the layered rocks. It is interesting to note that while chrysolite dunite pegmatoid pipes are restricted to the Basal Zone (Schwellnus, 1956) magnetitite pipes are restricted to the Main and Upper Zones. Although magnetitite pegmatoids form small bodies in the Critical Zone (Bafokeng) and Basal Zone (Cameron and

Desborough, 1964), the transition between pipes of hortonolite dunite with subordinate magnetite to magnetitite pipes with subordinate diallagite occurs within the Main Zone of the Complex, therefore it could be argued that iron enrichment in ultramafic pegmatoids progressed from the Basal to the Main Zone. Certainly iron enrichment of intercumulus liquids, and hence ultramafic pegmatoids seems to be easier to obtain in the vicinity of the magnetitite layers of the Upper Zone than at the Basal or Critical Zones. However there are several factors leading to iron enrichment of intercumulus liquids. Martin and Piwinskii (1969), showed that iron tends to fractionate into gas phases and that Fe_2O_3 may be leached from diabases by aqueous fluids. They also note that the migration of iron towards lower temperature zones differs markedly from that of Ca and Mg which remain fixed at the high temperature end. This process could produce iron enrichment almost in any part of the layered rocks. It is also worthy of note that Dreyer and Johnston (1967, p.62) suggested that consolidation in picrites was accompanied by an early magmatic migration of volatile rich material. "The chemistry of this migration, however vaguely conceived at present, seems effectively to stabilize Mg-rich olivine and Ca-rich plagioclase with relation, respectively, to iron and sodium,...."

To explain ilmeno-magnetite ilmenite concentrations, Buddington et alii (1955, pp.528-9) have advanced the theory that the ore is a product of liquid immiscibility with a water-rich silicate phase and has segregated from anorthositic, mafic or felsic magmas. Therefore liquid immiscibility is another possible process leading to iron enrichment in intercumulus liquids. Some other factors which may have lead to iron enrichment of intercumulus liquids are: partial pressure of oxygen (ρo), and oxygen fugacity (fO_2). Presnall (1966, pp.774-775) shows that high ρo may precipitate magnetite. O'Hara (1968) notes that, the fractionation trends of iron-bearing liquids, once they commence their ascent are greatly influenced by the partial pressure of oxygen if the system is not closed to volatiles. On the other hand, Ulmer (1969, pp.126-129) has shown that in the system Mg_2SiO_4-FeO-Fe_2O_3-$CaAl_2Si_2O_8$-SiO_2 at a constant $CaAl_2Si_2O_8$ content of 40 wt per cent, the field of magnetite increases at the expense of the anorthite field with increasing oxygen fugacity (fO_2). Factors controlling fO_2, which may have operated at the time of the formation of ultramafic pegmatoids especially underneath chromitite layers are: release of gases through vents and cracks, and loss of gases through diffusion. If iron enrichment was produced from intercumulus liquids, different conditions of growth of intercumulus crystals may have affected iron enrichment. Under conditions of orthocumulus growth iron enrichment of intercumulus liquids could progress further then under adcumulus conditions.

Finally it is interesting to note that if the iron enrichment was produced from intercumulus liquids, there would be a penecontemporaneous relationship between ultramafic pegmatoids and their host rock. At Bafokeng magnetite within ultramafic pegmatoids was the last mineral to crystallize, forming at the expense of all previous minerals, but there is no evidence against a penecontemporaneous relationship between magnetite and other silicate minerals in ultramafic pegmatoids. However it is worthy of note that Schweilnus (1956, p.166) states that "the fact that concentrations of pure magnetite occur as pipe-like bodies and veins within the peridotite rock indicates that 'magnetite liquor' continued to be fed to the pipes even after the peridotite was virtually crystalline".

ii. Selective remobilization of iron. - If iron, along with titanium and vanadium were selectively remobilized from the layered rocks, by the water-rich solutions which formed the ultramafic pegmatoids, a source for the iron-rich pegmatoids is obtained.

The geochemical mobility of iron and titanium, especially that of the latter, Korzhinsky (1950, p.50), is low under certain conditions; however, Mason (1952, p.124) notes that "gases at high pressure and temperature are capable of dissolving many substances not themselves volatile", and furthermore iron dissolution by aqueous fluids is postulated by Davidson and Wyllie (1968) to explain diabase-granophyre associations. Currie and Ferguson (1971) have shown that elements like Fe, Mg and Ca, can be reasonably mobile in the presence of anions like Cl-, F-, SO_4=, NO_3-. However petrographic evidence for the mobilization of iron from the layered rock has yet to be found.

Eastwood (1965) examines possible sources of iron for a magnetite body formed by replacement on Vancouver Island, and suggests, as a source, the adjoining country rock. Eastwood (op.cit.) interprets 'bleaching' of country rock as a possible criterion to indicate loss of iron.

Perhaps the main contention against this theory is given by Cameron and Desborough (1964) who note that the elements which constitute the ultramafic pegmatoid are also present in the layered rock, and state "If the process is merely rearrangement, one would expect that somewhere in the associated rocks of the Bushveld the source rocks of the constituents required would be identified. These would be rocks that have likewise undergone alteration, but one complimentary to that described above. No such rocks have yet been recognized".

iii. Underlying magmatic reservoir. - The possibility that a separate magmatic reservoir existed apart from the chamber where layering was taking place, finds support in the fact that several pulses of magma may have replenished the main Bushveld magma. Wager and Brown (1968, p.399) state that "Platinoid minerals also occur in relative abundance in the dunitic pipes which cut the Bushveld intrusion near its eastern margins, and there is probably a close genetic relationship between the source of these bodies and the fresh pulse of magma that is believed to have replenished the main Bushveld magma chamber immediately prior to the deposition of the Merensky Reef layers".

Iron enrichment in this underlying magmatic reservoir is necessary to provide a source for iron-rich material. At present it cannot be visualised how this hypothetical iron-enrichment could be connected with the different ultramafic pegmatoid types.

10. Conclusions

The origin of the magma which produced the ultramafic [illegible] is not known. However the suggested equilibrium conditions [illegible] most contacts between ultramafic pegmatoids and layered rock, taken in conjunction with the fact that fractionation or other processes can lead to iron enrichment of intercumulus liquids, all support the suggestion that the magma which produced the ultramafic pegmatoids originated from intercumulus liquids. Fluids in equilibrium with this magma were probably water and iron-rich and undersaturated. Other than the fact that ultramafic pegmatoids are emplaced along joints and that there are ultramafic pegmatoid occurrences where they were forcefully emplaced (Ferguson and McCarthy, 1969) there is not much evidence as to what was the amount of consolidation which had taken place in the layered rocks, at the time of their emplacement. If the layered rocks and ultramafic pegmatoids formed penecontemporaneously, the ultramafic pegmatoids had to have a lower solidus temperature and therefore be true late pegmatoids, and the fraction found emplaced in joints could represent the last to crystallize. This last magmatic ultramafic pegmatoid fraction being below the solidus of the layered rocks would only at this stage show a disequilibrium condition with the host rock.

If ultramafic pegmatoids originated from intercumulus liquids, the predominance of ultramafic pegmatoids in anorthositic cumulates could perhaps be related to the removal of more intercumulus mafic magma from this variety of cumulates than from any other cumulate type. However, this possibility remains to be proven.

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APPENDIX I

1. Magnetic surveys.

Magnetic surveys were carried out using Askania and Jallander portable magnetometers.

2. Estimate of ultramafic pegmatoids in the different layered rocks.

An estimate of the proportions of different cumulate types was made in boreholes not affected by ultramafic pegmatoid from 25m below the Merensky 'Reef' to 43m above it. Results are as follows:

51,01 vol. per cent Anorthosite cumulates
43,52 Norite cumulates
5,45 Pyroxenite cumulates.

In boreholes which intersected ultramafic pegmatoid a simple comparison with the above proportions would show the proportions of ultramafic pegmatoid which forms at the expense of the different cumulate types.

3. Chromitite-magnetite pegmatoid contacts.

Unit cell measurements of chromitite and magnetite were taken on the 311 d-spacing.

4. Methods of analysis of the different minerals.

Plagioclases.

Methods used. - Four different methods of analysis of plagioclase feldspars were used with variable results. This includes X-ray powder diffractometry, X-ray fluorescence and optics.

X-ray powder diffractometry. - Plagioclase concentrates from the top portion of the Critical Zone and lower portion of the Main Zone were analysed by the method described by Desborough and Cameron (1968, p.22). Most samples included both cumulus and intercumulus plagioclase. Samples taken within the Merensky 'Reef' include only intercumulus plagioclase.

The composition of the plagioclase in the ultramafic pegmatoid bodies was difficult to obtain because they were altered, especially around the periphery to sericite and/or penninite. Graphs obtained of this type of plagioclase usually showed d-131 poorly developed and d-220 masked by another unidentified peak. This method shows four to ten per cent An discrepancy when compared with chemical analysis, and four to six per cent discrepancy compared with results from the available literature, always towards a lower An content. The results of the powder diffractometry method are therefore considered to be less accurate than the results obtained by other methods, however differences between this and the other methods seem to be small. The possibility of analytical error is not disregarded, but the precision obtained by reading ten different concentrates from the same sample was ± 1,05 per cent An at the 66 per cent confidence limit, and ± 2,1 per cent An at the 95 per cent confidence limit, which suggests that larger differences are not attributable to analytical error.

X-ray fluorescence. - Two plagioclase concentrates were prepared for chemical analysis. One, No. 180 from the layered rocks, and the other PL2 from pegmatitic feldspars included in an ultramafic pegmatoid at the same structural height.

Samples No. 180 and PL2 were crushed to 100 mesh (0,147 mm) before separating with a Franz magnetic separator. As it was known that pegmatitic plagioclases within ultramafic pegmatoids nearly always have small amounts of alteration, sample PL2 was hand-picked under the microscope. Small amounts of alteration products may, however, be present. These concentrates were subsequently ground to -320 mesh, and analysed for major elements using a Philips 1540 Vacuum X-ray spectrograph. Several other Na analyses were made by reading the sodium peak and background on different standards, and plotting their known concentration against the intensity read. The intensity of the unknowns was referred to the variation line thus obtained. Several plagioclase feldspars from the layered rocks were analysed by X-ray fluorescence. The pressed pellets include both cumulus and intercumulus material.

Optical methods - Maximum extinction angles in sections cut perpendicular to X were obtained and values referred to the curve given by Deer et alii (1966, pp. 138-139). Zonation of plagioclase was measured by orthoscopic readings of 2V.

Clinopyroxenes.

Optic axial angles were measured by direct orthoscopic readings of 2V. Low refractive index hemispheres were used, and a correction made for refraction errors using Federov's diagram. In addition to this, β-refractive indexes were obtained. Due to the variation of the liquids with temperature, the true reading on the liquid was obtained immediately after the match between crystal and liquid was found. The precision of the indexes thus obtained was $\pm$ 0,005.

Olivines.

Olivines were analysed by the method outlined by Yoder and Sahama (1957), using a 114,8mm camera, Ni filtered Cu radiation. No internal standard was used. Ten analyses of the same sample were obtained and the standard deviation was calculated. For the sample chosen a mean of 49,54 Fe was obtained, and the standard deviation was 2,1 at the sixty six per cent confidence limit. To reduce the possibility of error two analyses per sample were obtained, and some of the samples were checked by the method outlined by Jambor and Smith (1964). Samples, smaller than 1mm. were drilled out of the thin section.

Orthopyroxenes.

All orthopyroxenes were analysed by direct orthoscopic readings of 2V using a low index hemisphere. Readings were referred to a Federov diagram and corrected. These values were then referred to the curve of Hess (1952) and En values obtained.

Sulphides.

Sulphide proportions were also calculated from the S, Ni and Cu contents obtained by X-ray fluorescence, in the following way:

- first, all Ni was calculated as chalcopyrite of formulae $(FeNi)_9S_8$,
- second, all copper was calculated as chalcopyrite of formulae $Cu\,Fe\,S_2$,
- third, all the S left was calculated as pyrrhotite of formulae Fe S.

The procedure is only semi-quantitative, since the paragenetic relations are altered, the real formulae of pyrrhotite shows a deficiency in iron and furthermore both copper and nickel can be present in pyrrhotite.

Amphiboles.

A single pegmatitic amphibole from a granitic pegmatoid was analysed. Major and trace elements were estimated by X-ray fluorescence. The intergrown character of mica magnetite and sulphides within this amphibole was overcome by a magnetic separation done with a Franz separator.

Opaque minerals.

Standard reflectivity and Vicker's hardness tests were carried out, on opque minerals, using Leitz equipment. Pyrite was used as a standard.

5. Chemistry.

On the different samples presented in this paper, major elements were estimated by X-ray fluorescence using a Philips PW 1540 vacuum X-ray spectrograph.

FeO was estimated wet-chemically by the dichromatic oxidation method, Schafer (1966, pp. 763-790), using dephelinamin as an indicator. International standards including W-1, AGV-1, BCR-1, GSP-1, GR, G-2, PCC-1 and DTS-1 were used for calibration purposes. The concentrations used were those given by Fleischer (1969) for W-1 Roubalt et alit (1968) for GR, and Flanagan for the remaining standards. Mass absorption corrections were applied for all elements heavier than copper. The Compton peak method of Reynolds (1963) was used in these instances. In the case of iron and manganese an aluminium filter interposed between the X-ray tube and the sample was used to remove tube interference.

Sampling procedure.

Seven samples of ultramafic pegmatoid were selected for chemical analysis, the basis for selection being as follows: three were taken from surface borehole 553 and four from underground exposures.

Sample 553 Ab consists of four 0,12m sections of core taken in ultramafic pegmatoid above the B.M.P. The samples were taken at approximately 30m intervals, starting at a depth of 150m and progressing downwards. Sample 553 Re. As only one ultramafic pegmatoid lense was intersected below the Merensky 'Reef', this sample is not composite, 0,36m of core represents the ultramafic pegmatoids below the Merensky 'Reef'. Sample 553, is a composite sample taken from 40 to 66m above the Merensky 'Reef', representing a section through highly serpentinized dunitic pegmatoid and associated troctolitic pegmatoid found in borehole 553. Three of the four samples of ultramafic pegmatoid taken underground come from 1 Shaft, 3 West Drive (Fig. 15, Section C), where an ultramafic pegmatoid is found immediately above, within and below the Merensky 'Reef'. Sample UPAMR, was taken above the Merensky 'Reef' where the host rocks are plagioclase-orthopyroxene cumulates. Sample UPMR, was taken at the Merensky 'Reef' elevation, where the ultramafic body cross-cuts the Merensky 'Reef'. The sample was taken next to an undisturbed portion of the Merensky 'Reef' which is over- and underlain by ultramafic. Sample GBGF, was taken at the same exposure, below the Merensky 'Reef'. The host rock is a plagioclase heteradcumulate. The seventh sample of ultramaf pegmatoids, UPBMR, was taken at 382 Raise, 5 Shaft, Fig.12. The sample was taken at the position where the ultramafic pegmatoid is emplaced conformably in an anorthositic cumulate.

The different cumulates of the layered rocks were analysed above and below the Merensky 'Reef'. Four anorthositic cumulates were sampled; samples 126 and 163 were taken at the a.c.n. Samples 518 and 680 come from above the B.M.R. and were taken from surface borehole cores of the same number. Samples 1637 and 722, both of them noritic cumulates, were taken immediately below the a.c.n., and are thought to represent the average magma composition between the UG 2 pyroxenite and the Merensky 'Reef' because they have approximately the same proportions of the two more abundant cumulates being deposited during this interval, namely orthopyroxene and plagioclase. Sample 510-15, a gabbroic cumulate, comes from the borehole of the same number approximately 590m above the Merensky 'Reef', in the Main Zone. Sample 68., a gabbroic cumulate from the Main Zone comes from the borehole of the same number.

Sample MRIS and MR284, are samples of the pegmatitic layer of the Merensky 'Reef' taken at different structural elevations, in the 1 and 5 Shaft areas respectively. They are both channel samples and do not include the chromitite layer. Sample PPUG4, represents the pegmatitic pyroxenite layer associated with the upper chromitite layer (UG 2) and was taken in the 4 Shaft area. Sample Nod5, is from a pyroxenitic nodule found within the a.c.n., and was collected in the 5 Shaft area. Sample Nod4 is also that of a pyroxenitic nodule within the a.c.n. which was collected in 4 Shaft. Sample Pxmfw is that of an intermittent pyroxenite layer and sample Annacn is that of an intermittent noritic layer, both are found within the a.c.n.

All samples taken underground are sections collected with a geological hammer, samples taken from surface borehole core measure 0,15m long, unless otherwise stated.

Trace elements.

All trace elements including sulphur, rubidium, strontium, nickel, copper and zinc were analysed by X-ray fluorescence, using a Philips PW1540 vacuum X-ray spectrograph. All trace elements were estimated on pressed pellets of the different rock samples.

In the case of Cu, Ni, Zn, which were analysed together, two separate runs were made and results averaged. As the peaks and backgrounds for each element were read twice in each run, four readings were available. Cu, Ni, Zn values are given to within ± 3 ppm.

Sulphur results are semiquantitative since the percentages were obtained by comparison with four standards having compositions of 0,1, 0,2, 0,5 and [illegible] per cent S respectively.

Determination of rubidium and strontium were duplicated. The first run was dome using a molybdenum tube, and the second, a tungsten tube. Agreement in the values obtained from both runs is good between the standard deviation limits. Standard deviations for S were always smaller than 2 ppm. and for Rb smaller than 1.6 ppm.

The instrumental conditions for the determination of trace elements is presented in Table No.

Micaceous pipe - 1 Shaft 1 East Drive.

From a 1 000 modal count on two slides of the matrix it was estimated that the analysis of the micaceous pipe was contaminated by at least 15 per cent, by volume, of the plagioclase-orthopyroxene cumulate. In this latter rock 12,25 per cent is plagioclase and 2,75 per cent orthopyroxene.

6. Calculation of the composition of intercumulus liquids at Rafokeng (Table 33).

I. 4% of orthopyroxene of composition $FeSiO_3$ 24, $MgSiO_3$ 76.

From the composition of the orthopyroxene we obtain that:

0,96% is $FeSiO_3$

and 3,04% is $MgSiO_3$ which adds to 4% orthopyroxene.

Breaking the ferrositite and enstatite molecules into oxides we obtain:

$FeSiO_3$ = FeO + SiO_2

$MgSiO_3$ = MgO + SiO_2

the respective weight % of which are

132 = 72 + 60

and 100,4 = 40,3 + 60,1

therefore in 0,96% $FeSiO_3$ the weight % of oxides are as follows:

[illegible] - 0,96

[illegible] - X X = 0,52 weight % FeO

132 - 0,96

[illegible] - X X = 0,44 weight % SiO_2

[illegible]e same way in 3,04 $MgSiO_3$

X = 1,22 weight % MgO

X = 1,82 weight % SiO_2

Finally the composition of the 4% orthopyroxene in weight % of oxides is as follows:

0,52% FeO + 1,22% MgO + 2,26 SiO_2

II. 5% Clinopyroxenes of composition $FeSiO_3$ 11, $CaSiO_2$ 44, $MgSiO_3$ 45

$\frac{11 \times 5}{100}$ = 0,55% $FeSiO_3$

$\frac{44 \times 5}{100}$ = 2,2% $CaSiO_3$

$\frac{45 \times 5}{100}$ = 2,25% $MgSiO_3$

5,0%

Following the same routine used in I

0,55%	$FeSiO_3$	is	0,25%	SiO_2	)
			0,3%	FeO	) The composition of the
2,2%	$CaSiO_3$	is	1,06%	CaO	) 5% clinopyroxene in
			1,14%	SiO_2	) weight % of oxides is
2,25%	$MgSiO_3$	is	0,90%	MgO	) 0,3% FeO, 1,06% CaO,
			1,35%	SiO_2	) 0,90% MgO, 2,74% SiO_2.

III. 26% of plagioclase of c   sition An80 gives us 5,2% of $NaAl_2Si_3O_8$ and 20,8% of $CaAl_2Si_2O_8$, plus an unknown negligible amount of the orthoclase molecule. Following the same routine used in I and II for the albite molecule we obtain:

$2(NaAlSi_2O_8)$ = NaO + Al_2O_3 + $6SiO_2$

weight % 518 = 62 + 102 + 354 = 518

5,2 = 0,62% NaO; 1,02% Al_2O_3; 3,55% SiO_2 weight %

in the same way for the anorthite molecule

CaO + Al_2O_3 + SiO_2

56 + 102 + 118 = 276

20,8% = 4,22 CaO; 7,69% Al_2O_3; 8,89 SiO_2 weight %

From I, II and III:

	SiO_2	MgO	FeO	CaO	Na_2O	Al_2O_3	
Orthopyroxene	2,26	1,22	0,52	-	-	-	
Clinopyroxene	2,74	0,9	0,3	1,06	-	-	
Albite	3,55	-	-	-	0,62	1,02	
Anorthite	8,89	-	-	4,22	-	7,69	
	17,44	2,12	0,82	5,28	0,62	8,71	= 34,99.

Table 4. Chemical analyses in weight per cent and C.I.P.W. [illegible] intrusives and late ultramafic [illegible] at [illegible].

		EARLY ULTRAMAFIC [illegible]						LAYERED ROCKS: [illegible]								Nodules and intermittent layers				Pegmatoid differentiates		
	Specimen numbers	553	553[illegible]	462[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	416-17	431	163	120	519	450	Nod 4	Nod 5	[illegible]	[illegible]	TS 17	[illegible]	[illegible]
OXIDES IN WEIGHT %	SiO_2	45,76	46,17	44,44	41,26	36,01	41,40	53,14	49,71	46,05	47,65	50,01	47,72	48,39	48,70	47,53	51,54	48,97	52,10	57,79	46,47	47,43	52,[illegible]
	TiO_2	0,89	0,67	1,74	2,99	1,24	4,40	5,17	0,11	0,00	0,07	0,14	0,06	0,09	0,10	0,11	0,11	0,15	0,22	0,13	0,14	5,15	0,5[illegible]
	Al_2O_3	8,79	2,11	2,37	2,87	1,34	1,95	1,75	22,31	33,70	18,96	16,76	27,51	30,20	29,81	27,77	7,11	11,69	7,40	12,72	5,14	7,34	4,[illegible]
	MnO	0,36	0,28	0,30	0,36	0,44	0,34	0,44	0,07	0,03	0,09	0,13	0,09	0,07	0,04	0,04	0,19	0,14	0,18	0,15	0,11	0,16	0,22
	MgO	17,94	15,76	10,01	27,06	30,32	21,61	35,46	7,45	3,10	3,60	3,69	1,94	1,05	2,44	2,09	4,85	5,55	6,11	5,72	4,52	5,2[illegible]	7,77
	Fe_2O_3	3,09	1,78	3,17	2,99	3,82	2,61	3,03	8,75	7,70	0,61	2,00	0,12	0,28	0,30	0,25	3,77	2,97	4,59	2,97	11,71	8,2[illegible]	4,0[illegible]
	FeO	17,17	16,19	17,45	15,21	14,85	17,15	13,19	6,10	11,24	4,47	16,34	2,74	2,00	2,99	2,61	22,15	19,41	25,70	18,67	23,[illegible]	23,13	23,13
	CaO	4,23	19,19	16,40	17,40	3,51	14,71	7,31	17,06	10,59	15,87	8,09	14,53	15,00	10,02	14,9	5,20	8,12	7,29	7,17	3,17	4,79	5,47
	Na_2O	0,03	–	0,01	–	–	0,02	–	0,11	0,14	0,18	0,12	0,27	0,12	0,37	0,31	0,03	0,15	0,06	0,03	0,05	0,11	0,41
	K_2O	0,50	0,11	0,10	0,05	0,05	0,06	0,01	1,42	1,67	1,57	1,47	2,33	2,91	3,45	2,99	0,45	0,56	0,96	1,11	0,74	0,49	0,34
	P_2O_5	0,31	0,14	0,16	0,15	0,09	0,14	0,04	0,15	0,11	0,19	0,10	0,16	0,17	0,12	0,17	0,07	0,11	0,08	0,06	0,04	0,04	0,09
	H_2O^+	2,97	1,98	1,02	1,32	1,01	1,23	1,10	1,42	0,93	2,58	0,32	1,31	0,37	2,32	0,22	2,76	2,85	0,97	0,53	4,57	3,10	3,11
	H_2O^-	0,14	0,07	0,24	0,11	0,04	0,06	0,09	0,09	0,07	0,03	0,04	0,08	0,03	0,19	0,03	0,03	0,41	0,07	0,03	3,99	0,07	0,2[illegible]
	TOTAL	99,90	100,18	100,29	99,74	100,21	100,24	99,46	100,00	99,55	99,83	99,67	99,89	100,02	100,09	100,40	99,88	99,89	100,37	100,54	96,77	97,93	100,[illegible]
C.I.P.W. NORMS	Quartz	–	–	–	–	–	–	–	3,27	–	–	0,44	–	–	–	–	–	2,30	2,95	1,00	1,56	0,87	1,7[illegible]
	Cor	–	–	–	–	–	–	–	–	–	–	–	–	–	2,67	–	–	–	–	–	–	–	–
	[illegible]	0,19	–	0,06	–	–	0,12	–	0,72	0,84	1,10	0,73	1,67	0,71	7,44	1,74	0,91	0,18	0,36	[illegible],18	0,33	3,99	2,74
	Or	4,95	0,66	0,05	0,43	0,47	0,51	–	12,19	14,14	13,65	12,45	19,79	24,68	29,67	24,57	6,08	3,92	4,77	9,39	2,2[illegible]	4,03	2,93
	An	20,74	5,37	4,03	4,90	3,19	5,34	3,47	56,94	49,28	45,57	38,93	70,20	70,50	83,94	62,37	29,52	17,60	17,88	19,27	16,57	17,24	9,9[illegible]
	[illegible]	–	–	–	–	–	–	8,09	–	–	–	–	–	0,10	–	–	–	–	–	–	–	–	–
	Di	25,89	57,39	67,07	50,02	32,44	54,65	23,08	7,81	2,92	27,43	4,46	1,45	2,39	–	9,87	8,70	4,95	14,09	9,20	3,27	4,00	14,[illegible]
	Hy	3,01	9,99	3,09	8,11	3,48	4,52	–	26,56	25,91	1,31	30,54	1,56	—	1,39	0,29	44,53	43,12	52,69	56,22	62,39	53,34	62,4[illegible]
	Ol	49,19	22,37	17,50	27,14	57,32	30,55	57,61	–	3,67	9,45	–	5,05	1,95	7,86	5,16	0,75	–	–	–	–	–	–
	Fe_3O_4	4,47	3,63	4,67	4,41	5,56	3,62	4,41	1,07	1,14	0,91	4,25	0,14	0,41	0,44	0,36	3,84	5,17	6,70	4,31	6,65	12,37	5,94
	Il	0,96	0,91	3,31	4,02	2,37	8,44	9,86	0,29	0,15	0,18	0,27	0,12	0,10	0,19	0,21	0,29	0,31	0,42	0,25	0,30	0,36	0,9[illegible]
	Ap	0,25	0,88	0,38	0,36	0,21	0,33	0,19	0,96	0,26	0,37	0,34	0,38	0,40	0,29	0,40	0,27	0,17	0,19	0,19	0,11	0,10	0,2[illegible]
	$CaSiO_4$	–	–	–	–	–	–	1,65	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Hm	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	[illegible]	–	1,46	–	–

TABLE 5. Zn, Cu and Ni contents in layered rocks and ultramafic pegmatoids analysed from Bafokeng.

Group	Sample	Zn	Cu	Ni	Ni/Cu	Nix1000/ Mg	Cux10000/ FeO
LAYERED ROCKS	Nod 5	73	39	599	15,6	0,045	0,059
	Nod 4	51	6	657	105,9	0,056	0,083
	Pxmfw	73	17	755	44,2	0,060	0,001
	Annacn	56	19	523	28,1	0,046	0,002
	PPUG4	89	16	969	59,8	0,069	0,001
	MR IS	65	5822	15907	2,73	0,69	0,202
	MR 284	76	2611	9424	3,6	1,13	0,362
	722	34	6	440	68,7	0,066	0,001
	1637	24	14	208	14,5	0,042	0,003
	163	7	5	70	15,1	0,017	0,003
	126	8	9	37	4,0	0,019	0,007
	510-15	32	5	192	40,7	0,038	0,001
	681	51	23	361	15,6	0,042	0,003
	680	20	5	42	7,7	0,026	0,002
	518	27	1	48	48,0	0,018	0,0003
ULTRAMAFIC PEGMATOIDS	553	116	235	752	3,2	0,073	0,011
	553 ab	93	306	508	1,6	0,052	0,017
	553 be	102	279	323	1,1	0,043	0,013
	UPAMR	130	84	276	3,3	0,038	0,003
	UPMR	208	245	817	3,3	0,091	0,007
	GBGF	133	29	267	9,2	0,036	0,001
	UPBMR	192	544	421	0,8	0,053	0,014
	Average ultramafic pegmatoid	143	248	435			

TABLE 6 .The average Ni, Cu, Zn and S in p.p.m. for different rocks of the Bushveld Complex as compared to those at Bafokeng.

		Ni	Cu	Zn	S	Ni/Cu	Data from
Average Bushveld magma		150	30	50	150	5	L. Liebenberg (1969)
Ultramafic pegmatoids		435	248	143	1750	1,75	Bafokeng
Hortonolite dunites		320-580	5-36	-	-	21	C.J. Liebenberg (1960)
Diallagite pyroxenites	Dyke-like bodies	396	43	87	842	9,21	L.Liebenberg (1969, Table 30)
Hortonolite dunites		400	30	793	158	8	
Anorthositic cumulates	Main Zone	45	3	23	-	15	Bafokeng
Gabbroic cumulates		192	5	32	-	40,7	
Average pegmatoid pyroxenite cumulates	Critical and Main Zones	6817	2116	80	11375	3,22	Bafokeng
Anorthositic cumulates	Critical Zone	54	7	8	-	7,7	Bafokeng
Norite cumulates		324	10	29	-	32,4	
Nodules		628	23	62	200-500	27,3	
Ultramafic rocks - Basal Zone Western Transvaal		2450	525	92	9575	4,66	L.Liebenberg (1969, Table 30)
Average for ultramafic rocks Bushveld Complex		700	35	70	200	20	L.Liebenberg (1969, Table 30)

TABLE 7 . S content of ultramafic pegmatoids and layered pyroxenites.

	Sample No.	S per cent
ULTRAMAFIC PEGMATOIDS	553ba	0,45 - 0,5
	553ab	0,08
	553	0,1
	UPAMR	0,06 - 0,07
	UPMR	0,15
	GBGF	0,01 - 0,02
	UPBMR	0,45
LAYERED PYROXENITES	MR IS	3
	MR 284	1,25
	PPUG 4	0,05
	Pxmfw	0,05
	Nod 5	0,02
	Nod 4	0,05

Analyst J.P. Jones.

TABLE 8. Rb/Sr analysis and averages.

	Sample No.	Gold Tube		Tungsten Tube		Averages			
		Rb	Sr	Rb	Sr	Rb	Sr	Rb/Sr	Normative Plagioclase Content (Ab + An)
LAYERED ROCKS	722	4,6	305,4	5,9	310	5,2	308	0,017	63,62
	1637	7,7	319	7,8	329	7,7	324	0,024	67,13
	163	9,2	411	11,7	440	10,4	425	0,024	90,18
	126	3,2	416,5	4,5	453	4	435	0,009	91,94
	510-15	8,0	285,5	9,5	288	8,6	287	0,030	59,26
	681	4,4	209,7	-	-	-	-	-	51,42
	680	4,8	349	6,7	360	5,8	354,5	0,016	86,90
	518	14	436	14,4	454	14,2	445	0,032	83,61
	NOD5	4,0	84,3	5,5	89	4,8	86,5	0,055	21,72
	NOD4	6,4	135,6	8,3	152	7,3	144	0,051	34,70
	Pxmfw	6,3	102,7	7,2	104	6,7	103	0,065	22,61
	Annacn	3,3	172,4	5,1	180	4	176	0,023	37,66
	PPUG4	17,7	27,3	17,7	34	17,7	30,5	0,58	11,46
	MRIS	5,5	82,4	5,3	79	5,4	81	0,666	16,64
	MR284	7,5	404,2	7,7	431	7,4	417	0,018	23,36
Ultramafic pegmatoids	553	5,5	144	5,9	122	5,5	133	0,041	25,09
	553Ab	4,5	23	5,1	30	4,8	26	0,185	6,32
	553be	4,0	24	3,3	26	3,7	25	0,148	6,89
	UPAMR	3,5	33,0	4,8	32	4,1	32,5	0,126	7,33
	UPMR	6,4	16,0	3,2	17	4,8	16,5	0,290	3,62
	GBGF	4,1	25	5,2	26	4,6	255	0,018	5,55
	UPBMR	6,0	15,0	4,3	17	5,2	16	0,325	3,43

TABLE 9. Rb-Sr content of different rock types at Bafokeng.

	Ultramafic pegmatoids	Px (Pegmatoidal) pyroxenites	Anorthosites (Main Zone)	Anorthosites (Critical Zone)	Norites (Critical Zone)	Gabbro (Main Zone)	Nodules and intermittent Px layers (Critical Zone)
Average Rb	4,5	12	10,5	7	6,5	9	6
Average Sr	23,6	60,5	400	426	315	287	111
Av. Rb/Sr	0,190	0,198	0,026	0,016	0,021	0,031	0,054

TABLE 10. Rb-Sr content of the same rock types in the Bushveld Complex.

	1. Rb	2. Sr
NORITES	0,2 -2,4	284-328
PYROXENITES	0,27-1,4	5,5-112
ANORTHOSITES	0,55-4,9	377-412

	3. RbO_2	4. Sr
CENTRAL NORITES	1-2	140-400
PEGM. PYROXENITES	3-12	18-42
CENTRAL ANORTHOSITES	1-2	140-400
HORTONOLITE DUNITES	-	9- 18
PERIDOTITES	1-15	4- 40

	5. Rb	6. Sr
NORITES - GABBROS	8	302
PYROXENITES	9	86
ANORTHOSITES	9	413
ULTRAMAFIC PEGMATOIDS	4.5	12

1 - 2 Data from Davies et alia, 1969
3 - 4 Data from C.J. Liebenberg, 1960
5 - 6 Data from Bafokeng

Px = Pyroxenites
Pegm. = pegmatoidal.

TABLE 35. Instrumental conditions for the determination of major and minor elements in rocks of Bafokeng Mine

ELEMENT	Fe	Mn	Ti	Ca	K	Al	P	Si	Mg	Na	Na (Bg)
Tube	Cr	—	—	—	—	—	—	—	—	—	Cr
kV	50	—	—	—	—	—	—	—	—	—	50
mA	50	—	—	—	—	—	—	—	—	—	50
Coll (um)	550	150	150	150	150	550	—	—	—	—	550
Crystal	Lif220	Lif220	Lif220	Lif220	Lif220	PET	PET	PET	ADP	Gypsum	Gypsum
Time (sec)	20	100	10	10	10	40	40	10	100	100	100
°2θ	85,85	95,26	86,17	113,12	136,7	145,15	89,65	109,30	136,9	103,45	97,15

ELEMENT	Cu	Ni	Zn	Rb	Sr	Rb	Sr	S
Tube	An	—	An	W	W	Mo	Mo	Cr
kV	65	—	65	65	65	—	65	50
mA	40	—	40	40	40	—	40	50
Coll (um)	150	—	150	150	150	—	150	550
Crystal	Lif220	—	Lif220	—	Lif220	—	Lif220	PET
Time (sec)	80	—	80		80		80	20
°2θ	65,54	71,26	60,57	37,915	35,79	37,94	35,81	75,90

PHOTOGRAPHS

[illegible]s used:

cpx	clinopyroxene
ch	chromite
il	ilmenite
m	magnetite
ol	olivine
opx	orthopyroxene
q	quartz
plag	plagioclase
py	pyrrhotite
si	silicates
UP	ultramafic pegmatoid

Photo No.	DESCRIPTION
1	Three sets of clinopyroxene exolution lamellae in an orthopyroxene host (in extinction). Observe intimate relationship between orthopyroxene and clinopyroxene (bottom portion). X Nicols. 1 x 20.
2	Olivine crystal in plagioclase feldspar, taken from a pyroxenite nodule. X Nicols. 1 x 20.
3	Bird's eye texture in pyrrhotite within the Merensky 'Reef' pegmatoid. Dark coloured minerals 'exfoliated' in pyrrhotite are silicates and an unidentified mineral. X Nicols. 1 x 50.
4	Nodules, intermittent pyroxenite layers, and bottom contact of the a.c.n. (broken line). The grey line at the hammer-head is paint.
5	Circular plan section of a pyroxenite nodule, seen to the right of a roof bolt. Approximate diameter of roof bolt 0,12m.
6	Bulging on the underside of pyroxenite a layer within the a.c.n. layer. The length of the scale is 0,35m.
7	Pyroxenite layers and coalescing nodules within the a.c.n. The grey line above the hammer is paint.
8	Intergrowth texture between orthopyroxene (in extinction) and clinopyroxene both showing exolution, in a pegmatitic lense. X Nicols. 1 x 20.
9	Top right anorthositic cumulate, bottom noritic cumulate. Top left ultramafic pegmatoid. Observe the different contacts produced against both cumulates. White line on top is paint. Approximate vertical distance 2,5m.

Photo No.	DESCRIPTION
10	Ultramafic pegmatoid (dark) enclosing anorthositic layered rock (light coloured).
11	Contact between ultramafic pegmatoid (right), and plagioclase cumulate. X Nicols. 1 x 20.
12	[illegible]ular pegmatitic augite crystals in a contact between ultramafic pegmatoid and layered rock.
13	Layering produced at a contact between ultramafic pegmatoid (top) and an anorthositic cumulate (bottom). The white area above the hammer is an anorthositic cumulate inclusion.
14	Irregularly shaped layers of feldspathic pegmatoid underlain by ultramafic pegmatoid. The base of the Merensky 'Reef' forms the hanging, 287 Stops.
15	Irregular outline of the Merensky 'Reef' chromitite layer (between red lines), produced by the penetration [illegible] underlying pegmatitic feldspars, 287 Stops.
16	Plagioclase-rich pegmatoid with a mafic rim, protruding into a noritic cumulate.
17	Contact between overlying Merensky 'Reef' and underlying finely crystalline phase of ultramafic pegmatoid. X Nicols. 1 x 20.
18	Fracturing and bending of cumulate orthopyroxene grain at the contact of an ultramafic pegmatoid (extreme right). X Nicols. 1 x 50.
19	Orthopyroxene cumulate in extinction, showing bent cleavages, being replaced by a fine-grained phase of ultramafic pegmatoid. X Nicols. 1 x 50.
20	The silicates between chromite cumulus (black) have been replaced by olivine and serpentine. The Merensky 'Reef' is underlain by ultramafic pegmatoid. X Nicols. 1 x 50.
21	Feldspathic intrusive pegmatoid. The triangular portion below the ruler is a pyroxenite 'remnant' of the Merensky 'Reef'. The scale is 0,5m long.
22	Ultramafic pegmatoid showing conformable relationship to the layering and also transgressing in a joint through undisturbed norite cumulate. Yellow = crayon. Red = paint. Width of conformable ultramafic pegmatoid 0,4m.

Photo No.	DESCRIPTION
23	Fracturing, granulation, and bending of twins produced at the interface between two plagioclase crystals in an ultramafic pegmatoid. X Nicols. 1 x 50.
24	Intergrown plagioclase crystals in ultramafic pegmatoid X Nicols. 1 x 50.
25	Contact between two plagioclase crystals in ultramafic pegmatoid. X Nicols. 1 x 50.
26	Granulation and rotation of portions of a plagioclase crystal in an ultramafic pegmatoid. X Nicols. 1 x 50.
27	Glide twinning in a pegmatoid plagioclase. X Nicols. 1 x 50.
28	Contact between two clinopyroxene crystals, one is at extinction, within an ultramafic pegmatoid. X Nicols. 1 x 50.
29	Relationship between two clinopyroxene crystals in an ultramafic pegmatoid. One crystal is at extinction. The other is twinned. X Nicols. 1 x 50.
30	Undulatory extinction in a pegmatitic olivine crystal within an ultramafic pegmatoid. X Nicols. 1 x 50.
31	Olivine, centre, replacing a single crystal of orthopyroxene, both included in plagioclase. X Nicols. 1 x 50.
32	Subhedral olivines within the Merensky 'Reef'. Note rims of orthopyroxene around the included olivine in the poikilitic plagioclase. X Nicols. 1 x 50.
33	Magnetite and ilmenite enclosing a silicate portion. Pyrrhotite has the highest reflectivity. X Nicols. 1 x 20.
34	Magnetite, ilmenite and pyrrhotite in magnetitite pegmatoid. X Nicols. 1 x 50.
35	Skeletal remains of ilmenite, and pyrrhotite bottom left corner. X Nicols. 1 x 50.
36	Magnetite in the margins and filling fractures within a single chromite cumulate of the Merensky 'Reef'. X Nicols. 1 x 200.
37	Pyrrhotite crystal showing bird's eye texture in a magnetitite pegmatoid. Note fracture in pyrrhotite filled by magnetite. X Nicols. 1 x 200.

Photo No.	DESCRIPTION
38	Migration of sulphides (light colours) included in silicates which are immediately underlain by magnetitite pegmatoid. X Nicols. 1 x 200.
39	Migration of sulphides (light colours) produced by the introduction of magnetite (left). X Nicols. 1 x 200.
40	Tonalitic-pegmatite vein which starts at the Merensky 'Reef' bottom contact, and pinches out in its hanging-wall.
41	Quartz and plagioclase in a tonalitic-pegmatite. Observe thin lamellae in plagioclase. X Nicols. 1 x 20.
42	Granitic pegmatite conformable below the Merensky 'Reef' (area of hammer) and also transgressing it (top right). White lines and circle were painted for mining purposes.
43	Gap produced in two pyroxenite layers by the sinking of a nodule.
44	The breaking of a noritic layer to form nodules. (The white lines around the nodules are crayon, the white area below the compass is a whitewashed area).
45	Break-up of a pyroxenite layer within the a.c.n. The black horizontal line below the hand is paint.

Photo 1

Photo 2

Photo 3

Photo 4

Photo 5

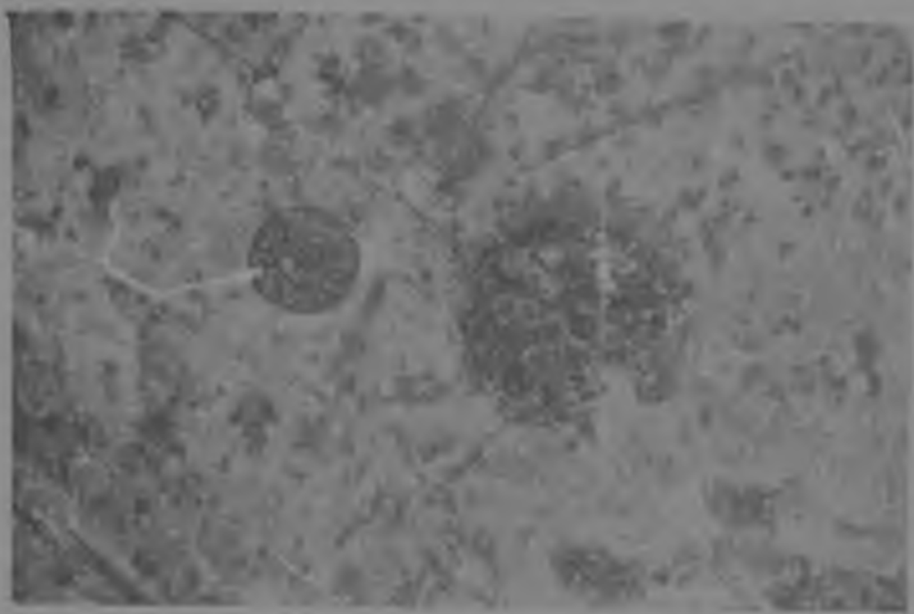


Photo 6

Photo 7

Photo 8

Photo 9

Photo 10

Photo 11

Photo 12

Photo 13

Photo 14

Photo 15

Photo 1[illegible]

Photo 17

Photo 18

Photo 19

Photo 20

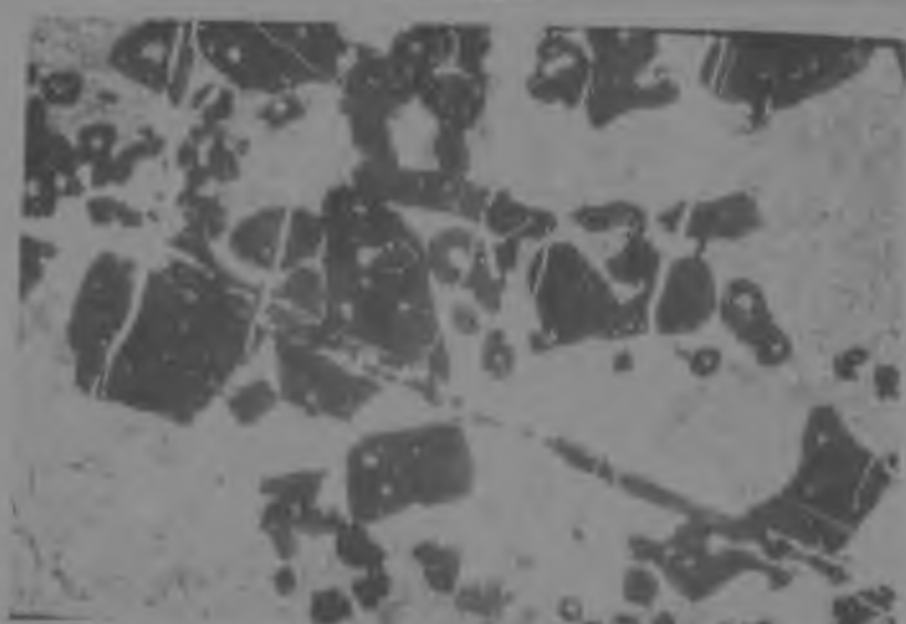


Photo 21

Photo 22

Photo 23

Photo 24

Photo 25

Photo 26

Photo 27

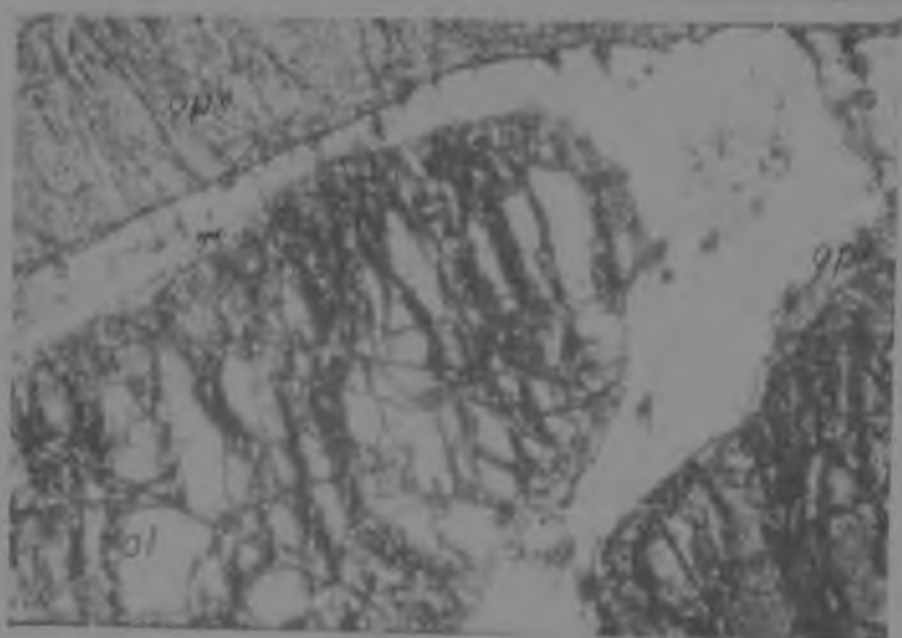
Photo 28

Photo 29

Photo 30

Photo 31

Photo 32



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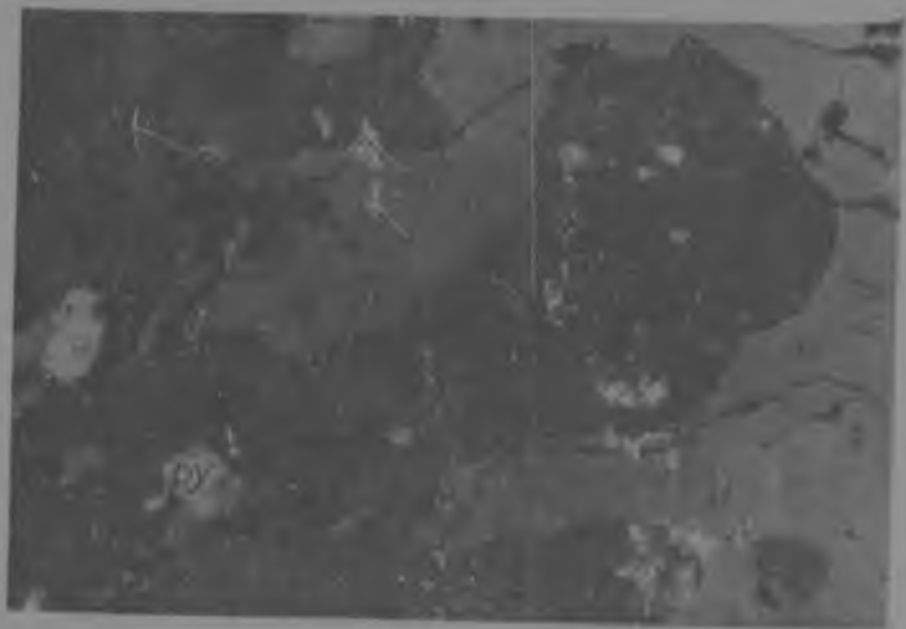
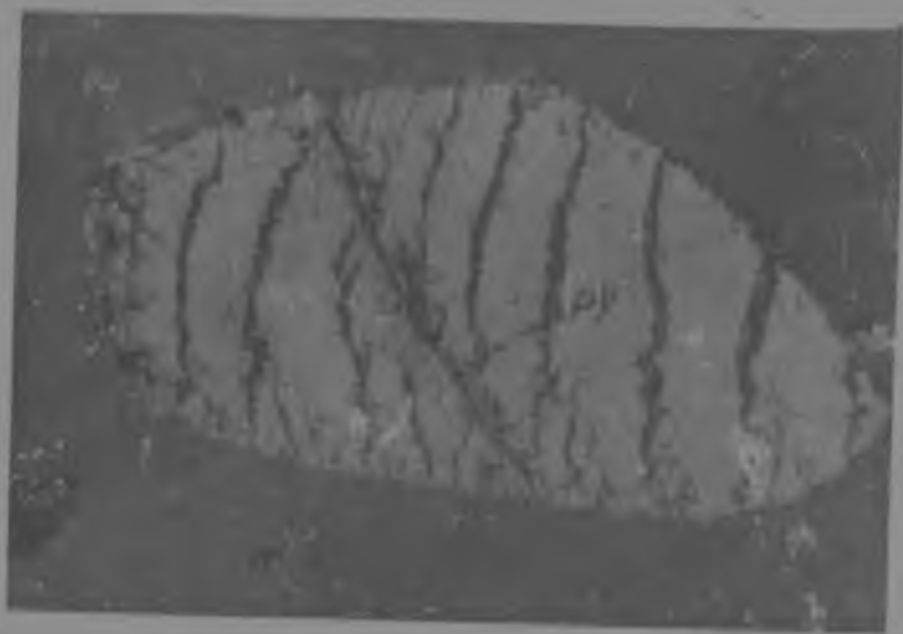


Photo 34

Photo 35

Photo 36

Photo 37



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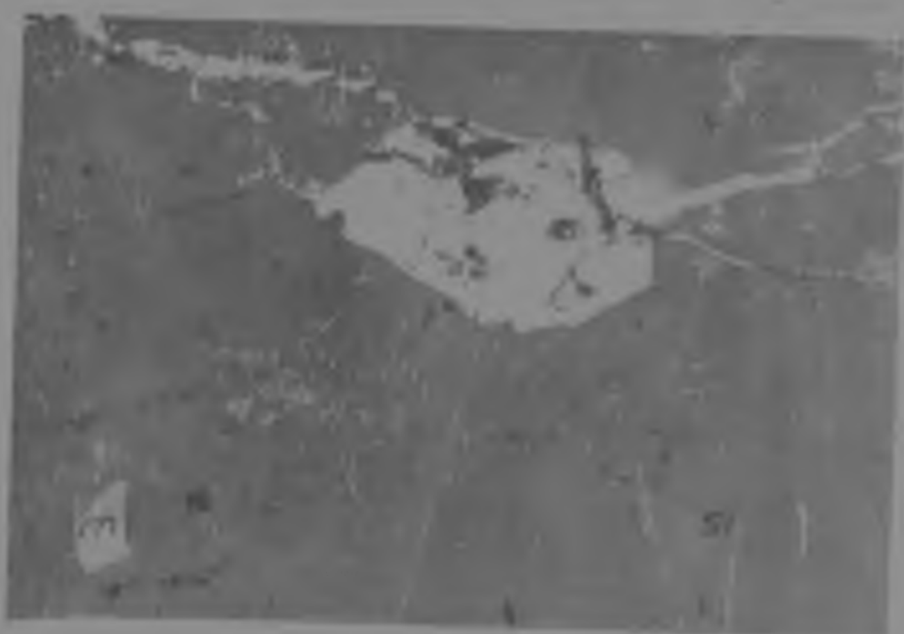

Photo 39

Photo 40

Photo 41

Photo 42

Photo 43

Photo 44