

**THE GEOLOGY OF THE BASIC PORTION OF THE  
WESTERN BUSHVELD IGNEOUS COMPLEX**

by

**F.J. COERTZE M.Sc.**

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## ABSTRACT

On the basis of field relations, the basic portion of the western part of the Bushveld Igneous Complex is subdivided into eight rock units: the basal norite unit, harzburgite unit, pyroxenite unit, anorthosite unit, norite unit, porphyritic pyroxenite unit, gabbro unit, and ferrogabbro unit.

According to the floor relations the basic rocks apparently follow concordantly on the Magaliesberg Quartzite of the Pretoria Series. Towards Rustenburg, in places, the basal norite unit is intrusive into this quartzite and portions of the quartzite have been lifted upwards. To the west and north the invasion of the quartzite becomes more extensive and immediately southwest of the Pilanesberg, basic rocks cut through the quartzite down into the underlying shale. The roof of the basic rocks is formed by quartzite and granophyre or granite, and quartzite seems to grade into the granophyre. Large-scale intrusive relations are shown by: the ferrogabbro unit north of the Pilanesberg, where in two places, it cuts across the whole sequence of basic rocks; a band of the porphyritic pyroxenite unit which occurs below the Merensky Reef north of the Pilanesberg but half way up in the norite unit south of the Pilanesberg; a large body of the porphyritic pyroxenite unit intrusive into the basal norite unit southeast of Rustenburg; and the pyroxenite unit which is interrupted by the norite unit in a few places. Small-scale relations between the various units are mostly represented by inclusions of one rock unit in another, tongues of one cutting another, and other contact phenomena.

Compositions of the plagioclase, orthopyroxene, and clinopyroxene not only indicate that upwards in the sequence in each one of the rock units the pyroxenes become more iron-rich and plagioclase more sodic but that this is also the case in the sequence as a whole and that reversed shifts in the compositional trends are confined to the contacts between successive units. Changes in chemical composition as indicated by oxide variation and other diagrams are also confined to the contacts between successive units.

The emplacement of the Bushveld magma which was derived from the peridotitic upper mantle by a process of partial zone melting, was regulated by alternating conditions of tension and compression. Thus the magma was emplaced in a

series of surges and crystallization differentiation took place in each one of them. Each successive layer overlaps the previous one and sagging of the floor and tilting towards the centre of the Complex resulted in a tilted funnel-shaped structure.

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## I. INTRODUCTION

### A. Location

The Bushveld Igneous Complex occupies a pear-shaped area with an east-west axis of about 480 kilometres in the central Transvaal. It extends from the Botswana border to Burgersfort in the eastern Transvaal (Plate I, inset). The total area of this gigantic feature, which dominates the geology of the central Transvaal is estimated at about 60,000 square kilometres of which about 26,000 square kilometres are covered by younger formations. According to Willemse (1964, p.95) the area occupied by the Bushveld Complex is about 67,000 square kilometres but he admits that owing to younger formations the extension in the northwesterly and southeasterly directions is by no means very definitely known.

The basic portion of the western part of the Bushveld Complex, which is the main subject of this thesis, actually constitutes the western outer edge of the Complex (Plate I, inset). It is a semi ring-shaped body trending for about 240 kilometres from the Crocodile River, south of Thabazimbi, in a southwesterly direction to fringe the Pilanesberg in the west, from where it swings in a southeasterly direction past Rustenburg and then thins gradually towards Pretoria where it fingers out northeast of this city. From west of the Pilanesberg, a lobe of the basic rocks extends towards the west for about 110 kilometres up to and over the Transvaal border. This extension forms a compartment which is more or less separated from the main western one by a range of sediments forming the Matlapynsberg (Plate II).

The basic portion of the western part of the Bushveld Complex covers about 5,000 square kilometres and together with the basic portions of the eastern and northern parts of the Complex constitute the most famous example of a layered intrusion in the world. The rest of the Complex consists of felsic rocks such as granite, granophyre, and felsite (Plate I, inset).

### B. Physiography

Physiographically the Bushveld Complex exhibits the features of a basin; it represents a topographical unit rimmed by a nearly complete girdle of relatively

high ground consisting mainly of rocks of the Transvaal System with a centripetal dip. According to Willemse (1964, p. 95–96) differential weathering of quartzite and shale of the Pretoria Series resulted in prominent parallel ridges which, in curvilinear fashion, envelop the Complex in sectors for miles on end, producing magnificent scenery.

The basic portion of the western part of the Bushveld Complex, (Plate II) is bounded in the south by the Magaliesberg Range formed by northward-dipping quartzite which trends from Pretoria westwards towards Rustenburg from where it swings in a northwesterly direction towards the Pilanesberg. Here a break in the topography represents the transgression of the Magaliesberg quartzite by the basic rocks which cut downwards to a lower horizon to form the western extension of the Complex. The topography is, however, partly revived in the quartzite hills of the Matlapynsberg. The western extension is bounded by the Enzelberg in the south and the Dwarsberg in the north which in turn swings from near the Pilanesberg northeastwards as the Witfontein Range which rims the northern margin of the basic rocks.

More or less in the centre of this area the Pilanesberg, which consists of younger alkaline rocks, forms a large, circular "inselberg", 29 kilometres in diameter, towering between 300 and 500 metres above the surrounding flats, the larger syenite dykes (Plate I) which radiate northwestwards and southeastwards from the Pilanesberg, trend across the flats as low, narrow ridges.

The basic rocks occupy remarkably flat country, covered in many places by deep black turf or red soil. The topography is described by Hall (1932, pp. 159–160) as having, on the whole, a mild degree of relief in comparison with the eastern part. The elevation of the ridges and hills is moderate when measured against the mountainous physiography of the Norite Zone in Sekukuniland. North of Pretoria, the so-called Pyramids, which consist of gabbro, rise from the surrounding flats to a height of some 60 metres. To the west, more hills occur along this line which is roughly parallel to the Magaliesberg Range. North of the Pilanesberg, however, there are only three isolated groups of conical hills on Elandsfontein 386 JR, Spitskop 46 KQ and Modderkuil 39 JQ. The reason for their sparse occurrence in this area is that the gabbro unit is cut off by the younger ferrogabbro unit

which is much less resistant to weathering (Coertze, 1958, p. 389). The pyramidal range of gabbro is the equivalent of the Leolo Mountains in the eastern part of the Complex, which rise to some 600 metres above the flats.

The only other conspicuous outcrops form isolated hills such as Mooskop, near the Zwartkop Chrome Mine; the pyroxenite hills northwest of the Pilanesberg on Witkleifontein 136 JP; some pyroxenite ridges west of the Pilanesberg; the dunite hills north of Boshoeck; and a single norite hill on Kroondal 304 JQ.

The southern part of the area is drained by the Crocodile, Hex and Elands Rivers, the last two of which drain into the Crocodile River on the Bushveld granite outside the area mapped. The northern part of the area is drained by the Bierspruit which also joins the Crocodile River outside the area, and the far western extension is drained by the Great Marico River with its tributary, the Rietspruit.

### C. Previous Work

Hall (1932, pp. 22–26) gives a detailed account of all the literature up to 1932 referring directly or indirectly to the Bushveld Igneous Complex. He states that knowledge of the Bushveld Igneous Complex had been gained in three fairly distinct stages: the first extends from the earliest reference to Bushveld rocks up to 1901 when Molengraaff published his first discussion of the Complex as a whole. The second period begins with the establishment of the Geological Survey of the Transvaal in 1902 when the systematic mapping of the Complex was started and ended with two outstanding contributions by Daly and Molengraaff after the visit of the Shaler Memorial Expedition in 1922. The third period began with the discovery of platinum in 1924. Hall (1932, p. 22) states that a unique event in the history of geological science in South Africa was the meeting of the International Geological Congress during 1929, when some of the most critical aspects of the Complex were shown to many geologists. He thought that this congress would bear good fruit in due course and that many new publications would appear.

Without doubt, the third period ended in 1932 with Hall's outstanding memoir entitled "The Bushveld Igneous Complex of the Central Transvaal". He did not claim that this work had finally settled the many problems, but it indeed marked

an important stage in the elucidation of Bushveld geology and has been of great value to those who worked there since. At that time it was generally believed that the basic portion of the Bushveld Igneous Complex had the form of a lopolith and Hall thought that the extreme petrographical diversity of this portion was due to differentiation in place after emplacement under the dominating, but not exclusive, influence of gravity (Hall, 1932, pp. 278–283).

A fourth period followed Hall's work, the first part of which was characterized by careful research, mainly mineralogical, by B.V. Lombaard and his students in the University of Pretoria. Lombaard (1934, pp. 5–52) studied the composition of the pyroxenes and the feldspars of the Complex and drew attention to the general trend of differentiation. According to him, several heaves or influxes of magma from an intra- or subcrustal reservoir were intermittently emplaced into the space now occupied by the Complex. The magma continually changed its composition so that the successive heaves were of slightly different composition and each new heave was differentiated in place.

Lombaard's students followed with more detailed work in limited areas. Here reference will be restricted to those publications dealing with the western part of the Complex.

Schwellnus (1939) made a detailed study of the differentiation of the basic rocks immediately west of the Pilanesberg. Special attention was given to the variation in the compositions of the orthopyroxene and plagioclase. He concludes that pyroxenite and anorthosite are the products of a common parent magma. Changes in temperature which were caused by successive influxes of magma resulted in the rhythmical precipitation of the minerals constituting the pyroxenites and anorthosites. He also describes the mineragraphy of the Vlakfontein copper-nickel sulphide deposits in detail and concludes that these deposits exposed at the present day surface could be offshoots from an "ore-magma" reservoir situated somewhere near the base of the Bushveld Igneous Complex. The ore was injected into the surrounding rock as molten material together with partly crystallized silicates.

Nel (1940) worked on the basic rocks north of Pretoria and gives a detailed mineralogical and petrographical description of the "diabase". According to him, it may also be regarded as a fine-grained hypersthene gabbro, which forms a composite

sill in the Pretoria Series. He also gives a brief description of the gabbro immediately overlying the diabase, with special reference to the variations in its mineralogical composition.

Liebenberg (1942) describes the geology of an area along the western margin of the Complex in the Marico district. A detailed mineralogical and petrological study of the basal rocks was undertaken for the purpose of correlating the igneous rocks in this area with those already described in other parts of the Complex. He concludes that the rocks belong to the "Basal Zone".

Fourie (1945) studied the lower basic rocks north of Rustenburg. He mapped a small area in detail and shows that some synclines and anticlines occur in the floor of the basic rocks. The mineralogy of rocks in this lower part of the Complex is described in detail.

During this period the Geological Survey carried out an investigation of the chromitite deposits (Kupferbürger and others, 1937). The chromitite bands in the eastern and western parts of the Complex are described and they are divided into lower, middle and upper groups. Wasserstein (1936) describes the "breaks" in the Merensky Reef and chromitite seams north of the Pilanesberg and claims that they were displaced by faults. De Bruyn (1944) carried out a petrographic investigation of mineralized bore-hole core from Middellaagte 382 KQ, north of the Pilanesberg.

From 1949 onwards geological interest again became sharply focussed on the Bushveld Igneous Complex, partly owing to the publication of a controversial paper by Van Biljon (1949). According to Van Biljon the several rock types of the Bushveld Igneous Complex resulted from transformation of sediments of the Pretoria Series. He considers the upper Magaliesberg rocks to have been transformed into pseudo-igneous rocks: shales were "transfused" into norite, and carbonate-rich layers into basic and ultra-basic rocks. He maintains that volatiles from the Dolomite Series and water and salts from the other strata converted carbonate bands into magnetite, chromitite, and platiniferous rocks. Renewed interest was also caused by economic developments. A short account of nickel-copper, chromite, and other mineral deposits, based on Boardman's mapping in the far western Bushveld Complex, is given in the quarterly information circular (April-June, 1949) of the Department of Mines. Owing to the increased demand, the enormous chromitite de-

posits of the Complex became more and more important and, with expanding usage, platinum prices began to soar. Eventually it became known that the vanadium content of the magnetitite could also be exploited economically. By this time it was already generally realized that more detailed studies of the Complex were of the utmost importance.

During 1951 the Geological Survey of South Africa began to remap the basic portion of the Complex on air photographs; mining geologists paid more attention to the economical possibilities, and universities continued their investigations. The accumulation of more information immediately led to the revision of existing ideas on the genesis of the Complex, and some old ideas were revived in new publications.

Finally the International Symposium on the Bushveld Igneous Complex and other layered intrusions took place in Pretoria in 1969. Hall's prophetic words (1932, p.19): "The Bushveld Igneous Complex is a vast treasure ground which for many years to come will provide the mineralogist, the petrographer and the geologist with a rich field to dig over", have indeed already proved to be true after only about 40 years.

#### 1. *Various Authors*

1. Schmidt (1952) investigated the emplacement of the Merensky Reef and associated rocks in the Rustenburg Platinum Mine by means of petrofabric analysis and with special reference to the so-called "pot-holes" and "hillocks". The mineralogy and petrography of the various rock types are described and petrographical data for the undisturbed Merensky Reef are compared with those of the reef in the "circular depressions". He suggests that the Merensky Reef and associated rocks were formed by crystal settling and that swirling currents in the magma were responsible for the formation of the "pot-holes".

2. Truter (1955) emphasizes some of the new ideas held by members of the Geological Survey regarding the emplacement of the Complex as a whole. He postulates four or five centres of intrusion and according to him emplacement of the main pear-shaped mass as a number of separate bodies connected in series must have been initiated and sustained in response to north-south tensional stresses acting along an east-west axis connecting the several centres of eruption. At each of the

two centres in the central portion a huge block of Transvaal rocks was floated bodily upwards by an initially ultrabasic magma. Each of these blocks was elevated to a height at which the weight of the superincumbent sediments adjoining the orifice so created could be overcome by the magma intruded radially into them. This was at an horizon just above the main Magaliesberg quartzite and, as the magmatic pressure remained constant, one surge of magma after another was emplaced in this manner, each one being injected under a constant load and therefore immediately above the one that preceded it.

3. Cousins (1959a) used geophysical data on the gravity map of the Union of South Africa supplied by the Geological Survey to work out a new hypothesis regarding the structure of the basic portion of the Complex. He concludes that the basic portion of the Complex is not part of a lopolith but consists of two deep curved troughs of basic rocks having a superficial synclinal structure. Structure sections drawn by him in selected areas illustrate this idea.

4. Feringa (1959) used bore-hole logs from the Union Section of the Rustenburg Platinum Mine to draw structure sections. His interpretation of these sections is that the rocks below the Merensky Reef were folded before emplacement of the latter and other overlying rocks. The higher portions of the floor are considered to have been "islands" in the magma which was actually extrusive. Discussions on this paper bring out the fact that there was indeed a roof under which the basic rocks were emplaced (Coertze, 1959, p. 233). Layers which Feringa regards as having been subjected to denudation before outflow of the higher layers could just as well have pinched out during emplacement.

5. Fourie (1959) studied the chromitite deposits in the Rustenburg area which occur from 560 to 3,150 metres below the well-known Merensky Reef. The chromitite is sub-divided into a lower, middle, and upper group and there are at least 25 "seams" which range in thickness from a fraction of a centimetre up to a maximum of about 6 metres. His correlation is based on the type of country rock, the presence of markers, thicknesses of individual seams, and rhythms in the succession. Methods used for ore concentration, grading, and marketing are also discussed.

6. Van Zyl (1960) made a detailed study of bore-hole cores from the Union Section of the Rustenburg Platinum Mine. He concludes that the rock types inter-

sected can be divided into a few main units, each one a separate intrusion which differentiated in place. He divides the basic rocks into five main units. All the rocks investigated are part of a central norite-anorthosite unit except for the ferrosodagabbro found in one bore-hole. The rhythmic layering is explained by postulating several heaves of magma each one of which was differentiated by fractional crystallization and differentiation in place. It is possible to subdivide this central norite-anorthosite unit into four sub-units.

7. Von Backström and others (1960) mapped the area covered by the Rustenburg sheet (5,550 square kilometres). They describe the following rocks of the Bushveld Complex in this area: hybrid rocks, epidiorite, diabase, porphyritic pyroxenite, pyroxenite, anorthosite, gabbro, and norite. They do not distinguish between gabbro and ferrogabbro. Chromitite, the Merensky Reef, magnetitite, and dunite pipes are also described. Although no new hypothesis regarding the genesis of the Complex is put forward, some of the old hypotheses are briefly reviewed.

8. McDonald (1967) investigated two bore-hole cores of pyroxenite and chromitite from Ruighoek 169 JP. He concludes that the pyroxenite and chromitite sequence resulted from a cyclic process in which cumulate minerals collected near the floor. Compositional changes of these minerals reflect the influence of a separate intrusion of undifferentiated magma or refusion in depth of crystals formed near the top of the magma chamber.

9. Wyllie (1967) gives a short summary of existing ideas on the genesis of ultrabasic and gabbroic rocks including those of both the western and eastern parts of the Bushveld Complex.

10. Wager and Brown (1968) explain the layered basic rocks according to an origin by crystal accumulation. According to them the intrusion displays a remarkably complete sequence of the fractionation products of a tholeiitic basalt magma.

11. Van Zyl (1970), who investigated bore-hole cores in the area north of the Pilanesberg, concludes that the rhythmic layering could be best explained if one accepts that different heaves of homogeneous magma were emplaced at intervals after which fractional crystallization took place. The chromitite bands are not early crystal accumulations.

12. Liebenberg (1970) who studied the sulphides in the Bushveld Complex also describes in detail those found in bore-hole cores west of the Pilanesberg and in the Merensky Reef. He establishes a definite trend in the differentiation of the major sulphides.

13. Vermaak (1970) gives an account of the structure in an area west of the Pilanesberg. Inliers of the sediment as well as small xenoliths in the basic rocks are described. Noritic sills in the Transvaal System are, according to him, not part of the Complex.

14. Interpretation of gravity results in an area west of the Pilanesberg (Biesheuvel, 1970) indicates two areas where substantial thicknesses of Bushveld rocks occur, one immediately west of the Pilanesberg and the other some forty miles to the west. There are several inliers of sediments of the Pretoria Series.

Even more publications on the eastern part of the Bushveld Complex have been made. These are not mentioned here, but reference is made to some of them in the text. Willemse (1964 and 1969) gives an account and a generalized map of the Complex as a whole.

## 2. *The present Author*

A considerable amount of work on the western part of the Complex by the present writer has already been published. A summary review of this work is given in the following paragraphs.

1. A study of the area north of the Pilanesberg (Coertze, 1958) has led to the conclusion that each of the constituent rock units of the basic portion of the Complex, namely pyroxenite with chromitite seams, anorthosite, norite, porphyritic pyroxenite, pegmatitic pyroxenite, gabbro, ferrogabbro, dunite, and magnetitite represents a separate intrusion. It was found that the so-called "breaks" which were known to occur in the platiniferous and chromiferous rocks along their strike, and which were thought to be due to faulting, are actually caused by the complete transgression of the uppermost ferrogabbro across the whole succession of layered basic rocks right down to the sedimentary base of the Complex at two localities (Plate LXVI). This transgression has caused the chromiferous and platiniferous rocks to be absent over no less than 27 km along the strike, although it had the effect

of more than doubling the strike length of the magnetitite bands.

2. A shear-zone in the gabbro of the Bushveld Igneous Complex, which can be traced from the Pilanesberg in a south-easterly direction for 22 km., was investigated (Coertze, 1960a). It was found that magnetite-bearing mottled anorthosite is intrusive into the gabbro along this zone and that fissures, with prehnite and quartz, and veins of graphic granite occur along it. Field and microscopic data suggest that the anorthosite was formed by the partial refusion of the lower anorthosite *in situ* and re-injection as a crystal mush into the overlying gabbro along the shear zone. The prehnite and graphic granite were probably formed under hydrothermal conditions.

3. A detailed study has been made of the stratigraphy and history of the Transvaal System, the upper part of which is intruded by rocks of the Bushveld Complex to such an extent that the geology of the central Transvaal is dominated by the Bushveld Complex (Coertze, 1961).

4. The Rustenburg fault and its influence on mineral deposits south-west of the Pilanesberg has also been studied (Coertze, 1962a). The faulting, which took place after the emplacement of the gabbro of the Bushveld Complex, caused displacement of the chromitite seams. On the other hand, the fault zone provided lines of weakness along which dunite, magnetitite, diallagite pegmatite, bronzitite pegmatite, and intrusive bodies containing sulphides were emplaced.

5. An account of the geology northeast of Pretoria has been given (Coertze, 1962b). The basic rocks finger out in the Pretoria Series towards the east in such a way that they do not correspond in strike and dip to the sediments. As it is impossible to tie up any single layer of sediment with any layer in the basic rocks, the latter could not have been formed by the transformation of the sediments as has been suggested by Van Biljon (1949). Smelterskop sediments around the syenite complexes have been metasomatised.

6. A joint investigation of the basic rocks north of the Pilanesberg (Coertze and Schumann, 1962) led to the conclusion that the following units were emplaced as separate intrusions: pyroxenite, anorthosite, norite, porphyritic pyroxenite, gabbro, and ferrogabbro. The dunite and magnetitite are also intrusive. The platinum, chrome,

and vanadium ore deposits are described and the chromitite seams are divided into lower, middle, and upper groups. It is pointed out that, apart from the Merensky Reef, there are other pegmatitic pyroxenite sills which may be platiniferous. Owing to the transgression of all the older basic rocks by the younger ferrogabbro with the magnetitite sheets, the distance along which magnetitite crops out is more than twice the distance originally expected. Diagnostic magnetic variations were found over the different rock types.

7. A study of the succession of the basic rocks associated with the Merensky Reef in the Rustenburg Platinum Mine (Coertze, 1963a) has shown that some of the structures known as "pot-holes" (Schmidt, 1952) are actually caused by faulting.

8. On the basis of field relationships (Coertze, 1970) the basic portion of the western part of the Bushveld Complex is subdivided into eight rock units. These units are shown on a simplified map. It is concluded that differentiation was a long continuous process which started in depth and came to an end in the present site. The magma was probably formed by partial melting within a mantle of inhomogeneous peridotitic composition and was emplaced in separate surges in the upper part of the Pretoria Series.

The present author has also published papers on the eastern part of the Complex, reference to which is in the text where appropriate.

#### D. Scope of Present Investigation

The present investigation was started in 1951 as part of the revision of the old Geological Sheet Map 4 and a small area of the basic rocks of the western part of the Bushveld Complex was mapped in detail by the author. Later, owing to the increasing importance of chromitite, the platiniferous Merensky Reef, and the magnetitite, it was decided to map the entire western part of the basic portion of the Complex. Some 2,590 square kilometres were studied in the field and mapped by the author during the period 1956-1965 (see key map, Plate I). In addition to the surface mapping several mines and many cores from bore-holes in the area were investigated.

A geological map of the main compartment could then be compiled on a

scale of 1:50,000 and reduced to 1:100,000 (Plate I) but as all the information could not be shown on this map, three detailed "stratigraphical columns" were also compiled (Plate III). Although the far western extension towards the Botswana border, was also visited and observations made which are included in this thesis, no detailed map of this extension was compiled, but its location is shown on the inset of Plate I.

All the rock units were studied microscopically and the volumetric compositions of the rocks and the compositions of the minerals were determined, especially along the routes indicated on Plate I (inset). The compositions of the plagioclase feldspars were determined by means of the universal stage and the stereograms of Reinhard (1936). For the clinopyroxenes the  $\beta$  refractive indexes were measured and for the sake of accuracy the optic axial angles were measured only when two optic axes entered the field of view. The diagram of Hess (1949, p. 634, Plate I) was used to determine the composition of the clinopyroxenes. For the compositions of the orthopyroxenes and the olivines the diagrams of Poldervaart (1950, pp. 1076 and 1073, Figs. 3 and 2) were used. The  $2V$  and  $\chi$  refractive index was used for the composition of the orthopyroxene and  $2V$  and  $\chi$  and  $\beta$  refractive indexes for the olivine. Modal determinations were mostly done by using a point counter. All other available mineral determinations of which the collecting points could be established were used together with the new determinations to establish the variation in mineral compositions across all the rock units. All available chemical analyses were also collected and some new analyses were made where necessary in order to establish the chemical variation across the Complex. They were all done by conventional methods. Analyses of magnetite were also collected and new ones added to study the iron:vanadium ratio across the sequence of the bands.

## II. GENERAL GEOLOGY AND SEQUENCE

### A. Rock Units Mapped and Rock Assemblages

On the basis of their field relations eight rock units, all part of the layered sequence, were mapped (Plate I). These are the basal norite unit, consisting of the quartz norite and marginal norite sub-units; the harzburgite unit; the pyroxenite unit; the anorthosite unit; the norite unit; the porphyritic pyroxenite unit, consisting of the porphyritic and pegmatitic sub-units; the gabbro unit; and the ferro-gabbro unit. The magnetitite bands, occurring mainly in the ferrogabbro unit, were also mapped.

Only the basal norite unit, pyroxenite unit, norite unit, gabbro unit, and ferrogabbro unit (Plate I) form fairly wide and continuous "zones". Apparently, according to their distribution, the anorthosite and porphyritic pyroxenite units are subordinate to the norite unit and the harzburgite to the pyroxenite unit because they occur as thin bands in the norite and pyroxenite units respectively. On the other hand, there are two very large occurrences of the porphyritic pyroxenite unit on Kroondal 304 JQ — Rietfontein 338 JQ and on Kroondal 304 JQ — Zuurplaat 337 JQ which are not associated with the norite unit at all. Neither are the smaller anorthosite occurrences in the gabbro unit south of the Pilanesberg associated with the norite unit.

The arrangement of the layered sequence into units is a chronological subdivision and not an attempt to subdivide into layers of approximately equal thickness and extent.

The names of the units as such should not be confused with true petrological names because, in fact, they only indicate that the unit, on the whole, consists predominantly of a certain rock type. Volumetric compositions across these units are shown in Plate VI and their petrography is described in section IV.

The chromitite seams were subdivided into three groups which are shown by means of symbols on the map (Plate I). The subdivision is based on the fact that there is a rough, natural grouping of the seams (Plate III). *The lower group* includes all the chromitite seams in the pyroxenite unit except those at or very near the

contact with the overlying members of the anorthosite and norite units. *The middle group* comprises all the chromitite seams in the pyroxenite and norite units occurring near the contact of the two units. *The upper group* is represented by the chromitite seams within and above a band of the anorthosite unit which overlies the norite unit north of the Pilanesberg but which occurs within the norite unit south of the Pilanesberg.

The term *Merensky Reef* is used for one of the bands of the pegmatitic sub-unit situated on the horizon where, up to the present, platinum has been mined, i.e. the second layer of this sub-unit from the top (Plate III). The *Merensky Suite* comprises chromitite, a layer of the pegmatitic sub-unit (Merensky Reef) and a layer of the porphyritic sub-unit situated between two bands of the anorthosite unit. At the platinum mine on Zwartklip 405 KQ, a similar combination lower down is called the *Swartklip Suite* (Coertze and Schumann, 1962, p. 8.)

In addition, composite pipe-like bodies of hortonolite dunite and magnetitite, which are not part of the layered sequence, but are often associated with diallagite-pegmatite, may occur in any one of the units, and especially in the ferro-gabbro unit.

#### B. Distribution of the Various Rock Units, Bands of Economic Importance, and Pipes

The general distribution of the rock units, chromitite, Merensky Reef, and magnetitite is shown on the geological map (Plate I). On the whole, apart from the western extension (not shown on the map), the basic rocks form a semi-arcuate body with dips of the igneous layering towards the centre of this body. Except for the far western extension, which is partly floored by Magaliesberg shale and Daspoort sediments, the basic body is floored by the main Magaliesberg quartzite.

The lower part of the basic rocks consists of the quartz norite sub-unit which is well developed in the Rustenburg area. It surrounds sedimentary inclusions west of the Pilanesberg and is sporadically represented towards Pretoria but is absent or covered by superficial drift north of the Pilanesberg. The quartz norite sub-unit thus occurs where the basal norite unit rests directly on Magaliesberg or Smelterskop

quartzite which indicates that it was probably formed by the incorporation of quartzite in the basic magma from which the basal norite unit formed. On the quartzite norite sub-unit follows the marginal norite sub-unit which could not always be distinguished in the field from the norite unit higher up. It is well developed in the Rustenburg area, especially towards Pretoria, where it is separated in many places from the norite unit by the pyroxenite unit. It also occurs in boreholes west of the Pilanesberg and in a few places in the far western extension of the Complex (not shown on Plate I). A noritic sheet low down in the pyroxenite unit west of the Pilanesberg may perhaps represent a feldspar-rich layer in the pyroxenite unit.

The marginal norite sub-unit is followed by the pyroxenite unit with the chromitite bands of the lower group in its upper part. The pyroxenite unit forms the base of the basic rocks north of the Pilanesberg, reaches its maximum development west of the Pilanesberg as well as in the far western extension near Nietverdiend, and trends past Rustenburg towards Brits. To the east it disappears near Brits. There are also isolated occurrences of intrusive pyroxenite in the basal norite unit on Elandsdraal 469 JQ and Bokfontein 448 JQ. On the other hand the pyroxenitic bands or lenses in the basal norite unit on Hartebeestfontein 324 JR, north of Pretoria, represent pyroxene-rich layers which alternate with feldspar-rich layers in the basal norite unit and were probably formed by crystallization differentiation. Although the pyroxenite unit occurs more or less on the same horizon all round, it does not form a continuous zone but is disrupted in a number of places, either by other rock units or by faulting.

In the pyroxenite unit, near its base, there are lens-like and sheet-like bodies of the harzburgite unit, almost completely serpentinized and silicified at the surface. The harzburgite unit is well developed in the far western extension near Nietverdiend, as well as immediately west of the Pilanesberg but disappears to the north near the platinum mine on Zwartklip 405 KQ (Plate I) and to the south near Boshoek where only a very thin layer occurs in a bore-hole.

The norite unit which follows on the pyroxenite unit was, except for disturbances caused by faulting and cross cutting by the ferrogabbro unit, followed from the Crocodile River in the north, around the Pilanesberg and past Rustenburg towards

Brits where it pinches out a few miles southeast of this town.

The anorthosite unit occurs as bands on a few horizons (Plates I and III). It is sporadically found at the contact between the pyroxenite and norite units and occurs in the norite unit below the Merensky Reef. The Merensky Reef itself occurs in a band of this unit. The Merensky Reef which is a member (band) of the porphyritic pyroxenite unit can be followed from the Crocodile River in the north to the Pilanesberg. It is again traceable from north of Boshhoek, past Rustenburg to south of Brits where it terminates. North of the Pilanesberg a band of the porphyritic pyroxenite unit also occurs in a band of the anorthosite unit immediately below the Merensky Suite, but south of the Pilanesberg, this porphyritic pyroxenite lies in a band of the anorthosite unit half-way up in the norite unit. There is also a large isolated occurrence of the porphyritic pyroxenite unit east of Rustenburg.

A wide zone of the gabbro unit follows on a band of the anorthosite unit and the Merensky Reef above the norite unit. It is interrupted in two places by the succeeding ferrogabbro unit north of the Pilanesberg and by the Pilanesberg itself. It thins and terminates northeast of Pretoria.

The ferrogabbro unit with the magnetitite bands follows on the gabbro unit and is also interrupted by the Pilanesberg, but in turn, transgresses the lower rock units in two places north of the Pilanesberg. The ferrogabbro unit trends further eastwards than the gabbro unit and fingers out in the Smelterskop quartzite northeast of Pretoria.

Pipes of magnetitite-hortonolite dunite and associated diallagite pegmatite may occur in any one of the layered rock units. They are mostly confined to the ferrogabbro unit and are also concentrated in places in the gabbro and norite units just above and below the Merensky Suite, and also occur along fault zones. Sulphides occur in a sheared and brecciated quartzite included in gabbro south of Matooster (Coertze, 1962a, p. 256). There are also the well-known nickel-copper sulphide pipes in the pyroxenite unit on Vlakfontein 207 JP, Tweelaagte 175 JP, Liliput 166 JP, and Vlakfontein 164 JP. All these sulphide bodies seem to occur mostly in pyroxenite along the big Rustenburg fault and other smaller faults and mainly above the noritic zone low down in the pyroxenite unit. Sulphide bodies are,

however, also present on Groenfontein 138 JP and were recently also found on other farms (Vermaak, 1970, Plate I).

### C. Sequence of the Various Rock Units

Because of the layering in the rock units, it has often been attempted in the past to sub-divide the basic rocks into "zones". Sub-divisions were made by Hall (1932, p. 271), Lombaard (1934, p. 23) and Schwellnus (1956, p.85). All these sub-divisions are fairly similar and differ only slightly as to where the contacts between succeeding "zones" should be. Such a zonal grouping is also applied by Willemse (1964, p. 101). The guiding principle on which his grouping into "zones" is based, is the recognition of certain economic horizons such as chromitite bands, the Merensky Reef, and magnetitite bands as markers. He states (p. 102), however, that petrologically there is very little justification for regarding these as lines of demarcation.

Van Zyl (1960, p.6) proposed a sub-division into units and compares it with that of Lombaard (1934, p.23) (which corresponds closely to Willemse's) and Schwellnus'.

During this investigation it was possible to work out the chronological sequence of intrusion of different units and a sub-division based thereon, is here adopted. On the basis of their field relations these units could be mapped individually. However, a further non-chronological sub-division of the basal norite unit into two sub-units, based on quartz content and grain sizes is made.

In Table I the sub-division is shown and compared with those of Van Zyl and Willemse.

The proposed sub-division corresponds closely to Van Zyl's but with the following differences: The noritic rocks at the base of the gabbro are considered to be part of the gabbro unit because there are no intrusive relations between the two rock types. On the basis of sub-division adopted in mapping this area, Van Zyl's norite-anorthosite unit is considered to be composed of three separate units; a norite unit, a porphyritic pyroxenite unit, and an anorthosite unit. Although the porphyritic pyroxenite unit and the anorthosite unit are relatively subordinate to the norite unit (occurring only in thin bands) in the "normal" layered sequence

there are, apart from intrusive relations in this sequence, also fairly large occurrences of the porphyritic pyroxenite unit in other rock units such as the basal norite unit, and anorthosite in the gabbro unit. The harzburgite which is found only in the pyroxenite unit west of the Pilanesberg is also shown separately as a unit, occurring in the pyroxenite unit. Although the sequence is fairly regular, there are also "irregularities". In two places north of the Pilanesberg, for instance, the ferrogabbro unit cuts down to the sedimentary floor across all the other units.

The columns of the sequence and thicknesses of rock units for three areas are shown in Plate III. A comparison of the sequence and an attempt to correlate some of the bands (Table II) is of value because it brings out the fact that some of them, representing more than 75 per cent of the total thickness of basic rocks, can be correlated, but others not. On the whole, apart from the transgressions mentioned, it seems that from the Merensky Reef upwards, all the rock units can be correlated and the Merensky Suite, therefore, forms a valuable marker.

In the area north of the Pilanesberg the pyroxenite unit forms the base of the basic rocks and the norite unit is followed by bands of the anorthosite unit and the porphyritic pyroxenite unit. South of the Pilanesberg the homogeneous norite unit is interrupted near its middle by bands of the anorthosite unit and the porphyritic and pegmatitic sub-units. This is also the case in the Rustenburg area where, in addition, there is also the thick basal norite unit below the pyroxenite unit. In the same area the large body of the porphyritic pyroxenite unit occurs immediately below the pyroxenite unit which is not the case in the other two areas. It seems feasible to correlate the pyroxenite unit in all three areas (Plate III), although the chromitite bands in them cannot be correlated throughout and there are no bands or lenses of the harzburgite unit in the Rustenburg area. Anorthositic bands in the gabbro unit north of the Pilanesberg could not be correlated with anorthosite bands in this unit south of the Pilanesberg.

Owing to scarcity of outcrops the ferrogabbro unit could not be sub-divided into smaller sub-units.

TABLE I

| Proposed Subdivision<br>& total max. thickness<br>in metres | Van Zyl's Sub-division         | Willemse's Zonal Grouping                |
|-------------------------------------------------------------|--------------------------------|------------------------------------------|
| Ferrogabbro Unit<br>1700                                    | Ferrosodagabbro Unit           | Upper zone<br><u>Main magnetite Band</u> |
| <u>Base of ferrogabbro</u>                                  | <u>Base of ferrosodagabbro</u> |                                          |
| Gabbro Unit<br>2700-4400                                    | Gabbro Unit                    | Main zone                                |
| Base of noritic<br><u>phase of Gabbro Unit</u>              | <u>Base of gabbro</u>          |                                          |
| Porphyritic Pyroxen-<br>ite Unit<br>85                      |                                | <u>Merensky Reef</u>                     |
| Norite Unit<br>600                                          | Norite Anorthosite Unit        |                                          |
| Anorthosite Unit<br>300                                     | Base of norite & anorthosite   | Critical zone                            |
| Pyroxenite Unit<br>600                                      | Pyroxenite Unit                | <u>Main Chromitite band</u>              |
| <u>Harzburgite Unit</u>                                     |                                |                                          |
| Base of pyroxenite                                          | Base of pyroxenite             | Basal zone                               |
| Basal Norite Unit<br>Marginal Norite<br>Sub-unit<br>450     | Basal Norite Unit              |                                          |
| Quartz norite<br>Sub-unit<br>700                            |                                | Chill zone                               |

TABLE II

## Generalized Succession of Basic Rocks

| North of Pilanesberg | South of Pilanesberg | Rustenburg Area     |
|----------------------|----------------------|---------------------|
| F                    | F                    | F                   |
| G                    | G                    | G                   |
| A5                   | A5                   | A5                  |
| P4(Bastard Reef)     | P4 (Bastard Reef)    | P4 (Bastard Reef)   |
| A4                   | A4                   | A4                  |
| P3                   | P3                   | P3                  |
| Pp3 (Merensky Reef)  | Pp3 (Merensky Reef)  | Pp3 (Merensky Reef) |
| A3                   | A3                   | A3                  |
| Pp2                  | N3                   | N3                  |
| P2                   | P2                   | A2                  |
| Pp <sup>1</sup>      | Pp <sup>2</sup>      | Pp <sup>2</sup>     |
| P1                   | A2                   | P2                  |
| A2                   | N2                   | N2                  |
| N2 + N3              | A1                   | A1                  |
| A1                   | P1                   | P1                  |
| Py                   | Py                   | Py                  |
| H                    | H                    | P                   |
|                      | N                    | N1                  |
|                      |                      | N                   |

N : quartz norite sub-unit; N1 : marginal norite sub-unit;

H : harzburgite unit; Py : pyroxenite unit; A1—A5 : bands of anorthosite unit; N2—N3 : successive bands of norite unit;

P-P3 : bands of the porphyritic sub-unit; P<sub>p</sub>1—P<sub>p</sub>3 : bands of the pegmatitic sub-unit; G : gabbro unit; F : ferrogabbro unit.

## D. Field Relations

### 1. *Floor Relations*

The basic portion of the Bushveld Complex is intrusive into the upper part of the Pretoria Series. A detailed account of the stratigraphy of the Transvaal System, including the Pretoria Series (the Timeball Hill, Daspoort, Magaliesberg, and Smelterskop Stages) has been published by the present author (Coertze, 1961).

For a considerable distance, westwards from Pretoria, the basic rocks apparently follow concordantly on the Magaliesberg quartzite, but northeast of Pretoria they finger out in sediments of the Smelterskop stage (Coertze, 1961, p. 59) which are fairly well developed in this area (Plate I).

On Buffelshoek 468 JQ to Zuurplaat 337 JQ, basic rocks emplaced along shale bands above the Magaliesberg quartzite separate a succession of overlying Smelterskop quartzite from the Magaliesberg quartzite (Plate I). Further eastwards sedimentary xenoliths (Plate I) occur higher up in the sequence. There are, for instance a zone of large sedimentary xenoliths which can be followed for about 22 kilometres from Schietfontein 437 JQ to Pretoria North. Westwards, past Rustenburg, basic magma invaded deeper into the sedimentary floor so that the Magaliesberg quartzite became broken up and the number of xenoliths increased. Apparently so much of the quartzite was incorporated by the first noritic magma that a contaminated magma was formed and most of the xenoliths are thus found in the quartz norite sub-unit.

The invasion of the Magaliesberg quartzite by basic magma becomes more extensive north of Rustenburg, and immediately southwest of the Pilanesberg the basic rocks cut through the quartzite down into the Magaliesberg shale. This is also confirmed by Biesheuvel (1970, p. 278) who states that the super-position of a geological map on his structural interpretation, based on gravimetric data, indicates that the 1500 foot contour corresponds to the north-west contact of the Mahobieskraal sediments. According to him it is clear that 450 metres of basic rocks underlie these sediments which confirms the geological interpretation that in this area the basic magma transgressed to a lower horizon and the Magaliesberg quartzite was broken up so that isolated masses are actually floating in basic rocks (Coertze, 1962a, p. 3). West of the Pilanesberg the Magaliesberg quartzite and some of the underlying

shale are represented by isolated ridges which form the Matlapynsberg. These sediments occur in the quartz norite sub-unit and the pyroxenite unit. There are also large occurrences of these sediments on Bierkraal 134 JP and Kameelboom 284 JP. Biesheuvel (1970, p. 269) states that according to a gravimetric survey these occurrences form one continuous zone and that these sediments form part of the floor of the Complex. They may actually be part of the floor but as they do not form a continuous ridge at the surface and because the areas between outcrops are occupied by basic rocks, it follows that the floor of Magaliesberg quartzite is at least in places intruded and disrupted by basic rocks. To the north of the Pilanesberg Magaliesberg quartzite occurs at a few isolated places only, namely on Nooitgedacht 406 KQ, where it forms a low ridge near the platinum mine, on Zwartkop 369 KQ, where a few small xenoliths occur in pyroxenite, and from Roodedam 368 KQ to Haakdoorn drift 374 KQ, where it again forms a low continuous ridge. For the rest the Magaliesberg sediments are either covered by superficial drift or incorporated by basic rocks. On the other hand the Daspoort sediments in this area form a conspicuous ridge, interrupted only on Vogelstruis Kraal 400 KQ and Elandsfontein 402 KQ, where apparently the basic rocks cut through them in a northerly direction. Owing to the crosscutting of the Magaliesberg quartzite by the basic rocks west of the Pilanesberg these basic rocks occur in the shale below the Magaliesberg quartzite in the far western extension of the Complex. The isolated xenoliths of quartzite in these basic rocks may be either Magaliesberg or Daspoort quartzite.

The Magaliesberg quartzite, up to 450 metres thick, forms the floor of the Complex south and southeast of the Pilanesberg. North of the Pilanesberg the Magaliesberg quartzite is poorly developed and rarely exceeds 30 metres in thickness and apparently the Magaliesberg shale forms the floor of the Complex over long distances. North of the Pilanesberg the pyroxenite unit follows directly on the shale and in places on the thin Magaliesberg quartzite band whereas in the south a thick succession of the basal norite unit follows on the very well developed quartzite. It seems indeed that the availability of large amounts of quartzite contributed at least to the formation of the quartz norite sub-unit.

The "diabase" sheets in the floor sediments, in places as far down as the Dolomite Series, are considered to be the forerunners of the basic rocks forming

the complex proper. Although they are not included in this study, they are intrusive into the sediments and according to a bore-hole core from east of Pretoria, even intrusive into the Ongeluk lava of the Daspoort Stage. Willemse (1964, pp. 98–99) notes that each sheet retains roughly the same stratigraphical position over long distances of strike, but locally they transgress from one horizon to another.

## 2. *Roof Relations*

From Buffelsdrift 281 JR, north of Pretoria to Zoutpansdrift 415 JQ, northeast of Brits, granophyre occurs on top of the basic rocks (Plate I). The granophyre forms fairly hilly country but parts of it is covered by either Karroo sediments or superficial drift. From Zoutpansdrift 415 JQ westwards and then northwards, past the Pilanesberg to the Crocodile River, Bushveld granite and/or granophyre follow on the basic rocks, but as exposures are very poor it cannot be claimed that this is the case all along the contact. The numerous quartzite relics found at the contact between the basic rocks and the granophyre and/or granite are considered the key to the roof relations.

On Haakdoornlaagte 277 JR and Waterval 273 JR small quartzite relics occur at the contact between the ferrogabbro unit and the granophyre. On Kruisfontein 262 JR, Kameelfontein 257 JR, and Zoutpansdrift 415 JQ there are larger strips of sediments, which can still be recognized as quartzite. From Losperfontein 405 JQ to Berseba 397 JQ a continuous strip, mainly quartzite, occurs at the contact between the ferrogabbro unit and the granite, but hornfels, containing metamorphic minerals such as garnet, is also present. Farther, towards the Pilanesberg, quartzite occurs at the contact between the ferrogabbro unit and the granite on Kafferskraal 133 JQ, Rooiwal 285 JQ, Bierkraal 120 JQ, and Rietspruit 83 JQ.

In some places such as on Haakdoornlaagte 277 JR and Waterval 273 JR, the quartzite has been feldspathized to such an extent that it seems to grade into granophyre. All the other quartzites between the ferrogabbro unit and the acid rocks have also been feldspathized, although some of them, especially the larger occurrences have been altered to a lesser extent.

On Bierkraal 120 JQ, the quartzite which occurs at the contact between the ferrogabbro unit and the granite was clearly deformed and all stages form normal

thin layers, through broken ones, to some type of breccia are present. Apparently the rock was mobilized and metamorphosed to such an extent that quartzite fragments occur in a quartzitic groundmass containing minerals such as biotite and cordierite.

There are also a few patches of felsite at the upper contact of the ferrogabbro, as on the border of Kameelfontein 257 JR, Sjambok Zyn Oude Kraal 258 JR, Syferfontein 430 JQ, and Zoutpansdrift 415 JQ. The ferrogabbro is intrusive into the felsite. In the northeastern corner of Sjambok Zyn Oude Kraal 258 JR a tongue of granophyre cuts the ferrogabbro unit and must therefore be younger than the ferrogabbro.

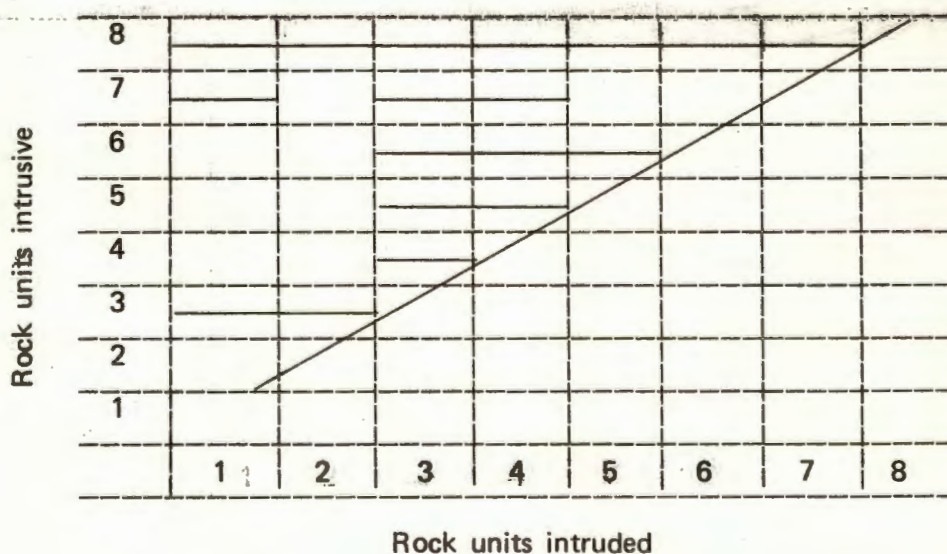
Truter (1955, p. 85) states that the Bushveld granite is intrusive into the "Main zone gabbro" in the Zaaipplaats area. Willemse (1964, pp. 111–112) describes isolated occurrences of Bushveld granite away from the main mass, such as the one near Magnet Heights, which, according to him, is of the same age as the Main granite. He points out that the contact between the main body of granite and the main plutonic phase of the Complex is nowhere clearly exposed. It is either soil-covered or "leptite" intervenes and obscures the relationship. Intrusive breccia formed by the Magnet Heights granite in the gabbro, and granite veins in gabbroic rocks near Potgietersrus prove the younger age of the granite. An age of 2050 million years was determined for the basic rocks and an age of about 1950 million years for the granite (Nicolaysen and others, 1958, p. 145).

In the area mapped, patches of coarse-grained granite occur in the ferrogabbro unit on Sjambok Zyn Oude Kraal 258 JR, even below the magnetitite horizon near the base of the ferrogabbro unit. More such patches occur on Zoutpansdrift 415 JQ, and there are numerous outcrops of granite in the ferrogabbro unit on Losperfontein 405 JQ and Berseba 397 JQ. The fact that some of the patches of coarse-grained granite occur so low down in the sequence of basic rocks suggests that the granite is intrusive. Other outcrops of granitic rock occur in the gabbro below the ferrogabbro on Hartbeestspuit 88 JQ, just south of the Pilanesberg, where they have a dyke-like appearance. The coarse-grained granite is typical Bushveld granite and is probably the equivalent of the Main granite as described by Truter and Strauss (1944, p. 48). It ranges in colour from light pink to red and consists of quartz,

orthoclase, biotite, and hornblende. It differs from the outcrops south of the Pilanesberg which consists mainly of quartz and alkali feldspar and in which the optical continuity of some of the quartz grains in the feldspar suggest the replacement of quartz by feldspar. This type of granitic rock is considered a mobilized syntectonic granite formed from feldspathic quartzite which had been subjected to the metasomatic action of the successive mafic intrusives (Coertze, 1960a, p. 76). North of the Pilanesberg no relationships between the granite and the basic rocks could be observed but granite has been found on Nooitgedacht 11 JQ in a bore-hole situated in the ferrogabbro (Coertze and Schumann, 1962, p. 16). Whether this granite is intrusive or syntectonic could not be established.

### 3. Relations of the Basic Rocks

The sub-division of the basic rocks into eight units is based on large-scale and small-scale intrusive relations between these units and their contact features, discussed in the following paragraphs. The intrusive relations are shown in the following chronological scheme:



1. Basal norite unit. 2. Harzburgite unit. 3. Pyroxenite unit.  
 4. Anorthosite unit. 5. Norite unit. 6. Porphyritic pyroxenite unit.  
 7. Gabbro unit. 8. Ferrogabbro unit.

#### (a) Large-scale Intrusive Relations

The most spectacular large-scale intrusive relations occur north of the

Pilanesberg in the vicinity of Northam. Usually the ferrogabbro unit lies on top of the gabbro unit and the igneous layering is similar in both units. But at two localities the ferrogabbro unit, including the magnetitite bands, cuts across the whole sequence (Plate I) causing two "breaks" in which the ferrogabbro unit has a trough-like transgressive structure. North of Northam, the ferrogabbro unit, together with the magnetitite sheets cuts northwards through all the other rock units right down to the base of the Complex on Moddergat 389 KQ and Oskuil 390 KQ. South of Northam, on Haakdoornfontein 12 JQ, the sequence is normal again. Another similar "break" occurs from Middelkuil 8 JQ in a northwesterly direction to Elandsfontein 402 KQ, Vogelstruiskraal 400 KQ, and Rhenosterkraal 132 JP. In both these "breaks" the strike and dip of the igneous layering change completely in the ferrogabbro unit so that the dip is towards the axis of the "break", indicating a trough-like transgressive structure (Plate IV), which truncates all the other units, including the chromitite seams and the platiniferous Merensky Reef, over distances of 16 and 11 kilometres respectively (Plate I and Coertze, 1958 p. 390 and Plate LXVI).

A succession of bands of the porphyritic pyroxenite unit and chromitite occurs in a layer of the anorthosite unit on top of the norite unit immediately below the Merensky Reef north of the Pilanesberg. South of the Pilanesberg, and towards Rustenburg and Brits, a similar succession is found lower down, more or less half way up in the norite, with the sequence below the Merensky Reef not present. This phenomenon represents a large-scale transgression of the norite unit by these bands of the porphyritic pyroxenite unit, probably guided by the band of the anorthosite unit at a lower horizon in the norite unit south of the Pilanesberg.

Although the actual transgression is obscured by the Pilanesberg as well as by the displacement along the Rustenburg fault, such a transgression cannot, according to the sequence, be denied (Plate I).

West of the Pilanesberg, as well as in the far western extension of the Complex (not on Plate I), a continuous zone of the pyroxenite unit is found. Immediately south of the Pilanesberg the pyroxenite unit is cut off by a fault. To the south east, it is interrupted by the norite unit and is seen between the basal norite unit

and the norite unit as large "lenses" up to 16 kilometres and more in length. (Plate I).

From this regional distribution of the pyroxenite unit it is clear that at least part of the norite unit invaded the pyroxenite unit, cutting it off at a number of places. On the other hand, a large body of the porphyritic pyroxenite unit is intrusive into the basal norite unit southeast of Rustenburg on Kroondal 304 JQ, Rhenosterfontein 336 JQ, Zuurplaat 337 JQ, and Rietfontein 338 JQ. Apart from transecting this unit, it contains numerous inclusions of the basal norite unit, a feature which is treated under the next heading.

(b) *Small-scale Intrusive Relations and Contact Features.*

Small-scale relations between the various units are mostly represented by inclusions of one unit in another and tongues of one cutting the other. Most of these features could not be shown on the map and are, therefore, described by referring to the units in chronological order.

(i) *The Basal Norite Unit.* — Usually rocks of this unit, up to 550 metres thick, occur at the base of the sequence of basic rocks but outcrops are very poor. These rocks are not intrusive into any of the other units and rocks of the quartz norite sub-unit grade into the overlying marginal norite sub-unit by a decrease in the quartz content and an increase of the crystal sizes. Rocks of this unit are mostly confined to the area south of the Pilanesberg where they are floored by a thick succession of Magaliesberg quartzite. The quartz norite sub-unit especially seems to have incorporated some of the floor sediments, mainly quartzite, and cooling of this sub-unit took place comparatively fast. The pyroxenitic "lenses" or "bands" occurring in the marginal sub-unit on Hartebeestfontein 324 JR (Plate I) represent pyroxene rich layers in the basal norite unit and were apparently formed by normal crystallization differentiation.

(ii) *The Harzburgite Unit.* — In the far western extension of the Complex serpentinized and silicified layers of the harzburgite unit alternate with layers of the pyroxenite unit in a kidney-shaped basin, about 40 kilometres long and 16 to 20 kilometres wide. West of the Pilanesberg only numerous lenses and layers of the serpentinized and silicified rocks occur in rocks of the pyroxenite unit and

there are no wide transition zones.

Almost all contacts between the rocks of the harzburgite unit and the surrounding pyroxenite unit are covered by either rubble or soil. Schwellnus (1935, p. 12) states that in the old nickel mine on Vlakfontein 207 JP, the main rock types encountered, are bronzitite and harzburgite which grade into each other and the contact can be defined within a few centimetres. No signs of an intrusive relation are evident and the harzburgite is clearly a differentiate of the magma. However, in such a limited observation field as the old vertical shaft intrusive relations may probably not be exposed.

Kruparz and Van Rensburg (1965, p. 144) state that no conclusive evidence of intrusive relationships between the various rock types in the kidney-shaped basin, in the western extension of the Complex, near Nietverdiend was observed, but that the "main pyroxenite" transgresses the lower harzburgite and that this pyroxenite unit may be a separate intrusion.

In this far western extension of the Complex the relations between the alternating bands of harzburgite and pyroxenite are also obscured, but higher up, where the chromitite seams are found, some intrusive relations can be seen in the workings. Chromitite occurs on three horizons in the pyroxenite unit above the zone of alternating layers of harzburgite and pyroxenite. These chromitite "seams" should not be confused with the three groups of chromitite seams (the lower, middle, and upper groups) occurring in the pyroxenite unit and the anorthosite and norite units higher up in the sequence. The lower "seams" in the western extension of the Complex actually occur in serpentinite, i.e. in the harzburgite unit which in turn is included in and invaded by rocks of the pyroxenite unit so that the serpentinite band is cut and disrupted by pyroxenite.

Disseminated chromite also occurs in the serpentinite above the chromitite seams and many distorted inclusions (Plate V) of serpentinite occur in the chromitite bands. Tongues of chromitite also cut the serpentinite. The middle "seams" are actually represented by irregular stringers of chromitite, ranging from very thin up to 5 or 8 centimetres thick, in the pyroxenite unit. The upper "seam" or "seams" are represented by disseminated chromite crystals in serpentinite.

The chromitite associated with the harzburgite unit, is on the whole, fairly coarse grained and it seems as if it originally belonged to the harzburgite unit, which was then later invaded by the magma from which the pyroxenite unit crystallized and some of the chromitite was probably disintegrated and incorporated by the intruding magma from which the pyroxenite unit crystallized and the xenocrysts of chromite were concentrated in turn in pyroxenite. Chromitite "seams" may thus occur in the pyroxenite and even apparently invade the distorted serpentinite (harzburgite).

Kruparz and Van Rensburg (1965, p. 141–143) describe the chromitite seams. The lower seams have an average  $\text{Cr}_2\text{O}_3$  content of 43 to 46 per cent, the middle seams 44 to 48 per cent, and the upper seams about 43 per cent. These values compare favourably with an average of 44 per cent for the Complex.

One of the few chromitite bands associated with the harzburgite unit, farther to the east, is found on Palmietfontein 208 JP where a band, about 15 centimetres thick, occurs in a serpentinitized lens or band of the harzburgite unit (Plate I). Here the upper contact of the chromitite with the harzburgite unit is sharp and disseminated chromite crystals occur in the harzburgite below the band and create the impression of a transitional contact. On the adjoining farm, Vogelstruisnek 173 JP, a chromitite band, 43 centimetres thick, occurs in a serpentinitized harzburgite lens, invaded by the pyroxenite unit.

In a bore-hole, on Turffontein 262 JQ, between Rustenburg and the Pilanesberg, a thin band of chromitite was found in a band of the harzburgite unit occurring in the pyroxenite unit about 20 metres below the lower chromitite group.

(iii) *The Pyroxenite Unit.* — In most of the pyroxenite hills, such as those on Witkleifontein 136 JP and Ruighoek 169 JP, igneous layering can be recognized from a distance (Plate VI A) owing to the differential weathering of the pyroxenite unit.

Up to about 8 chromitite seams, the so-called lower or main group, occur in the upper part of the pyroxenite unit. In each of the occurrences of this unit the chromitite seams seem to be fairly persistent over considerable distances. In places near the upper contact of the pyroxenite unit with the anorthosite or norite units,

some chromitite seams, members of the middle group, occur.

Near the top of the lower group of chromitite seams, "inclusions" of chromitite are found in the pyroxenite unit. The length of these inclusions ranges from a fraction of a centimetre up to 5 or 8 centimetres and they are lens-shaped. They are well exposed in this unit on Swartkop 369 KQ and are also frequently found west of the Pilanesberg. On Witkleifontein 136 JP, stringers, of chromitite up to 22 centimetres long, occur in the pyroxenite unit and on Groenfontein 138 JP chromitite nodules are common in the pyroxenite unit below the upper seam.

In a prospecting pit of Haakdoorn drift 374 KQ, pyroxenite cuts the chromitite in irregular fashion and on Nooitgedacht 406 KQ, in an old shaft, on the third chromitite seam of the lower group, there is a tongue-like offshoot of chromitite upwards into the pyroxenite for about one metre (Coertze and Schumann, 1962, Plate I). This seems to be chromitite intrusive into the pyroxenite but may also be due to the intrusive pyroxenite having wedged part of the chromitite seam upwards.

The contact between the chromitite and the pyroxenite in the pyroxenite unit may be sharp or transitional. Usually the base of the chromitite bands is sharp and the rock on top of a chromitite seam contains disseminated chromite but in other places both the base and the top may be either sharp, or transitional. The upper part of the pyroxenite unit may contain up to 10 per cent or more of plagioclase (Plate VII) which may be an indication of differentiation in place. Within the pyroxenite unit there are also zones containing more plagioclase, for instance west of the Pilanesberg.

In the far western extension of the Complex, as has already been pointed out, the pyroxenite unit invaded the harzburgite unit and can therefore probably be considered to be a younger intrusion.

In the light of all the other available field evidence, such as regularity of chromitite seams and disseminated chromite crystals above the bands, it seems probable that the chromitite bands formed in place by crystallization differentiation. Settling of pyroxene crystals or rather rising of the liquid from which the plagioclase crystallized might have caused the more feldspathic layers now containing up to 10 per cent of plagioclase. A succeeding heave of magma, or just a continuation of magma inflow of similar composition, however, might have caused

the pyroxenite to show intrusive relations to the chromitite seams already formed. On the other hand, contemporaneous movement or slumping of the crystal accumulates (Wager and Brown, 1968, p. 365) might have caused cross-cutting of chromitite seams and chromitite inclusions although it is difficult to explain why slumping should have affected only certain chromitite seams over such vast areas. Thus, although the relations between the pyroxenite and the chromitite in the area investigated can be explained in various ways, relations between the pyroxenite unit and the harzburgite unit at the few outcrops in the area mapped and outside this area in the far western extension of the Complex suggest that the pyroxenite unit is intrusive into the harzburgite unit.

(iv) *The Anorthosite Unit.* — The anorthosite unit occurs as bands on four or more horizons, mainly in the norite unit (Plates I and III). Intrusive relations between the anorthosite unit and the pyroxenite unit and between the anorthosite unit and the pyroxenite and chromitite are clearly exposed at a number of places. West of the Pilanesberg on Ruighoek 169 JP, a band of the anorthosite unit occurs fairly low down in the sequence below a chromitite band in the pyroxenite unit. Near the top of the pyroxenite unit, a band of the anorthosite unit wedges off chromitite bands from the pyroxenite unit, cuts irregularly through them and encloses numerous large and small blocks of chromitite and pyroxenite. Such a wedge-like intrusion of the anorthosite unit into chromitite on top of the pyroxenite unit is seen on Schilpadnest 385 KQ (Plate VIB). Inclusions of the pyroxenite unit and chromitite in the anorthosite unit are also found on Schilpadnest 385 KQ (Coertze and Schumann, 1962, Plate III), on Turfbult 262 JQ (Fourie, 1959, p. 45, photo), and on Boschkoppie 104 JQ in a stream bed. Another place where chromitite has been brecciated by invading anorthosite is near the boundary between Uitvalgrond 416 JQ and Bokfontein 448 JQ. These phenomena, especially the chromitite inclusions, are found in all the bands of the anorthosite unit, but are less distinct in the upper ones. Inclusions of the pyroxenite unit and chromitite thus occur in the anorthosite unit but never inclusions of the anorthosite unit in the pyroxenite unit.

At places rhythmic layering similar to inch-scale layering (Hess, 1960, p. 51) occurs in the pyroxenite unit just below its contact with a band of the overlying anorthosite unit as for example on Ruighoek 169 JP (Plate VIIIA). According to Truter (1955, p. 86) this type of layering may be due to the combined effect of

"chilling" concordant with the floor (pyroxenite) and the roof, laminar flow in the magma of the incoming (anorthosite) surge under more or less constant conditions of confinement, and slight intergranular movement caused in the pyroxenite unit at and near its top by the incoming of the succeeding surge. Such an explanation seems a bit complicated, especially the effect of "chilling".

Hess (1960, p. 57) states that in the Stillwater Complex in the "Lower Gabbro Zone" this type of layering, which has not been described in the Skaergaard intrusion, consists of layers slightly less than twenty-five millimetres thick and comprised of alternations of pyroxene and plagioclase. He calls it inch-scale layering and states that its origin is uncertain. As the zone of layering actually forms the top of the pyroxenite unit it represents the last phase of crystallization of the pyroxenite unit when plagioclase also crystallized as a cumulus mineral and settled from time to time. Thus this type of rhythmic layering in the Bushveld Igneous Complex may be a phenomenon occurring near the top of rock units and not very wide.

The relation between the anorthosite unit and the chromitite bands in the platinum mine on Zwartklip 405 KQ is illustrated by Van Zyl (1960, Plate VIII). This is the only place where a structure of this kind is exposed completely. Some of the relations between the chromitite bands and the anorthosite unit already mentioned may represent parts of similar structures. Even the well-known Dwars River outcrop (Plate VIIIB) in the Eastern Transvaal may be part of a similar structure. In places rocks of the anorthosite unit are apparently intrusive into the chromitite whereas in other places it seems to be the other way around. A similar structure, but on a very small scale occurs in a sample from near Brits (Plate IXA). Van Zyl's explanation (1960, p. 104–105) is that the structure in the platinum mine may perhaps be due to interrupted unmixing of chromiferous liquid from the magma and settling of this liquid. Wager and Brown (1968, p. 365) think that the layering at Dwars River is due to alternating layers of chromite cumulates and plagioclase cumulates. These structures create the impression that movement took place while neither the chromitite nor the anorthosite were yet completely solidified. Disintegration of chromitite seams in an invading magma, from which the anorthosite unit crystallized, could also have taken place and led to the settling of xenocrysts of chromite.

North of the Pilanesberg, on Elandsfontein 386 KQ and Moddergat 389 KQ, two closely spaced thin anorthositic bands occur in the gabbro unit on a persistent horizon about 1580 metres above the Merensky Reef. These bands are considered to be the result of crystallization differentiation because the composition of the plagioclase ( $An \pm 55$ ) corresponds to that of the gabbro. South of the Pilanesberg, on Styldrift 90 JQ and Doornspruit 106 JQ magnetite-bearing mottled anorthosite with a mineral composition similar to that of the anorthosite unit, is intrusive into the gabbro unit along a shear zone. It is considered to be a partially refused fraction of the lower anorthosite unit which under conditions of high temperature and in the presence of water was mobilized and re-injected as a crystal mush into the overlying gabbro unit (Coertze, 1960a, p. 80).

(v) *The Norite Unit.* — The gradation of anorthosite into norite, accompanied by an increase in pyroxene, as seen in places like the canal cuttings on Uitvalgrond 416 JQ and above the Merensky Reef in the Rustenburg-Kroondal area, previously led to the conclusion that all the anorthositic and noritic rocks are equivalent in age. Such anorthositic phases, which are probably due to crystallization differentiation in the norite and gabbro units, are illustrated in Plate VII'. On the contrary, indications of an intrusive relationship between the norite unit and the anorthosite unit were found during this investigation. North of the Pilanesberg numerous inclusions of the anorthosite unit occur throughout the norite unit but are especially common near the lower and upper contacts. Some of the inclusions are flat, tapering bodies concordant with the igneous layering and their contacts with the norite unit are sharp. This relationship is illustrated in Plate IXB. Other inclusions are quite irregular and do not conform to the igneous layering at all (Plate XA). Some of these inclusions are displayed in a most spectacular way on Schilpadnest 385 KQ (near the lower and upper contacts of the norite unit), in the platinum mine on Zwartklip 406 KQ, on Kroondal 304 JQ, just east of the tar road to the Rustenburg Platinum Mine, where there are so many anorthosite inclusions that as a whole the norite almost resembles a breccia, and also in the Rustenburg Platinum Mine. On the other hand there is not a single inclusion of the norite unit in the anorthosite unit and the norite unit is thus clearly a younger intrusion which invades the anorthosite unit.

In the Rustenburg Platinum Mine the contact between the noritic phase (lower

part) of the gabbro unit and the band of the anorthosite unit above the Merensky Reef resembles inch-scale rhythmic layering. However, according to the irregular shapes of the anorthosite layers or lenses, this phenomenon does not represent a normal transition from the anorthosite to the gabbro unit but it seems as if the anorthosite was disrupted by the gabbro unit (Coertze, 1963a, Plate III).

Large and small lenses of the pyroxenite unit, some containing chromitite, are found in the norite near its base on Schilpadnest 385 KQ. There are even inclusions in the norite unit of anorthosite intrusive into chromitite (Coertze and Schumann, 1962, Plate V). One pyroxenite inclusion, a few metres in diameter, occurs in the norite near its upper contact on the same farm. On Kroondal 304 JQ the pyroxenite unit is invaded by the norite unit in such a way that patches of the darker pyroxenite are surrounded by the light-coloured norite. These phenomena together with the large-scale relations, show that the norite is intrusive into the pyroxenite unit, the chromitite bands, and the anorthosite unit.

(vi) *The Porphyritic Pyroxenite Unit.* — Except for the large bodies south-east of Rustenburg, this unit consists of a number of relatively thin sheets of the porphyritic and pegmatitic subunits occurring mainly in the norite and anorthosite units (Plate III). Bands of the pegmatitic sub-unit usually occurs below bands of the porphyritic sub-unit. Although all the bands, such as the highest one (the Bastard Reef) could not be shown on the map (Plate I) they are, however, all shown, together with their thicknesses, on Plate III.

A tongue of the sheet of the porphyritic sub-unit occurring in a band of the anorthosite unit below the Merensky Reef cuts irregularly into the hanging wall anorthosite on the border between Zwartkop 369 KQ and Schilpadnest 385 KQ (Plate I). Numerous inclusions of chromitite and also some of the pyroxenite unit occur in the sheets of the porphyritic pyroxenite unit in the platinum mine on Zwartklip 405 KQ. On Kroondal 304 JQ, just west of the chrome mine, the porphyritic sub-unit is intrusive into the pyroxenite unit where it includes blocks of pyroxenite as well as chromitite layers and "stringers". On Boschkoppie 104 JQ, in an old inclined shaft, an inclusion of pyroxenite, about one metre in diameter, occurs in the band of the porphyritic sub-unit on top of the Merensky Reef. In other places, like on Zuurplaat 337 JQ, in the stream bed, the porphyritic sub-unit

surrounds blocks of the basal norite unit.

Bands of the porphyritic sub-unit usually have sharp lower and upper contacts with the anorthosite. Owing to the fact that the feldspar content increases higher up in the sheets, it was previously thought that the upper contacts are transitional into norite. The bands of the porphyritic sub-unit overlying the Merensky Reef and the "Bastard Reef" were often described as grading into norite (Cousins, 1970, p.21). Investigations in the Rustenburg Platinum Mine and of bore-hole core prove that the lower parts of the bands of the porphyritic pyroxenite unit are pyroxenitic but higher up they become noritic and the contacts with the overlying bands of the anorthosite unit is sharp (Plate XB and Coertze, 1963a, Plate II). Thus the bands of the porphyritic pyroxenite unit are differentiated sheets (Coertze, 1970, p.21). This is in accordance with Cousins' statement that what he considers to be the Bastard Reef is the result of differentiation *in situ* of a magma heave.

In the platinum mines some thin but coarse-grained pegmatitic veins, consisting mainly of biotite and calcite, are encountered above the Merensky Reef and in the "Bastard Reef". These veins terminate against the contacts or thin out to such an extent that they can hardly be traced in the adjacent rocks (Coertze, 1963a, Plate II). This suggests the formation of the veins in the porphyritic sub-unit after its emplacement into the anorthosite unit.

About three sheets of the pegmatitic sub-unit occur between sheets of the porphyritic sub-unit and between the porphyritic sub-unit and the anorthosite unit (Plate III). As they are relatively thin, they are not shown on the map (Plate I) except for the upper one, the Merensky Reef, which is indicated by a symbol.

In places, such as the platinum mines, bands of the pegmatitic sub-unit (Merensky Reef) pinch out completely. It was also found by geologists of the Falconbridge South African Exploration Company (personal communication) that 19 kilometres southwest of Brits the Merensky Suite is either absent or has coalesced with the Bastard Reef. Inclusions of anorthosite, some more than 30 centimetres in diameter, and of chromitite occur in the Merensky Reef in the Rustenburg Platinum Mine and in the old inclined shaft on Boschkoppie 104 JQ. In addition inclusions of the porphyritic sub-unit are also present.

North of the Pilanesberg, the thickness of the Merensky Reef ranges between 120 and 210 centimetres with chromitite bands at the base and at the top, whereas in the south, the average thickness is about 15 to 30 centimetres with a narrow chromitite band only at the base. The Merensky Reef is disposed in gentle undulations (Coertze, 1963a, Plate I) which is a characteristic of the reef in most places. Although it occurs as a regular layer, there are also some exceptions like the small irregular apophyses into the band of the porphyritic sub-unit. In the Rustenburg Platinum Mine there is a small dome of the anorthosite below the reef (Coertze, 1963a, Plate VI). The contact between the Merensky Reef and the overlying band of the porphyritic sub-unit is more or less straight, but a tongue of the Merensky Reef protrudes into the anorthosite floor.

All these relations lead to the conclusion that the porphyritic pyroxenite unit could have been emplaced at least after the basal norite, pyroxenite, and anorthosite units, with the pegmatitic sub-unit forming the last phase.

(vii) *The Gabbro Unit.* — The lower part of the thick succession (2500 metres) of the gabbro unit consists of a noritic phase (Plate VII). In the Rustenburg Platinum Mine the transition between the noritic phase ( $\pm$  300 metres thick) of the gabbro unit and the band of the anorthosite unit above the Merensky Reef resembles an irregular inch-scale rhythmic layering described under norite. According to the irregular shapes (Coertze, 1963a, Plate III) of the anorthosite, this phenomenon does not represent a normal transition from the anorthosite unit to the gabbro unit but apparently the anorthosite was disrupted by the gabbro unit.

Some pyroxenite inclusions in the gabbro unit which range from a few centimetres up to a few metres in diameter, occur on Boschkoppe 104 JQ, just north of the railway line. The gabbro unit is thus at least younger than the pyroxenite unit. On Schietfontein 437 JQ the coarse-grained gabbro is intrusive into the finer-grained basal norite unit and contains xenolithic blocks of the basal norite unit.

According to Schwellnus and others (1962, p. 41), the gabbro in the eastern part of the Complex cuts downwards through the pyroxenite, norite, and anorthosite units and even transgresses the Magaliesberg quartzite.

(viii) *The Ferrogabbro Unit.* — The ferrogabbro unit which is up to 1800

metres thick, occurs on the top of the gabbro unit. Outcrops are very poor. Slight banding (rhythmic layering) is present on Uitvalgrond 431 JQ, Hartebeestpoort 419 JQ, and Sjambok Zyn Oude Kraal 258 JR. A few quarries for ornamental gabbro are situated more or less along this contact zone. The reason for this is that the igneous layering provides "bedding" planes along which the rock can easily be wedged.

North of the Pilanesberg, in the Bierspruit on Moddergat 389 KQ, Oskuil 390 KQ, Vlakpoort 388 KQ, and in the core of a bore-hole on Zwartklip 405 KQ, the ferrogabbro unit includes numerous fragments of older basic rocks such as those of the norite and anorthosite units. Inclusions of the gabbro unit, if present, could not be recognized.

Although it could not be established in the area, there may also be more than one intrusion forming the ferrogabbro unit, as was found in the Eastern Transvaal (Coertze, 1964, p. 17–20 and 53). There are, for instance, sheets of magnetite anorthosite, which are actually part of the ferrogabbro unit, in the vicinity of the lower magnetite bands north of the Pilanesberg and on Berseba 397 JQ below the lower bands. This magnetite anorthosite is similar to that in the Eastern Bushveld, which is considered a separate intrusion (Coertze, 1964, p. 53), but it could not be mapped separately as was done there.

The magnetite bands or sheets in the ferrogabbro unit, which are part of the layered sequence, contain gabbroic "inclusions" in many places. In the field, the lower contact of the magnetite bands with ferrogabbro or anorthositic bands (still part of the ferrogabbro unit) are always sharp, but in many places the upper contacts are gradational into ferrogabbro or anorthositic ferrogabbro. In bore-hole core from De Onderste Poort 300 JR there are sharp lower contacts with the anorthositic rock but the plagioclase content in the magnetite band increases upwards till the plagioclase is in excess of the magnetite and the rock is again anorthositic. There is in turn a sharp upper contact with the succeeding magnetite band which, in any case, is also the sharp lower contact of the succeeding magnetite band or member. Thus some of the magnetite bands which are part of the layered sequence seem to have formed by differentiation in place and they are also part of the ferrogabbro unit although there could have been more than one influx of magma from which this unit

formed (Coertze, 1966, p. 40).

(ix) *Rock Types not Part of the Layered Sequence.* — As magnetitite occurs in many places together with hortonolite dunite and diallagite pegmatite as composite pipe-like bodies, their inter-relationships are treated together. This magnetitite is not part of those bands which normally form part of the layered sequence. It was established in the eastern part of the Complex that there are magnetitite bands which are connected with the pipes and that they are contemporaneous (Coertze, 1966, p. 44). They have sharp lower and upper contacts.

North of the Pilanesberg numerous magnetitite and magnetite-dunite pipes occur on Oskuil 390 KQ, Leeuwkopje 415 KQ, Rhenosterkraal 132 JP, Vogelstruiskraal 400 KQ, Kruidfontein 40 JQ, and Middelkuil 8 JQ. In places, as on Rhenosterkraal 132 JP and Leeuwkopje 415 KQ, some of the pipe-like bodies appear to be linked with some of the magnetitite bands in the ferrogabbro unit and these bands may be intrusive into the ferrogabbro unit. All the pipes which are situated in the ferrogabbro unit are, in fact, intrusive therein.

There are also pipes, although not so numerous, in the other rock units north of the Pilanesberg. The magnetite-dunite pipe in the pyroxenite unit on Zwartkop 369 KQ might have been the feeder of a magnetitite sheet just below the Merensky Reef. On the border between Haakdoorn drift 374 KQ and Elandskuil 378 KQ a hortonolite dunite pipe with a magnetitite core occurs in the middle group of chromitite seams in the pyroxenite unit. The magnetitite follows some chromitite seams from the pipe-like body in sheet-like fashion, transgressing them in places and enclosing chromitite fragments. There are similar phenomena west of the Pilanesberg on Groenfontein 138 JP, Zandspruit 168 JP, and Ruighoek 169 JP.

South of the Pilanesberg, magnetitite, dunite, and diallagite-pegmatite occur as pipes, dyke-like bodies, and veins all along a wide fault zone trending in a north-westerly direction in the gabbro unit (Plate I). Large hortonolite dunite pipes occur on Boschkopje 104 JQ (Plate XIIA), Elandsfontein 102 JQ, Onderstepoort 98 JQ, and Koedoesfontein 94 JQ. In the northwestern corner of Boschkopje 104 JQ diallagite-pegmatite forms the southern part of a pipe consisting mainly of hortonolite dunite. In places the diallagite-pegmatite cuts the dunite and includes blocks of

it. Dyke-like bodies of diallagite-pegmatite occur in the gabbro unit near the Elands River on Frischgewaagd 96 JQ and adjoining farms. Pipes and dyke-like and sheet-like bodies of magnetitite occur in the gabbro unit on Dorskry 95 JQ and Koedoesfontein 94 JQ along the fault zone and form a strong contrast to the usual occurrence of magnetitite bands in the ferrogabbro unit.

To the east magnetite dunite pipes occur on Klein Doornspruit 108 JQ and Goedgedacht 114 JQ and here too diallagite-pegmatite dykes are present.

To the south, in the Rustenburg area, numerous dunite pipes occur on Uitvalgrond 105 JQ, Vaalkop 275 JQ, and Kookfontein 265 JQ, all of them situated immediately above the Merensky Reef which is transected by them in many places.

In the east, from Rustenburg towards Pretoria, there are also "swarms" of dunite pipes as on Rooikoppies 297 JQ and Middelkraal 466 JQ below and above the Merensky Reef and on Klipfontein 268 JK in the gabbro unit.

On De Kroon 444 JQ, south-east of Brits, a pipe-like body occurs in the norite unit immediately above the pyroxenite unit containing the lower chromitite bands. This is a very interesting occurrence as far as relationships between various rock types are concerned and a section through the chromitite seams and the pipe is shown in Plate XI. It is not a typical hortonolite dunite pipe, but the rock is more magnesium-rich and is completely serpentinized and surrounded in the south by diallagite pegmatite. The dunite and harzburgite core includes numerous large and small blocks of chromitite (Plate XIIB) as well as anorthosite and norite. Diallagite-pegmatite, in turn, cuts the dunite and many veins and tongues of it occur in an excavation immediately next to the main road to Brits. At a lower level, diallagite-pegmatite occurs in sheet-like fashion along the chromitite seams, but in places transgresses them.

In the pipes where dunite and magnetitite are associated, the magnetite crystallized after the dunite and veins of magnetitite frequently cut the dunite.

The well-known nickel-copper "pipes" (Schwellnus, 1935) in the pyroxenite unit west of the Pilanesberg, occur on or near the Rustenburg fault zone. They are present from Vlakfontein 207 JP in the south to Vlakfontein 114 JP in the north, and, according to Schwellnus (1935, p. 30), they are associated with bronzitite

pegmatite which may have irregular forms and may, for instance, follow contacts between harzburgite and pyroxenite in sheet-like fashion.

### III. STRUCTURE

#### A. Structure of Intrusions

There are a number of hypotheses in connection with the structure or form of the basic rocks as a whole. These will be briefly mentioned here and a new idea will be added which will be treated in more detail.

##### 1. *Lopolith*

Previously it was believed that the basic portion of the Bushveld Igneous Complex has the form of a lopolith (Hall, 1932, pp. 459–463). The depressed foundation and its general sheet-like form justified this description. It was assumed that some major feeders lie deeply buried somewhere within the central part of the Complex. The Transvaal System was gradually bent down by the magma load combined with lack of adequate support through the withdrawal of originally underlying magma. However, interpretation of a gravimetric survey (Cousins, 1959a, pp.178–189), indicates that the basic portions of the Complex as a whole are not structurally part of a lopolith. Willemse (1964, p. 112) also expresses doubt about the existence of a lopolith and his Plate I infers that the basic portions of the Complex in the west and in the east are not connected. However, on the basis of a more recent detailed gravimetric survey, Biesheuvel (1970, p.281) interprets the local structure of the basic rocks in the far western extension of the Complex, in the Marico area, as a lopolith.

##### 2. *Series of Intrusion Centres and Separate Intrusive Bodies*

Doubt in connection with the lopolithic form was expressed by Truter (1955, pp. 81–82). He suggests that there were four intrusion centres for the basic rocks and states that the emplacement took place in a number of separate bodies connected in series. The intrusion centres along the major east-west axis of the Complex are: a westerly one in the vicinity of Nietverdiend, an easterly one east of Burgersfort and two others, respectively, below the Marble Hall and Crocodile River fragments which were floated up initially by ultramafic magma. Verwoerd (1963, p. 65, Fig. 7) is also in favour of a feeder below the Crocodile River fragment. He discusses four hypotheses on the relationship between this fragment and the Bushveld Complex. Preference is given to cone-fracturing whereby the Crocodile River fragment is supposed to form the core of a great feeding channel. Biesheuvel

(1970, p. 281) states that in the far western extension of the Complex the basic rocks are the thickest adjacent to the Goudini volcano near Nietverdiend where a thickness of 2160 metres is estimated. He suggests the most likely locality for the feeder there is the Goudini volcano.

According to Truter (1955, p. 86) some time after the Critical Zone came into existence, north-south tensional stresses were superceded by compression from the north which resulted in reverse faulting. The hydrostatic pressure of the magma increased and the gabbro intruded at lower levels, disrupting already consolidated basic rocks. Although the idea of more than one feeder postulated by Truter was strongly supported by subsequent workers, he did not give a clear indication of the structure of the separate bodies of basic rocks.

### 3. *Deep Curved Trough Fillings*

On the basis of his interpretation of gravity anomalies published by the Geological Survey, Cousins (1959a, pp. 182–184) postulates two deep-seated curved troughs of basic rocks, occurring respectively beneath the eastern and western portions of the Complex. These structures were fed, according to him, by dyke-like fissures. The exposures, such as the Crocodile River fragment in the Central Transvaal, is postulated to form part of the updomed central portion of the Transvaal basin. Updoming predated emplacement of the basic rocks and the two troughs, one on the east and one on the west, have curved axes and partly surround the updomed core over much, or all, of which the basic portion was never emplaced. The observed anomalies on the gravity map show a considerable degree of symmetry on the basic rocks, the values falling as rapidly as they rise. At the centre of the Bushveld, the gravity values are similar to those found on some Archaeangranite outside the Complex. According to him these anomalies can only be interpreted as being due to a light central area, partly surrounded by the troughs of high density rocks. The calculated anomalies are those due to dyke-like bodies. He stresses, however, (p. 184) that there is no geological evidence of the presence of dyke-like fissures.

Verwoerd (1963, p. 57) who studied the structure of the Crocodile River fragment, states that the updoming along the edges of this fragment contradicts the possibility of any connection with the floor of the Complex.

However, Cousins' hypothesis is of importance because it is the first to take geophysical data into consideration. It brought to attention that the Complex is not a lopolith and that it consists of two separate basic bodies, whatever the form of the feeders.

#### 4. *Cone Sheets forming Funnel Intrusions*

Wilson (1956, pp. 290–292) interprets lopoliths as funnel-shaped in cross section and states that the Bushveld intrusion is not sill-like, but that the bottom dips more steeply than the layering. Willemse (1964, p. 113) emphasizes the transgressive relationship of the Complex to the encircling sediments. He discusses the distribution of the Magaliesberg quartzite relative to the outer contact of the igneous body and also the most pronounced transgression which took place north of Potgietersrus where the entire Transvaal System is transgressed and the Bushveld Complex is ultimately in contact with the Archaean granite of the Basement. He draws attention to the Magaliesberg quartzite which is disrupted north-west of Rustenburg and even transgressed south-west of Pilanesberg. To explain these transgressive features, the emplacement of the basic rocks is compared with that of cone-sheets corresponding to funnel intrusions and more than one feeder is postulated. He takes, for instance, the Crocodile River fragment to represent the uplifted core of a cone sheet structure. According to him (pp. 113–114), it is also noteworthy that igneous horizons terminate against sedimentary rocks, like the chromitite and Merensky Reef in the Eastern Bushveld which fade out against sedimentary rocks north of Dullstroom.

The results of the present investigation is very much in accordance with the points mentioned in this hypothesis and are discussed in detail under the following heading.

#### 5. *Proposed Structure*

The following facts in connection with the *present investigation* must be noted: North of the Pilanesberg the general dip of the igneous layering is about  $25^{\circ}$  to the south-east. South of the Pilanesberg towards Rustenburg, it flattens to about  $10^{\circ}$  to the north-east and towards Pretoria it steepens to about  $45^{\circ}$  to the north. It is clear from the dips shown on the map that the dip of the igneous layering of the lower

units does not always correspond to that of the units higher up. Therefore, an isopach map showing the Merensky Reef and the main lower magnetitite band was drawn (Plate XIII). It is assumed that the dips remain constant in depth and isobaths at 3000-metre vertical intervals are shown. It is flat country and the Merensky Reef and the magnetitite crop out practically at the same height all around. The Merensky Reef outcrop was used as datum. According to this map, the Merensky Reef, on the whole, gradually dips in a north-easterly direction in the southern area. The magnetitite, on the other hand, shows a deep trough between the Crocodile River fragment and the Pilanesberg with another trough east of the fragment. Thus, if the dips remain constant, the rocks higher up in the succession, i.e. the magnetitite and the ferrogabbro unit, must transgress the lower rocks, i.e. the Merensky Reef in depth. At the surface such a transgression did indeed take place northeast of the Pilanesberg (Plates I and IV) where the ferrogabbro unit with the magnetitite bands transgress from the top of the basic units to their base in two places. In these transgressions or "breaks" the strike and dip of the igneous layering change completely in the ferrogabbro unit so that the dip is towards the axes of these "breaks", causing trough-like transgressive structures (Coertze, 1958, p. 390).

Apart from these transgressions, each succeeding unit occurs farther north and east along the northern and southern sectors of the western part of the Complex respectively. For instance, the harzburgite unit can be traced from the Pilanesberg to Nooitgedacht 406 KQ in the northern sector and as far as Turffontein 262 JQ in the southern sector. The northern sector is cut off by a fault trending more or less along the Crocodile River, but in the southern sector all the other rock units can be followed to where they thin and disappear. The pyroxenite unit can be traced as far as Zilkaatsnek 439 JQ, the Merensky Reef and associated rocks as far as Schietfontein 437 JQ, the gabbro unit to Kameeldrift 298 JR, and, lastly, the ferrogabbro unit to Kameelfontein 297 JR and Leeuwfontein 299 JR where it fingers out in the sediments. The ferrogabbro unit actually transgresses the sediments north-east of Pretoria (Plate I and Coertze, 1962b, pp. 67–70). Thus the strike and the dip of the igneous layering do not correspond to the strike and dip of the sediments north-east of Pretoria.

The Pilanesberg is situated in a central position as far as the basic rocks are concerned. On the whole, it seems as if the surges of magma spread out from feeding channels, one of which could have been where the Pilanesberg is situated today. The fact that this is also the place where the basic rocks cut down through the Magaliesberg quartzite to a lower horizon, supports the idea of a feeder in this position. Another could have been below the Crocodile River fragment. The main point, however, as far as the main structure of the intrusions is concerned, is that at the surface, disregarding the basal norite unit, each succeeding unit occurs farther east along the relatively uninterrupted southern sector.

In Plate XIV a simplified schematic illustration is used to show the development of the main structure and only three layers are used. After emplacement of all the layers in a funnel-shaped intrusion, sagging of the floor and tilting towards the centre of the Complex resulted in a *tilted funnel-shaped structure* built of units fitting like saucers on one another with each successive saucer overlapping the previous one. Movement along the big Rustenburg fault is also illustrated. The eastern part is faulted downwards so that after denudation only the lower rock units in the far western extension, west of the fault still exists whereas the whole succession is still found in the main eastern compartment. Another feeder could have existed in the far western extension of the Complex where there is a fairly thick development of the lower rock units as suggested by Biesheuvel (1970, p. 281). Because the transgressions of ferrogabbro mentioned form smaller trough-like structures within the main structure (Plate XIII), they are not shown on Plate XIV, but are illustrated in Plate IV.

## B. Faults

On Plate XV the major faults affecting the western basic portion of the Complex are shown but not the smaller faults shown on Plate I and those indicated by Vermaak (1970, Folder). Hall (1932, p. 204, Fig. 14) shows most of the faults affecting the Complex as a whole.

### 1. Major Faults

The basic rocks in the western part of the Complex are cut by a few very prominent faults, all of which trend in a north-westerly direction and are most

probably of the same age and younger than the ferrogabbro.

The Rustenburg fault is the most spectacular one and dominates the structure in the western part of the area (Plates I and XIV). It is probably the extension of the Bank fault and enters the area mapped south of Rustenburg from where it has been followed north-westwards past the Pilanesberg to Vlakfontein 164 JP (Plate I). It is a normal fault and in the Rustenburg area it displaces the Magaliesberg quartzite; the downthrow is to the east and the vertical displacement there is approximately 900 metres. Because it cuts the Magaliesberg quartzite where the strike changes to north-west, it continues all along the eastern foot of the Magaliesberg to the Pilanesberg.

South of the Pilanesberg, on Onderstepoort 98 JQ and Koedoesfontein 94 JQ, the fault branches. The north-eastern branch, trending mostly through the gabbro unit, also cuts off the pyroxenite unit, norite unit, anorthosite unit, and the Merensky Reef on Elandsfontein 102 JQ and Boschkopie 104 JQ and the gabbro unit is thrown down against the basal norite unit. This branch coalesces with the main fault on the border between Zandriverspoort 210 JP and Mahobieskraal 211 JP. South of the Elands River on Onderstepoort 98 JQ the two are connected by a normal transverse fault. To the west another branch cuts southwards through the Magaliesberg quartzite from Onderstepoort 98 JQ to Elandsfontein 102 JQ. Northwards the fault swings westwards to skirt the Pilanesberg. Pipes of hortonolite dunite and magnetitite were apparently intruded along some of the branches. On Vlakfontein 207 JP a series of smaller branches and subsidiary faults, parallel to the main fault, were traced for short distances where they displace the noritic sheet low down in the pyroxenite unit. The main fault continues farther northwards and also displaces this noritic sheet on Vlakfontein 114 JP. Actually the displacement decreases deeper into the basin and the three dimensional picture (Plate XIV) of a fault cutting a basin should be kept in mind.

To the east of the Rustenburg fault, immediately northwest of the Pilanesberg, a wedge-like block of the norite unit is faulted down into the pyroxenite unit between two normal faults trending from Welgewaagd 133 JP to Ruighoek 169 JP and from Witkleifontein 136 JP to Rooderand 46 JQ respectively. Another normal fault with downthrow to the north branches from Zandspruit 168 JP to Bierkraal 134 JP.

The swarm of dykes trending parallel to the Rustenburg fault (Plate XV) must follow a zone of weakness and the gabbro is sheared in places (Coertze, 1960a, pp. 75–85). Apparently, the Rustenburg fault with its branches together with the zone along which the dykes were emplaced, form one big fault system representing a zone of weakness in the upper crust.

Whereas the structure is dominated by the Rustenburg fault system in the west, in the east a series of faults trending past Brits, is the most obvious structural feature (Plate XV). The two parallel normal faults at Brits which cut the Magaliesberg quartzite in the south, form a graben in which the granophyre north of Brits is preserved in the form of fairly conspicuous hills. Two big normal faults on either side of a horst transect the Crocodile River fragment. The eastern one also cuts the northern sector of the basic rocks and granite is thrown down against the basic rocks. The Western one is more or less in line with the Brits faults as well as two smaller normal faults to the north-west which also form a small graben. Apparently, this zone represents a weak zone in the crust along which movement took place in the past and the presence of the Crocodile River fragment on this zone is explained by cone-fracturing which developed when basic magma was emplaced along a great feeding channel (Verwoerd, 1963, p. 66).

On the whole it seems that the two major fault systems, namely the Rustenburg system and the Brits system must both be controlled by or connected with the pre-history of the Bushveld Complex, Pilanesberg, and the Crocodile River fragment. The significance of this will be discussed later.

## 2. *Minor Faults*

Some minor faults are also shown on Plate I but a few others, not possible to show on the maps, must also be mentioned because they may help to illuminate the understanding of the structural development of the Complex which will be discussed later.

On a more or less constant horizon in the anorthosite below the Merensky Reef in the Rustenburg Platinum Mine a gliding plane called the "mud seam" occurs, (Coertze, 1963a, pp. 69–77). This is a fault because dykes from above as well as from below terminate against it. The fault pattern is shown in a sketch (Coertze,

1963a, Fig. 1, p. 71). Schmidt (1952, pp. 238–240) describes some fascinating “dome-structures” and “circular depressions” in the mine, locally known as “hill-ocks” and “potholes”. He suggests that the “circular depressions” could have been formed by the swirling motion of currents in the magma chamber. During the present investigation, it was found that some of the structures regarded as “potholes” are caused by faulting (Coertze, 1963a, Plate V).

Vermaak (1970, pp. 256–258), apart from describing the Rustenburg fault, also draws attention to other fault directions such as his “Vlakfontein direction” west of the Pilanesberg, which, according to him, displaces the Rustenburg fault.

## IV. PETROGRAPHY OF THE BASIC ROCKS

### A. Rock Units and Rock Types

Published and newly determined compositions of the plagioclase and orthopyroxene of the different rock units are given in Appendix I and in Plate XVI they are shown graphically. The volumetric percentages of the constituent minerals are shown in Plate VII. All these diagrams actually show averages of numerous determinations by previous authors and the present author.

As there are some variations in the sequence from place to place (Plate I and Table 1), the units are shown chronologically in Plates VII and XVI. In these Plates the bands of various rock units, such as the anorthosite unit and those of the porphyritic pyroxenite unit, are thus grouped together.

The following are descriptions of the rock units mapped and must be read together with Plates VII and XVI because it will then be clear that within each one of these units there may be more than one rock type. Some rock types are described after the units.

#### 1. *The Basal Norite Unit*

(a) *Quartz Norite Sub-unit.* — The rocks of this sub-unit were previously called "diabase" and, on the whole, they are finer grained than the rocks higher up in the sequence and show a sub-ophitic texture because the plagioclase is partly included by the pyroxene or amphibole (Plate XVIIA). There are no sharp contacts between these rocks and the overlying rocks of the marginal norite sub-unit between Rustenburg and Pretoria. It thus seems that the thick Magaliesberg quartzite on which the basal norite unit rests, contributed to the formation of the quartz norite sub-unit.

The rocks of this sub-unit consist mainly of plagioclase, orthopyroxene, clinopyroxene, amphibole, biotite, quartz, magnetite, and in places olivine. Although the volumetric mineral composition may vary in the succession (Plate VII) and perhaps also laterally in places, these rocks are distinguished from all the other rocks by the amount of quartz (up to 20 per cent) and the amphibole (also up to 20 per cent) (Plate VII). Near quartzite inclusions

the percentage of quartz is higher than in areas devoid of quartzite. The colour of the rocks ranges from light to dark, depending on the amount of dark minerals present.

In many localities the pyroxenes in these rocks are partly altered to urallite. The clinopyroxene is subordinate and occurs as interstitial grains and exsolution lamellae in the orthopyroxene. The composition is about  $\text{Wo}_{38}\text{En}_{60}\text{Fs}_2$  and corresponds to endiopside. The orthopyroxene ranges in composition from bronzite (Of 14) to hypersthene (Of 42) (Plate XVI), and the biotite, up to 7 per cent in volume, is mostly associated with the orthopyroxene and may represent an alteration product of the amphibole. The plagioclase content ranges from 18 to more than 50 per cent (Plate VII) and the anorthite content also varies considerably from place to place, even from crystal to crystal, and variations of more than 8 per cent were measured for some twins. In most cases the plagioclase is zoned and the An contents of the cores are higher than those of the rims. On the whole, variations of 43 to 86 per cent, corresponding to andesine and bytownite, (Plate XVI) were measured for the plagioclase of these rocks. The plagioclase is usually saussuritized and kaolinized to a certain degree. Fourie (1945, p. 22) reports olivine crystals, not exceeding 2 per cent, north of Rustenburg (also shown on Plate VII), having the characteristic olivine cracks. It is chrysolite and the composition ranges from Fo 90 to Fo 87.

On studying Plate VII, it becomes clear that the rocks of this sub-unit may be named quartz norite although they may be pyroxene rich in places, and on Grootfontein 346 JQ and Kafferskraal 342 JQ, where they cut into the sedimentary floor, they may even be called quartz gabbro because clinopyroxene is in excess of orthopyroxene (not shown on Plate VII).

Vermaak (1970, pp. 250–253) describes "mafic sills" and "marginal norite" neither of which are shown as such on his map (Vermaak, Plate I). He also mentions "Maruleng norite" which is not indicated as such on his map. According to his description, the quartz norite sub-unit could correspond to either these "mafic sills" or the "Maruleng norite". He states that the "marginal norite" was originally noritic in composition. The numerous sedimentary in-

clusions did not alter its composition and he suggests that the "marginal norite" is a chilled phase of the Bushveld magma. Apparently, the quartz norite sub-unit corresponds to Willemse's (1969, p. 7) Maruleng norite in the Eastern Transvaal which, according to him, can hardly be considered to represent the undifferentiated magma of the Bushveld Complex because it is highly contaminated with sedimentary rocks, noticeably quartzite, and is commonly quartz-bearing.

(b) *Marginal Norite Sub-unit.* — The marginal norite sub-unit consists of light-coloured and medium-grained rocks. Plagioclase and pyroxene can be recognized megascopically. The orthopyroxene and plagioclase form subhedral to anhedral crystals with the clinopyroxene interstitial. In only a few places in the lower part, the rocks have a sub-ophitic texture. The rock resembles the quartz norite sub-unit lower down to a certain extent and no sharp contact could be found between the two, which indicates that the lower part of this unit (the quartz norite sub-unit) and the upper part (the marginal norite sub-unit) was probably formed from one magma. On the whole, the marginal norite sub-unit is more coarse-grained and it contains less quartz which decreases rapidly upwards. Hornblende occurs only in subordinate amounts as an alteration product of the pyroxene and this alteration decreases higher up, away from the sedimentary floor. Water from the sediments apparently contributed to the formation of hydroxyl-bearing minerals such as hornblende. The rocks consist of plagioclase, ortho- and clinopyroxene, biotite, magnetite, and quartz and the volumetric proportions of the constituent minerals are shown in Plate VII. It is clear that certain layers are more leucocratic whereas others are melanocratic and on Plate I pyroxenitic lenses or bands north of Pretoria, all part of this sub-unit, are indicated. Apatite is an accessory mineral.

The plagioclase is still characterized by some alteration like sericitisation and to a certain extent by zoning with the cores more calcic than the rims. The differences in composition in the same crystal and between different crystals on the same horizon are, however, not so pronounced as in those of the underlying quartz norite sub-unit, but a decrease in anorthite is obvious upwards in the sequence (Plate XVI), ranging from between An 68–81 near the base to An 62–79 at the top. This is an indication that cooling took

place more slowly than in the finer grained quartz norite sub-unit and that crystallization differentiation took place. The orthopyroxene is bronzite, ranging from Of 19–24 in the lower part of the marginal norite to Of 24–30 in the upper part (Plate XVI). The composition of the clinopyroxene is  $Wo_{34}En_{58}Fs_8$  and corresponds to diopside.

## 2. *The Harzburgite Unit*

At the surface only serpentized and silicified outcrops of this unit, which consists of harzburgite, occur. On Vlakfontein 207 JP the harzburgite is usually serpentized (Plate XVII B) and farther to the north, as on Groenfontein 138 JP, there is both serpentized and silicified harzburgite. North of the Pilanesberg only the silicified harzburgite is present, and in the vicinity of Niet-verdiend mostly the silicified harzburgite, although in this area at a few places the silicified rock forms a capping on serpentized harzburgite. In bore-hole core from Vlakfontein 207 JP the olivine in rocks of this unit shows the tendency of being much serpentized near the surface, but deeper down serpentization occurs along fissures in the rock and in places the outer rims of the olivine crystals are altered.

Well preserved harzburgite occurs in the workings on Vlakfontein 207 JP. It is a dark-coloured, heavy rock, composed of interlocking grains of olivine. Large greyish-green crystals of enstatite (En 90), in places with irregular outlines, are present. The bronzite poikilitically encloses olivine which is usually partly altered to serpentine along cracks. The composition of the olivine ranges from Fo 96–88 in the lower bands of this unit to Fo 81–79 in the higher ones. During serpentization, a fine-grained magnetite dust is segregated from the olivine along cracks and sometimes it forms irregular bands, giving the rock a streaky appearance.

The bronzite content varies considerably and in places the rock consists almost wholly of olivine. On Vlakfontein 20 JP interstitial chromite grains, in the form of octahedra, occur frequently.

Wagner (1924, pp. 51–53) describes bronzite serpentinite, in which the original bronzite is still wholly or partially preserved, and bastite serpentinite, in

which the original bronzite is completely replaced by bastite. In the opal-bearing serpentinite, the serpentine is intersected by narrow stringers of bluish-grey or white opal, cutting through matrix and phenocrysts.

The silicified harzburgite is a characteristic brown, iron-stained siliceous pitted rock (Wasserstein, 1936, p. 217), which forms low rugged ridges. Wagner (1924, p. 56) states that the original serpentine has been largely or even completely replaced by opal, quartz, and hydrous iron oxide. There are intermediate types such as rocks showing a curious spongy texture, consisting of a meshwork of iron-stained opal and quartz in which the cells are occupied by earthy limonite resulting from the oxidation of the iron present in the serpentine, the iron oxide giving the rock a brownish-red colour.

### 3. *The Pyroxenite Unit*

The pyroxenite unit consists of heavy medium-grained hypidiomorphic-granular rocks. It has a greenish colour when fresh, but on weathering, it becomes greenish-brown and yellowish or reddish-brown. In most places, it consists of more than 85 per cent of cumulus bronzite (Plate XVIII A), the volumetric composition of which is indicated on Plate VII. Some of the bronzite crystals, which can always be recognized megascopically in fresh samples, display a yellowish greenish-brown colour whereas others are almost black depending on the orientation of the crystals in the sample. The *Of* content of the bronzite ranges from 15 per cent at the base to 20 per cent at the top of the unit (Plate XVI). Generally the plagioclase content (*An* 73–83) is very low, but it may be as high as 10 per cent and may even exceed this amount near the contact with the anorthosite at the top (Plate VII) where the rock, with pyroxene still in excess of plagioclase, may be called a melanorite. West of the Pilanesberg, apparently owing to crystallization differentiation, a band of noritic composition occurs (Plate I).

In the pyroxenite there are a few diopside crystals present and near the chromitite seams the rock usually contains a variable amount of intergranular chromite. Accessory minerals, which may or may not be present, include olivine (near the base of the pyroxenite unit) and sulphides such as pyrrhotite, pentlandite, and chalcopyrite, which are more abundant in the pyroxenite west of the Pilanesberg where the nickel-copper sulphide pipes occur. The petrography of the chromitite, which is actually part of this unit, is treated separately.

#### 4. *The Anorthosite Unit*

Members of this unit are medium-grained and white, strongly resembling marble when fresh. In many places the rocks contain up to 10 per cent and more of pyroxene (Plate VII) and may be named leuconorite. Where the pyroxene crystals, mostly cumulus orthopyroxene, are more or less evenly spaced, they give rise to the spotted variety (Plate XVIII B) also called spotted leuconorite. In other places small intercumulus clinopyroxene grains are concentrated into large clusters, separated by plagioclase cumulate, thus forming the mottled variety (Plate XIX A). In places in the platinum mines, the mottled variety grades into a spotted variety along the strike of the igneous layering. A "pure" variety of anorthosite may contain up to 95 per cent and more of plagioclase and up to about 3 per cent of orthopyroxene, but this variety is, however, rare and is, for instance, to be seen immediately below the Merensky Reef. Accessory amounts of apatite may occur in places and chromite grains and fragments occur in this unit in many places near the chromitite seams. Generally the composition of the plagioclase varies between An 75 and An 85 and that of the orthopyroxene between Of 18 and Of 28. The average composition of the clinopyroxene is Wo<sub>43</sub>Fs<sub>16</sub>En<sub>41</sub>.

Near contacts with the pyroxenite or norite units the pyroxene content may be much higher, even up to 20 per cent. Because the bands of the anorthosite unit are grouped together in Plate VII, higher pyroxene content is shown not only at the lower boundary of this unit, but also within the unit as such.

At contacts between bands of the anorthosite unit with the norite or pyroxenite units thin alternating bands of feldspar-rich and pyroxene-rich rock may occur and, according to Willemse (1969, p. 12) the composition of the minerals in the pyroxene-rich layers differ from those in the feldspar-rich layers. This can be explained if a magma from which the anorthosite unit formed was added to the last liquid of the previous unit, followed by crystal settling.

#### 5. *The Norite Unit*

The norite unit consists of pale grey, medium to coarse-grained equigranular rocks. Plagioclase and orthopyroxene can be recognized megascopically and the minerals are usually fresh (Plate XIX B). On the whole, this unit contains more orthopyroxene

than clinopyroxene (Plate VII). As in the marginal hornite sub-unit, layers of this unit are in places more leucocratic owing to crystallization differentiation.

The plagioclase and orthopyroxene, representing two cumulus phases, form sub-hedral crystals with interstitial clinopyroxene. Amphibole and biotite are usually absent, but may form as much as 3 per cent by volume of the rock in places. Fourie (1945, p. 27) describes the presence of olivine crystals ranging in composition from forsterite to chrysolite (Fo 95–82). The composition of the plagioclase (Plate XVI) ranges from An 75–86 in the lower part of this unit to An 70–75 in the upper part, and the orthopyroxene (bronzite) from Of 18 to Of 30. The composition of the clinopyroxene in the vicinity north of the Pilanesberg is about Wo40En45Fs15 and in the Rustenburg area about Wo40En40Fs20, corresponding in both cases to augite.

## 6. *The Porphyritic Pyroxenite Unit*

(a) *The Porphyritic Sub-unit.* — Outcrops of the porphyritic sub-unit are not very often found at the surface. It is only seen in extremely weathered exposures in stream-beds, such as the large occurrence south-east of Rustenburg. Large scattered crystals of pyroxene stand out in a yellowish weathered groundmass.

Fresh samples were, however, obtained from the mines and from bore-holes in the vicinity of Zwartklip 405 KQ. It is greenish grey and, except for some large clinopyroxene (diplage) crystals, it is an equigranular medium to coarse-grained rock in which pyroxene and plagioclase can be recognized megascopically. The texture resembles that of a porphyritic rock.

The rock consists of 80 per cent or more of orthopyroxene (bronzite, Of 14–19) (Plate XX A), 8 per cent or more of interstitial plagioclase (An 69–84), and a little clinopyroxene (Wo41En48Fs11) with accessory minerals such as biotite, phlogopite, chromite, sulphides, and sometimes magnetite. The variations in volumetric composition of the rock and compositions of the plagioclase and orthopyroxene from the lower to the upper bands, are shown in Plates VII and XVI. The composition of the clinopyroxene ranges from Wo36En54Fs8 north of the Pilanesberg to Wo41En46Fs13 in the Rustenburg area (Schmidt, 1952).

The clinopyroxene forms large sparsely scattered crystals, up to 50mm or more in diameter, which include orthopyroxene and plagioclase in poikilitic fashion. The biotite and phlogopite are usually interstitial or fill cracks in the orthopyroxene. Chromite crystals are interstitial to the orthopyroxene, but small crystals may also be included in the orthopyroxene or in the interstitial plagioclase. Van Zyl (1970, pp. 88–89) describes four ways in which the chromite occurs. Apart from those already mentioned, he also describes the occurrence of bigger euhedral to subhedral crystals in the margins of the orthopyroxene where they are totally or partly enclosed. Chromite crystals are generally found in interstitial plagioclase in this unit near chromitite bands but small chromite crystals may also be included in the orthopyroxene and interstitial plagioclase. The highest band known is the so-called Bastard Reef.

(b) *The Pegmatitic Sub-unit.* — Mineralogically the pegmatitic sub-unit is almost identical with the porphyritic sub-unit (Plate XX B). It is, however, a very coarse-grained rock with a pegmatitic appearance and it contains a greater proportion of sulphides.

It forms a greenish coarse-grained weathered material where exposed in prospecting pits, and outcrops are not to be found. The Merensky Reef (the band mined for platinum), shown by a symbol on Plate I, was followed by means of prospecting pits, guided by the very useful marker of anorthosite on top of it. The other bands of this unit are only exposed in the Zwartklip and Rustenburg platinum mines.

The pegmatitic sub-unit is a holocrystalline hypidiomorphic-granular greenish-grey rock, consisting mainly of bronzite (Of 15–18), chrysolite (Fo 80–78), and bytownite (An 72–84) (Plate XVI). The constituent amounts of the main minerals are shown in Plate VII. Like the porphyritic sub-unit, it also contains some clinopyroxene (approximately Wo<sub>41</sub>En<sub>48</sub>Fs<sub>11</sub>) and accessory minerals such as biotite, phlogopite, chromite, and sulphides. Van Zyl (1970, p. 91) also records some hornblende, magnetite, and ilmenite.

All the minerals from samples taken in the mines are usually fairly fresh. Some of the plagioclase, however, may show some cracks due to strain, may be sericitized

and kaolinitized, or be partly replaced by sulphides. The plagioclase is interstitial to the pyroxene and olivine. The orthopyroxene forms fairly equigranular sub-hedral crystals and, according to Van Zyl (1960, p. 44), the olivine, forming round crystals, shows the tendency to be concentrated in clusters in the Merensky Reef. Some of these crystals are altered to serpentine. Like in the porphyritic sub-unit, the clinopyroxene consists of large crystals, enclosing orthopyroxene and plagioclase in a poikilitic fashion. Chromite usually occurs near the chromitite bands on the contacts. Van Zyl (1960, p. 45) describes the replacement of plagioclase and pyroxene by chromite and the presence of magnetite and ilmenite with chromitite. The magnetite is interstitial to all other minerals. Van Zyl (pp. 47–48) discusses the possibility of a hydrothermal origin for this chromitite and associated minerals, but stresses the lack of hydrothermal alteration in the country rock. Should the chromite and associated minerals be the late crystallization products of the magma from which this unit crystallized, olivine and orthopyroxene are the primary precipitate minerals and plagioclase, clinopyroxene, chromite, and magnetite the interprecipitate minerals, whereas the biotite, phlogopite, and sulphides crystallized hydrotogenetically. The plagioclase is indeed interstitial to the orthopyroxene and the clinopyroxene includes orthopyroxene in poikilitic fashion. The orthopyroxene and olivine thus represent the cumulus minerals and the plagioclase, clinopyroxene, at least some of the chromite, and the magnetite the intercumulus minerals. Wager and Brown (1968, p. 370) accept all the chromite as one of the first cumulus minerals, but this does not seem to be so.

## 7. *The Gabbro Unit*

The gabbro unit consists of grey, medium to coarse-grained hypidiomorphic rocks in which plagioclase and pyroxene can be recognized megascopically. These rocks have dull, rusty-brown and dark-grey weathered surfaces and usually build fairly conspicuous hills. The rocks of this unit can, on the whole, be classified as gabbro (Plate XXI A) because clinopyroxene is in excess of orthopyroxene. The ratio orthopyroxene: clinopyroxene varies considerably up in the sequence (Plate VII) and also laterally so that in some places the rocks contain more orthopyroxene than clinopyroxene and may locally be called norite. The best example of a predominant norite phase in the unit is the lower part of the unit

(Plate VII), which implies that after emplacement of the magma from which this unit crystallized, orthopyroxene was the dominant dark cumulus mineral, but later clinopyroxene was the primary cumulus pyroxene.

Willemse (1969, p. 8, Fig. 5) states that the gabbro unit in the eastern part of the Complex is also generally considered to be noritic: towards the base and gabbroic higher up in the sequence. According to him (p. 10), many of the rocks would qualify as hyperite because both clino- and orthopyroxene are generally present in variable amounts. On the basis of orthopyroxene content, expressed as percentage of total pyroxene, many rocks of the gabbro unit in the western part of the Complex may also be termed hyperite because this percentage ranges between 50 and 75 in places. Anorthositic layers also occur in places, such as about 800 metres up in the sequence north of the Pilanesberg (Plates I and VII).

In this unit there are three cumulus phases: plagioclase, augite, and orthopyroxene (hypersthene), the latter being inverted pigeonite. According to von Gruenewaldt (1970, pp. 68–69), orthopyroxene which formed from pigeonite by inversion, appears at about 1000 metres above the Merensky Reef, but orthopyroxene continued to crystallize over another 300 metres together with pigeonite which is then present over a thickness of more than 1000 metres before orthopyroxene appears again.

Willemse (1969, p. 8, Fig. 5 and pp. 14–15) describes textural relations of the minerals and layers of porphyritic norite and gabbro, anorthositic gabbro, "mottled markers", and a "needle norite", all members of this "main zone", which corresponds largely to the gabbro unit. The hyperite near Bon Accord dam (north of Pretoria), consists of subhedral plagioclase laths surrounded by equant grains of orthopyroxene. The orthopyroxene extinguishes practically simultaneously in groups. The layer of "needle norite" occurs 300 metres above the Merensky Reef and contains characteristic needle-like grains of orthopyroxene. According to him, the needles represent primary precipitate material and the clinopyroxene present is intercumulus.

In general, the plagioclase in this unit ranges between 60 and 80 per cent by volume and the total pyroxene may form up to 40 per cent or more of the rocks (Plate VII). Small crystals of pleochroic biotite were observed in many places and especially near quartzite inclusions. Rocks in this unit contain practically no

magnetite.

The plagioclase forms polysynthetic twins and is fresh. The anorthite content ranges between An 50 and An 70 (Plate XVI) and corresponds to labradorite. The orthopyroxene ranges from bronzite (Of 25) to hypersthene (Of 40) and the clinopyroxene is augite (approximately Wo<sub>38</sub>–42En<sub>34</sub>–36Fs<sub>24</sub>–26).

#### 8. *The Ferrogabbro Unit*

The ferrogabbro unit, which follows on top of the gabbro unit, occurs in flat country and is weathered to such an extent that outcrops are only present in or near stream beds. Whereas the gabbro unit contains no visible magnetite, this mineral can always be recognized megascopically in rocks of the ferrogabbro unit. Magnetite pipes are more abundant in the ferrogabbro unit and magnetite sheets are, with a few exceptions present only in this unit. Although most of the magnetite sheets are actually part of the layered sequence of the ferrogabbro unit, magnetite is treated under a separate heading.

Like the other units the ferrogabbro unit also consists of a variety of rock types. Names such as ferrosodagabbro and ferrodiorite were used by various authors for rocks forming the greater part of this unit and bands of magnetite anorthosite and troctolite also occur in it.

The name "ferrogabbro" was originally introduced by Wager and Deer (1939, pp. 98–99) for a group of rocks in the Skaergaard intrusion rich in iron, largely present as ferrous iron in the olivine and pyroxene. According to their proposal a "ferrogabbro" should contain olivine with more than 50 per cent molecular fayalite. The iron content of the clinopyroxene of the ferrogabbro unit of the Bushveld Complex is lower than that of the ferrogabbro of Skaergaard, the magnetite content is higher and it contains some iron-rich orthopyroxene and olivine which is not so rich in iron as that of Skaergaard, but is still high (Fa 50) (Coertze, 1964, pp. 18–20). On the other hand, the anorthite percentages of the plagioclase in both intrusions are low. Both the Skaergaard ferrogabbro and the ferrogabbro unit of the Bushveld contain plagioclase, clinopyroxene, magnetite, and olivine, and although the olivine and pyroxene in the Skaergaard ferrogabbro are richer in iron than those in the Bushveld ferrogabbro unit, the iron con-

tent of the pyroxene and olivine reaches higher values in both cases than that of the other basic rocks in these intrusions.

Van Zyl (1960, pp. 62–66) describes a ferrosodagabbro from a bore-hole near the platinum mine on Zwartklip which contains 23 per cent of olivine (Fa 60), 22 per cent of clinopyroxene (Wo37En29Fs34) and 48 per cent of plagioclase (An 48–50). More recently, the name ferrodiorite has been suggested for the low calcic rocks (Wager and Brown, 1968, p. 376). As the composition of the plagioclase is An < 50 in the upper part of this unit, the name ferrodiorite can according to their definition be used for rocks in the upper half of this unit. In places, at the top of this unit a dioritic rock, consisting mainly of hornblende and plagioclase with some biotite and magnetite and quartz occurs.

Troctolite occurs on Krokodilkraal 436 JQ and Zoutpansdrift 415 JQ. Apparently it occurs in layers, but could not be followed very far owing to scanty outcrops. The rock has a brownish colour and a vitreous appearance. Olivine exceeds pyroxene (not shown in Plate VII) and biotite forms reaction rims between the magnetite and plagioclase. The olivine and plagioclase crystallized together (cumulates), but the olivine continued to crystallize longer and is moulded on the feldspar in places (adcumulate).

A poorly exposed rock type, magnetite anorthosite, which consists of 50 per cent of plagioclase and 50 per cent of magnetite, occurs in the lower half of the ferrogabbro unit below the magnetite bands on Berseba 397 JQ and north of the Pilanesberg in the vicinity of the lower magnetite bands (Coertze and Schumann, 1962, p. 14). Also in the eastern part of the Complex a magnetite anorthosite is associated with the magnetite bands (Coertze, 1964, pp. 27–28).

In general rocks of the ferrogabbro unit (Plate XXI B) are hypidiomorphic, granular medium to coarse-grained and consist of plagioclase, pyroxene, magnetite and, in places especially high up in the sequence, also iron-rich olivine and apatite. Where orthopyroxene occurs, it is actually an inverted pigeonite. According to Von Gruenewaldt (1970, p. 69), orthopyroxene formed from pigeonite by inversion appears at about 1000 metres above the Merensky Reef which is still low down in the underlying gabbro unit. A second-phase pigeonite started to crystallize at about 450 metres below the main magnetite band which is roughly the base of

the ferrogabbro unit.

In the ferrogabbro unit the anorthite content of the plagioclase ranges from An 60 at the base of the unit to An 30 at its top. The composition of the orthopyroxene is Of 39–44 (Plate XVI) and the composition of the clinopyroxene ranges from augite (Wo<sub>42</sub>En<sub>34</sub>Fs<sub>24</sub>) to a composition approaching ferro-augite (Wo<sub>40</sub>En<sub>30</sub>Fs<sub>30</sub>) and ferro-augite (Wo<sub>39</sub>En<sub>29</sub>Fs<sub>34</sub>) (Van Zyl, 1960, pp. 62–64). The olivine is hortonolite (Fo 50–40), but higher in the sequence the iron content may be higher. A layer of fayalite diorite is described by Groeneveld (1970, p. 41) in the eastern part of the Complex.

### 9. *Chromitite*

Although chromitite outcrops are scarce, there are numerous trenches and prospecting pits where the chromitite seams can be studied. In the mines, some of the seams could be inspected to a depth of 150 metres and boreholes intersected some of the seams at still greater depths. Most of the chromitite is "friable" and pulverises upon blasting or exposure to the atmosphere, but there is also a "hard lumpy" variety which is very fine-grained. The chromitite is a black, fine to medium-grained rock. Black lustrous crystals of chromite form the main mineral which is associated with silicates such as bowlingite and bronzite.

The bowlingite crystals, with inclusions of small chromite crystals, are set in a matrix of larger interlocking grains of chromite and these together constitute the chromitite. A mottled effect is noticeable because of the yellow to greenish-yellow colour of the bowlingite in contrast with the black colour of the chromite. Some of the chromite grains occur as interlocking crystals without any interstitial material.

The chromite (Kupferburger and others, 1937, p. 29) is black in colour and opaque under the microscope except in splinters and along thin edges where it is translucent and of a deep brown colour. The crystals are usually more or less octahedral and vary considerably in size from place to place.

It has been explained (Kupferburger and others, 1937, p. 29) that the use of the name chromite is not strictly correct. Fourie (1959, p. 2) states that in mineralogy the term chromite is reserved for a spinel composed of pure, or nearly pure

$\text{FeO} \cdot \text{Cr}_2\text{O}_3$ , but that it is also used to designate the gangue-free spinel mineral that in the Bushveld is mainly composed of the oxides  $\text{Cr}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{MgO}$ . According to him, the name *chromepicotite* was suggested for ores that contain appreciable quantities of  $\text{Al}_2\text{O}_3$  and  $\text{MgO}$  in addition to the oxides mentioned, and the Bushveld chromite may thus more accurately be so named. Fourie concludes that, according to Niggli's suggestion for the classification of the spinel group, the mineral in the Bushveld ore should be called *beresovite*, but that it has been customary, however, to use the name *chromite*. Because *chromite* is an opaque mineral, it is not amenable to the type of optical study which, in the case of the silicates, enables one to determine vertical fluctuations in composition. The lower group of chromitite seams occur in bronzitite and the bronzite and chromite are cumulates. Higher up in the upper group of chromitite seams, especially those associated with anorthosite, the chromite apparently crystallized from an interprecipitate. It is also stated by Cameron (1970, p. 49), who investigated chromitite in the eastern part of the Complex, that chromite is a cumulus mineral in parts of the sequence.

#### 10. *Magnetitite*

Although in literature dealing with the Bushveld Complex, it has become general practice to refer to the magnetic iron ore as "*magnetite*", the author, in order to avoid confusion, prefers the term "*magnetite*" for the mineral and uses the term "*magnetitite*" for the rock (Coertze, 1964, p. 22).

Compared with the other basic rocks, the magnetitite is more resistant to weathering and outcrops are fairly prominent. The pipe-like bodies usually form small conical hills on the flats and in places the thicker sheets form low ridges which can be followed for kilometres. Enormous quantities of magnetitite rubble usually occupy the immediate vicinities of the outcrops. Owing to their black colour, the magnetitite outcrops can always be recognized at a distance in the field and on air photographs.

The magnetitite is a heavy, lustrous and coarsely crystalline rock. The colour on weathered surfaces is usually black and on fresh surfaces it ranges from blackish to brownish-red.

In places the magnetitite is extremely magnetic, but the magnetism varies con-

siderably over short distances. As shown by the magnetometer, the magnetism changes from positive to negative over short distances across both the magnetitite sheets and pipes (Coertze and Schumann, 1962, pp. 23–24).

In fresh samples ilmenite can usually be recognized megascopically. It forms irregular patches in the rock and has a metallic lustre.

The following minerals were identified in the magnetitite: Magnetite, maghemite, ilmenite, spinel, limonite, and the sulphides pyrite, chalcopyrite, and pyrrhotite. These identifications correspond to identifications by Schweltnus and Willemse (1943, pp. 29–31) and by Coertze (1964, pp. 32–36) on magnetitite samples from the Eastern Bushveld Complex. Willemse (1969, pp. 197–202) also describes most of these minerals, especially ilmenite, spinel, and maghemite in detail. Molyneux (1970, pp. 233–238) adds a description of a new mineral, probably diasporite, which was previously identified as pleonaste.

Microscopically the magnetite is a grey-pink mineral with a slight brownish tint and isotropic, and the maghemite, a grey-white isotropic mineral which can always be recognized when present. The ilmenite is light brown with a pink tint, strongly pleochroic and anisotropic. The limonite, a mixture of goethite and hematite, is dull grey with a bluish tint. Exsolution lamellae of spinel, always of microscopic dimensions, are arranged according to crystallographic directions, apparently parallel to (111).

Magnetite and maghemite are the main minerals. The magnetite alters to maghemite which begins to form all along contacts between the magnetite grains, along cracks, and along spinel lamellae from where it spreads into the magnetite crystals so that eventually the magnetite forms irregular patterns within the grains and the so-called "moth-eaten" structure is formed (Coertze, 1964, pp. 32–36). A few alteration stages may be present between the magnetite and maghemite because more than one shade exists in a ring of "less brownish mineral" between magnetite and maghemite. In places the magnetite may be completely altered to maghemite. At the surface, the magnetite may occur in any stage of alteration, whether it is from the lower or upper bands or from the pipe-like bodies. The degree of alteration may also vary considerably over short distances in the same band.

The ilmenite forms coarse granular grains, interstitial to the magnetite or maghemite, but it may also occur as fine exsolution lamellae. Usually the limonite, where present, cuts the magnetite and maghemite in thin veins.

The present investigation of magnetitite in the Western Bushveld Complex thus actually confirms the suggestion by Coertze (1964, pp. 38–39) that, just after crystallization, the original rock was composed of magnetite and ilmenite. At or near the surface, the magnetite is altered to maghemite, goethite, and hematite. The alteration, which is probably still proceeding, takes place through a series of intermediate stages, and the rock at the surface may exist in any one of these stages.

#### 11. *Hortonolite Dunite*

The hortonolite dunite occurs as pipe-like bodies, or at least as part of composite magnetite dunite pipes, which, in many places, are also associated with diallagite pegmatite. The hortonolite dunite and magnetitite in the pipes thus do not form part of the normal layered sequence.

The hortonolite dunite is a heavy coarse-grained rock, the colour of which ranges from yellowish to black and it has a vitreous appearance. The rock (Plate XXII) may contain up to 20 per cent or more of interstitial magnetite and up to 5 per cent of plagioclase ( $An \pm 80$ ). The composition of the olivine ranges from Fa 50 to Fa 60, whether the pipes occur as low down in the sequence as the pyroxenite unit or as high up as the ferrogabbro unit. Amphibole reaction rims occur along the margins of the magnetite, especially where the magnetite crystals adjoin the feldspar.

#### 12. *Diallagite Pegmatite and Bronzitite Pegmatite*

Like the hortonolite dunite, the diallagite pegmatite and bronzitite pegmatite do not form part of the normal layered sequence. The diallagite pegmatite is in most cases associated with the magnetite dunite pipes and forms the outer rims of these composite pipes. It also extends from these pipes in the form of dyke-like or sheet-like bodies resembling some of the magnetitite occurrences.

Like the rocks of the pegmatitic sub-unit, the diallagite pegmatite is always very much weathered and, because there are no mines or excavations in it, no fresh samples

could be collected for study. The weathered diallagite pegmatite is a greenish-yellow coarse-grained rock with a pegmatitic appearance. In places it contains inclusions of anorthosite, chromitite, and hortonolite dunite. The rock consists of 90 per cent or more of large diallage crystals, some a few centimetres long, a small amount of plagioclase ( $An \pm 80$ ), amphibole which may be an alteration product of pyroxene, and a few biotite crystals. Various amounts of interstitial magnetite and sulphides may occur. In a "pegmatoid" pipe in the eastern part of the Complex (Ferguson and McCarthy, 1970, p. 76), the clinopyroxene forms large crystals, 2 centimeters in diameter, and the composition varies from  $Wo_{42}En_{52}Fs_6$  to  $Wo_{41}En_{43}Fs_{16}$ . Amphibole and orthopyroxene ( $En_{66} - En_{64}$ ) are present and the composition of the plagioclase is also rather calcic ( $An_{78-85}$ ).

Bronzitite pegmatite, occurring on Vlakfontein 207 JP, is described by Wagner (1924, p. 45). The rock forms patches and vein-like bodies which usually conform to the igneous layering, but which also transgress the country rock in places. According to Wagner, some of the bronzitite pegmatite bodies consist of large bronzite crystals. Others consist of large rounded grains of bronzite, held together by interstitial calcic feldspar and in places are accompanied by considerable amounts of phlogopite. Schweltnus (1935, pp. 12 and 17) describes pegmatite which consists of exceptionally large crystals of bronzite, in places exceeding 12 centimetres in length and 5 centimetres in breadth, plagioclase, and biotite and occasional crystals of chromite. This pegmatite forms part of the composite nickel-copper sulphide bodies west of the Pilanesberg. It is obvious that the mineral assemblages in the "pegmatoid", in the diallagite pegmatite, and in the bronzitite pegmatite, are very similar to those found in the porphyritic sub-unit. The clinopyroxenes in all the occurrences are of low iron content and the plagioclases are rather calcic.

### 13. *Sulphide Bodies*

West of the Pilanesberg, gossan outcrops occur from Vlakfontein 207 JP to Vlakfontein 164 JP and Groenfontein 138 JP (Plate I). Nickel-copper sulphide bodies occur below the gossan. Although some of the sulphide bodies continue vertically in a regular fashion, others display rapid enlargements and constrictions. These nickel-copper sulphide bodies, emplaced more or less vertically, are taken to

be pipe-like bodies.

Wagner's description (1924, pp. 123–128) of the gossans is so comprehensive that nothing can be added. He describes various colours of gossans such as many shades of red, yellow, green, blue, etc. The gossans consist of a base of isotropic opal with some minute patches and elongated areas of red hematite. Opal pseudomorphs after bronzite, patches of limonite, and irregular patches of magnetite, are also present.

The sulphide bodies are composed of a variety of ore minerals which can be identified under the ore microscope. The primary ore minerals are pyrrhotite, pentlandite, which is the chief nickel bearer, with its fine-grained alteration product violarite  $(\text{Ni,Fe})_3\text{S}_4$ , chalcopyrite, valleriite, and cubanite. Some of the more important secondary ore minerals are pyrite, marcasite, chalcocite, and malachite. These minerals, together with some others, have already been described in detail by Wagner (1924, pp. 92–110) and later by Schweltnus (1939, pp. 89–131). Liebenberg (1970, pp. 108–207) recently made a detailed study of the Vlakfontein ore. He adds cubanite, pyrite, machinawite, sphalerite, and some nickel-arsenic bearing minerals to the list. He lists valleriite as a secondary sulphide, together with melnikovite-pyrite, bravoite, and covellite. Schweltnus (1935, pp. 22–27) lists nickel and copper values. The average for his No. 3 ore body is 3.06 per cent nickel and 0.76 per cent copper. He shows that the values vary according to the levels. Gold, silver, and platinum are also known to occur together with these minerals. Schweltnus (1935, pp. 18–22) gives assays showing up to 12 dwts per ton of gold, 12 dwts of silver and 15.4 dwts of platinum. According to Schweltnus, these precious metals are probably intimately associated with the sulphides. Their presence can only be proved by assay. On the other hand, these precious metals also occur in the Merensky Reef. Van Zyl (1960, p. 76) identified sperrylite and braggite as well as native platinum in a non-magnetic fraction of platinum concentrate from the Rustenburg Platinum Mine. He states that these identifications prove that all the platinum is not in solid solution in the sulphides. Stumpfl (1961, pp. 833–847) describes some new platinoid-rich minerals in sulphides from the old Driekop Platinum Mine in the eastern part of the Bushveld Complex. They are so finely intergrown that they could only be identified by using an X-ray microanalyser. He also

identified small flakes of native gold in some of the platinoid minerals. He stresses that the bulk of the platinum metals is fixed in independent platinum minerals, but that the possibility of traces in the lattice of sulphides should not be disregarded.

The sulphides on Zandriverspoort 210 JP occur in a sheared and brecciated quartzite located in the gabbro along the fault-zone south of Matooster. Unfortunately, samples of these sulphides are much weathered and did not polish very well. Only pyrrhotite, a small amount of pyrite, and encrustations of malachite, occurring at the surface, could be identified. These sulphides were exploited for gold by the Zandrivers Poort Mining Co. Ltd. during the period from 1934 to 1937.

Gangue minerals in the Vlakfontein ore bodies such as bronzite, biotite, hornblende and graphite, are also described by Wagner (1924, pp. 104–110). During the present investigation, the workings at Vlakfontein had already been closed for years and in the weathered sulphide samples collected by the author, only a few of the main minerals mentioned could be identified. It is believed, however, that had the samples been fresh, very little could have been added to the excellent descriptions of Wagner (1924), Schwellnus (1939), and Liebenberg (1970).

### B. Composition of the Dominant Silicate Minerals

The compositions of the plagioclase and orthopyroxene covering the sequence of basic rocks, are given in Appendix 1. In order to illustrate the compositional variations the data are also shown graphically for the rock units arranged chronologically (Plate XVI). The values in Appendix 1 and on Plate XVI represent all those published values, the positions of which could be traced on maps (Plate I, inset), and about 31 new values, but it should be remembered that each one of these actually represents the average of many determinations. Many other mineral determinations, such as those on rocks which do not form part of the layered sequence (e.g. the pipes) and determinations on gabbro and anorthosite along the shear zone south of Pilanesberg, are not included in Appendix 1. In addition, the average compositional variation for the clinopyroxene, orthopyroxene, plagioclase, and olivine of the different rock units, is illustrated in Plate XXIII. This plate, however, gives only a general idea of estimated averages and of the general trend. As the range for some of these

units is very wide, such as that for the basal norite unit (compare Plate XVI for measured values), plotting of the averages may be confusing. Plate XXIII should thus not be studied without consulting Plate XVI.

Volumetric compositions are shown in Plate VII. Countings were done on all the samples on which new determinations were made as well as on many other samples, also from the routes for which published data are available (Plate I, inset).

### 1. *Plagioclase*

In Plate VII the volumetric proportion of the plagioclase is shown for the whole sequence and the variation in each one of the rock units is thus also shown. In the pyroxenite unit, the plagioclase content may be as low as 5 per cent whereas in the anorthosite unit it is up to 95 per cent in places.

In general, the composition of the plagioclase becomes more sodic higher up in the sequence (Plate XVI). From an average of about An 75–80 near the base of the basal norite unit the anorthite content decreases to an average of about An 45 near the top of the ferrogabbro unit. However, at the base, in the quartz norite sub-unit, the composition of the plagioclase varies considerably from place to place, from crystal to crystal, in adjacent twinning lamellae, and even from core to mantle in zoned crystals and all values between An 43 and An 86 were recorded. Higher up, in the marginal norite sub-unit, less lateral variations were observed. For each rock unit the same tendency as that in the sequence as a whole can be observed, i.e. becoming more sodic higher up, but there are compositional differences between succeeding units. In the norite unit a few samples showing lower values were examined. They are actually from inclusions of the quartz norite sub-unit, forming contamination patches in the norite unit.

### 2. *Orthopyroxene*

The orthopyroxene makes its appearance low down in the sequence. It forms between 13 and 60 per cent by volume of the quartz norite sub-unit and up to 90 per cent and more of the pyroxenite unit. In the gabbro and ferrogabbro units it mostly represents inverted pigeonite. In Plate VII the variation of the volumetric proportion from the base to the top of the sequence is shown.

In general the iron content of the orthopyroxene increases upwards in the sequence (Plate XVI) and the trend is very similar to that shown by Atkins (1969, p.239) and is also illustrated in Plate XXIII. Although it varies considerably in the quartz norite sub-unit, it ranges from Of 15–20 low down in the sequence in the marginal norite sub-unit to Of 35–45 high up in the gabbro and ferrogabbro units. This trend in the composition of the orthopyroxene is also evident in each one of the separate units. There are, however, small displacements in the trend between the succeeding units (Plate XVI) and the trend shown for the orthopyroxene in Plate XXIII does not follow the sequence of units in all aspects. The porphyritic pyroxenite unit, for instance, appears prior to the norite unit and anorthosite unit along the trend line. The trend shown by Atkins (1969, p. 239, Fig. 3) and also indicated on Plate XXIII, displays the same phenomenon. His number 4 (Merensky Reef) appears after number 2 and is followed by number 3. The significance of these compositional shifts will be discussed under the clinopyroxene which displays similar phenomena.

### 3. *Clinopyroxene*

Generally very little clinopyroxene is found in the lower part of the sequence of basic rocks (Plate VII). However, it gradually becomes more abundant in the younger units so that more clinopyroxene than orthopyroxene is present in the gabbro unit and only very little orthopyroxene in the ferrogabbro unit.

In Table III the average composition of the clinopyroxene for each one of the units, arranged chronologically, is indicated. These data are also shown on Plate XXIII.

TABLE III  
Composition of Clinopyroxene

| Rock units                  | Average Composition           |
|-----------------------------|-------------------------------|
| Ferrogabbro unit            | Wo42 Fs24 En34—Wo37 Fs34 En29 |
| Gabbro unit                 | Wo40 Fs25 En35                |
| Porphyritic pyroxenite unit | Wo42 Fs8 En50—Wo41 Fs13 En46  |
| Norite unit                 | Wo40 Fs 18 En42               |
| Anorthosite unit            | Wo43 Fs16 En41                |
| Pyroxenite unit             | —                             |
| Harzburgite unit            | —                             |
| Marginal norite sub-unit    | Wo34 Fs8 En58                 |
| Quartz norite sub-unit      | Wo38 Fs2 En60                 |

On the whole the clinopyroxenes become progressively more iron rich in the younger intrusions. There is, however, a gap in the harzburgite and pyroxenite where practically no clinopyroxene is found. This gap is also reflected in Plate VII where it is shown that the clinopyroxene content is low in the porphyritic pyroxenite unit and practically nought in the pyroxenite and harzburgite units.

In a general way the trend in the clinopyroxene compositions (Plate XXIII) corresponds to that shown by Wager and Brown (1968, p. 39, Fig. and p. 391, Fig. 214) for the Skaergaard intrusion and the Bushveld Complex, respectively. The clinopyroxenes become progressively more iron-rich, but the curves are not similar. Wager and Brown based their trend line on work by Atkins (1969, p. 239) who made use of analyses of clinopyroxenes and expressed the composition of the clinopyroxene as atomic percentages of Ca, Mg, and Fe. The present investigation of clinopyroxenes is based on optical determinations and the composition expressed as Wo, Fs and En. Although the curve by Wager and Brown can thus be considered more accurate, it is mainly for rocks of the eastern part of the Complex. Atkins included two analyses of rocks from the western part of the Complex. As shown in his Fig. 3, they are displaced from the trend line. According to him (pp. 239–240), there may be small but significant differences between the trends from the eastern Bushveld and those from elsewhere in the intrusion. Atkins also shows the composition of his ferrogabbro No. 10 to be anomalous and could offer no explanation to account for the anomaly. This composition coincides with that of the first of the ferrogabbro unit indicated on Plate XXIII. On the other hand, the points shown for the basal norite unit do not correspond to the trend line on Plate XXIII. This can perhaps be explained by the fact that part of this unit is contaminated and that mineral compositions in this unit vary considerably from place to place.

Although the porphyritic pyroxenite unit occurs higher up in the sequence than the anorthosite and norite units, the average iron content of its clinopyroxene is lower than that of the clinopyroxenes in the rock units mentioned (Plate XXIII) and thus represents a shift in the crystallization trend also illustrated by the composition of the orthopyroxene. According to Atkins (1969, p. 241), despite the general fractionation sequence whereby pyroxenes become more iron-rich with increasing height, optical measurements indicate small-scale "reversals" in the cryptic

variations of pyroxenes. His analysed pyroxenes also indicate one important "reversal", both for the clino- and orthopyroxene. His specimens 4 and 4a were obtained from the Merensky Reef horizon, whereas his more iron-rich pyroxenes Nos. 3 and 3a occur some 370m lower. According to him, this reversal was probably due to the fresh influx of undifferentiated magma. The findings during the present investigation are in agreement with such an explanation.

Samples 14 and 15 of Wager and Brown are of rocks very high up in the sequence in the eastern part of the Complex, no equivalents of which could be sampled in the western part.

#### 4. *Olivine*

Olivine occurs low down in the sequence in the harzburgite. It is the first silicate mineral to have formed. Some olivine also occurs near the base of the basic rocks in the quartz norite sub-unit north of Rustenburg in the pyroxenite unit and in the Merensky Reef (Plate VII). It appears again in the upper part of the sequence near the top of the ferrogabbro unit and also in the transgressive pipe-like dunite bodies.

The average composition of the olivine is also plotted in Plate XXIII together with the compositions of the other minerals. Low down in the sequence a magnesium-rich variety, which ranges from forsterite to chrysolite, and which crystallized together with magnesium-rich orthopyroxene, is present. In the lower harzburgite lenses and sheets the composition ranges from Fo 96–88 and it gradually changes to Fo 81–79 in the higher harzburgite lenses and to Fo 78–80 in the Merensky Reef. The composition of the olivine in the quartz norite sub-unit (Fo 81–79) also falls in this category.

The olivine in the upper part of the ferrogabbro unit and in the dunite pipes is an iron-rich variety, hortonolite, which may range in composition between Fo 50 and Fo 40, and there is no difference in composition whether the pipes occur in the rocks low down in the sequence or high up in the ferrogabbro unit. This olivine cumulated with sodic plagioclase and pigeonite which has been inverted to orthopyroxene.

It is thus clear that two types of olivine were formed during the intrusion of the basic rocks; the magnesium-rich variety which occurs only in the earlier basic intrusives

and which was one of the first minerals to form, and the iron-rich variety occurring in the later intrusives. There is obviously a great interval in time between the crystallization of the two varieties. Reference will again later be made to the olivine.

## V. CHEMISTRY OF THE BASIC ROCKS

In Appendix 2, selected available chemical analyses of rocks of the Western Bushveld Complex are given in approximate ascending chronological order. Two new analyses representing the ferrogabbro unit are added. The lists of analyses for each unit are followed firstly by tables of the C.I.P.W. norms and then by tables of the Niggli values. The chemical compositions of the units are discussed and analyses of magnetite sheets and pipes are also given (Table IV) and the relation between the vanadium and iron content discussed. Of the 36 magnetite analyses given, 9 were published by Schweltnus and Willemse (1943), 16 available, but unpublished, analyses were collected by G.P. Fourie, previously a member of the Geological Survey, and 11 were collected by the present author. In addition, 15 analyses of samples collected by the author from the lower two magnetite bands north-west of Pretoria, are discussed in general, but are not given in Table IV.

### A. Chemical Compositions of the Rock Units

The ratio  $\text{MgO} : \text{FeO} : \text{total alkalies}$  is graphically shown on Plate XXIV and this diagram is used because it can be compared with similar diagrams for the Bushveld (Poldervaart, 1949, p. 183 and Wager and Brown 1968, p. 402). Diagrams for other complexes are shown by Hess (1960, Plate II).

According to Hess (1960, p. 175), the  $\text{MgO} : \text{FeO} : \text{Na}_2\text{O} + \text{K}_2\text{O}$  weight-per-cent diagrams furnish an exceedingly useful simplification of the trend of change in the magma. It was used by various workers in the past and its applicability is described by Poldervaart (1949, pp. 177–188). He discusses the method of graphical representation of chemical analyses and gives a plot of 123 Bushveld analyses (Fig. 5, p. 183). His diagram shows a line towards the FeO apex and another line towards the  $(\text{Na}_2\text{O} + \text{K}_2\text{O})$  corner, which according to him, corresponds to the calc-alkaline line of descent. According to him, this line reflects the fractionation of the salic minerals throughout the crystallization sequence.

The rocks investigated by means of 33 analyses include only the basic part of the Complex. Consequently there is no line from the FeO apex towards the  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  corner, but the one to the FeO apex, and the one from the MgO corner to the  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  corner, can be recognized in Plate XXIV.

Wager and Brown (1968, p. 402) also show a diagram with 5 Bushveld analyses plotted: one apparently of the basal norite unit, and an average of each of the ferrodiorite (apparently near the top of the basic rocks), ferrosyenodiorite and melagranophyre, felsite and granophyre, and granite. These five analyses show the line from the FeO apex towards the  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  corner and, according to Wager and Brown (p. 403), is an impressive demonstration of the overall similarity between the Bushveld and the Skaergaard trends. On the other hand, they do not attempt to show the complete trend in the basic rocks. They state (p. 402) that the analyses of layered cumulates from the lower zones do not mean much in view of crystal accumulation, but nevertheless, they still plot 4 averages: one each of bronzite-rich cumulates of their "Basal Series", olivine-rich cumulates of their "Critical Series", and gabbroic cumulates of their "Main Zone".

Comparing these with the fields shown on Plate XXIV, their bronzite-rich and olivine-rich cumulates may perhaps correspond to the harzburgite and pyroxenite units and their gabbroic cumulates to the norite unit, but the averages of their feldspar-rich and pyroxene-rich cumulates do not fit any of the fields shown.

It is admitted that it is practically impossible, owing to differentiation within each one of the units, to have a true average composition for each unit. By indicating all the available compositions of the different rock units, the lines mentioned are shown for the Complex as a whole. These lines correspond roughly to those shown by Bowes and others (1970, p. 426), although they did not include the upper part of the Complex. In Plate XXIV the idea of separate units is accepted and fields for these units are indicated as such.

The harzburgite unit containing olivine is magnesium-rich and occurs near the magnesium corner. For all three samples the alkali content is very low and remains stable, although the  $\text{MgO} : \text{FeO}$  ratio varies slightly. The alkali content of the pyroxenite is more or less the same as that for the harzburgite, but the group shows increased FeO. The anorthosite unit, on the other hand, falls right on the alkali side at the expense of MgO. This could be expected, because on the whole, this unit is feldspathic. Within the norite unit the FeO content remains more or less constant, but the  $\text{MgO} : \text{K}_2\text{O} + \text{Na}_2\text{O}$  ratio varies so that the field of the norite unit extends from the pyroxenite unit towards the anorthosite unit.

This indicates its mineralogical position but, with fairly high MgO content, it is still clearly separated from the anorthosite unit. It is of interest that the MgO content for norite of the Sudbury lopolith (Hess, 1960, p. 174, Fig. 35) is much lower, and that it shows surprisingly little differentiation in spite of its size and hence long time available for differentiation. This norite thus shows practically no variation along the lines of fractional crystallization as discussed and also indicated by Hess (Plate II). According to Hess (1960, p. 173), the high Or + Ab had increased the viscosity enough to inhibit crystal sorting.

With alkalis still fairly low and constant, the gabbro unit (Plate XXIV) shows increased FeO which increases still further in the ferrogabbro unit. The dunite is near the FeO corner, but the alkali content is very low, resembling that of the harzburgite.

Comparing the weight percentages of the normative minerals (Appendix 2) with the volumetric compositions of the rocks, it is clear that in certain respects there are differences, but similar trends, in a general way, are obvious in others. According to the norms, small amounts of orthoclase are present in most of the samples, but no orthoclase was observed microscopically. On the other hand amphibole is present in the contaminated rocks (no analyses available) and in some gabbro samples, and small amounts of biotite occur in most of the rocks and no provision is made for these minerals in the calculation of the norm. Although small amounts of apatite are shown normatively in many rocks, it is only in the ferrogabbro where this mineral was identified in notable quantities. Small amounts of quartz are recorded both volumetrically and normatively in most units. Low down, according to both microscopical and chemical investigation, in the pyroxenite and norite units, orthopyroxene is clearly in excess of clinopyroxene, but in the gabbro unit, clinopyroxene increases whereas in the ferrogabbro, the clinopyroxene is in excess of the orthopyroxene. Volumetrically and normatively, the plagioclase and pyroxene contents compare very closely in both the pyroxenite and anorthosite units. Variation in the pyroxene and plagioclase contents in the norite and gabbro units are also reflected in both the volumetric and normative determinations. There is also a similarity in the relative magnetite content although the volumetric percentages are much lower than the normative percentages. However, the high specific

gravity of the magnetite could account for this. Microscopically, there is practically no magnetite present in the gabbro unit and up to nearly 20 per cent of magnetite is present in the ferrogabbro unit, but in the gabbro unit the normative magnetite content may be as high as nearly 5 per cent. Comparing the anorthite percentages of the plagioclase, a similar trend, in a general way, is obvious in both cases: the anorthite content becomes progressively lower in the younger rock units (higher up).

There is close correspondence between the normative and volumetric percentages of the olivine in the harzburgite unit. In the pyroxenite unit, small amounts of normative olivine are present in some samples as well as a small amount in one sample of the anorthosite unit and two of the norite unit, but no olivine was identified in the anorthosite and norite units microscopically. In the pegmatitic sub-unit, up to more than 50 per cent of olivine was normatively indicated. This analysed sample was actually from a platinum mine and although the author did not establish more than 5 per cent volumetrically in similar samples, it can at least be accepted that the olivine content may be much higher in places. No normative or volumetric olivine occurs in the gabbro unit whereas a fair amount may be present in the ferrogabbro unit. In the hortonolite dunite higher percentages of olivine are present both volumetrically and normatively. Except for the two newly analysed samples of the ferrogabbro unit, it should be remembered that the other analyses are from the literature and the rocks which were microscopically investigated were not the analysed specimens although they are of the same units, in many places as close as possible to the analysed specimens.

In Plates XXV and XXVI, the Niggli values  $al$ ,  $c$ , and  $fm$  are plotted against  $si$  (Reuning, 1930, Fig. following p. 48 E). The  $k-si$  and  $mg-si$  which indicate similar trend lines, are not shown. Tie lines link the points in the separate units to illustrate the possible differentiation trend in each one of these units, but no attempt has been made to link the units because there are gaps between some of them, and others, such as the dunite, apparently do not fit.

In all three diagrams, the harzburgite unit bridges the dunite (lowest  $si$  content) and the porphyritic pyroxenite unit. The pyroxenite unit, in turn, falls between the pegmatitic and porphyritic sub-units on the lower  $si$  side and the norite unit on the higher. In the diagrams, the field of the norite unit cuts those of the gabbro and

ferrogabbro units, with the field of the ferrogabbro unit showing the lower si content, but still clearly separated from the porphyritic and pegmatitic sub-units as well as the pyroxenite unit in fm, c, and al content. According to all three diagrams (Plates XXV and XXVI), the anorthosite unit is clearly separated from all the others by a lower fm content and higher c and al content, owing to the very low pyroxene content.

The diagrams show si increases from dunite through the harzburgite unit, porphyritic and pegmatitic sub-units, pyroxenite unit, norite unit, gabbro, and ferrogabbro units to the anorthosite unit. As it is known, for instance, that the harzburgite unit is one of the first intrusions and the dunite unit one of the last, it is clear that the sequence mentioned cannot be a normal differentiation sequence. On the other hand, the gabbro unit may be tied with the ferrogabbro unit which, in turn, can be tied up with the hortonolite dunite (to be in line with the correct chronological order). Such a trend line will, however, be cut by a pyroxenite-norite-anorthosite line. Because the emplacement of all the units followed in chronological order and each one was differentiated in place, it follows that more analytical data will reduce the gaps between units.

According to Kuno (1957, pp. 193–194), it appears that  $\text{MgO} \times 100 / \text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O}$  decreases at nearly the same rate as the amount of residual liquid of crystallizing magma decreases. This ratio serves as an index representing the degree of solidification of a magma and is termed the solidification index (SI). Oxide variation diagrams of the Skaergaard intrusion are also plotted (p. 192) and revised by Kuno (1968, p. 634). SI is actually the percentage of MgO in the MFA diagram. SI variation diagrams are plotted for the Bushveld rocks (Plate XXVII) and are discussed together with other diagrams in the next chapter.

#### B. Vanadium and Iron Content of Analysed Magnetitite

In Table IV the  $\text{Fe}_2\text{O}_3$ , FeO,  $\text{TiO}_2$ , and  $\text{V}_2\text{O}_5$  values of thirty-one analysed magnetitite samples, representing the lower, middle, and upper magnetitite bands, are given. In addition, five analyses of magnetitite from pipe-like bodies are also given.

Owing to its economic value, the vanadium in the magnetitite has become of great importance during the past few years and to-day the Bushveld magnetitite can be considered as one of the largest sources of vanadium in the world. A description

of the recovery of vanadium from Bushveld magnetitite has been published (Coertze and Schumann, 1962, p. 43).

The  $V^{3+}$ ,  $Fe^{2+}$ ,  $Fe^{3+}$  and total Fe in the 36 analysed samples were calculated and are given in Table V. In addition, the Fe : V ratios are also shown.

TABLE IV  
Chemical Analyses of Magnetitite

| Locality     |                         | No.     | $Fe_2O_3$ | FeO   | $TiO_2$ | $V_2O_5$ |
|--------------|-------------------------|---------|-----------|-------|---------|----------|
| Upper bands  | Kafferskraal 133 JQ     | GF 806  | 68.7      | 4.8   | 17.1    | 0.6      |
|              | Berseba 397 JQ          | GF 831  | 69.3      | 4.7   | 18.7    | 0.7      |
|              | Rooiwal 285 JQ          | R 14    | 59.25     | 9.19  | 16.21   | 0.4      |
|              | "                       | R 7     | 56.69     | 11.50 | 15.17   | 0.4      |
|              | "                       | R 4     | 63.40     | 9.05  | 19.26   | 0.4      |
| Middle bands | Berseba 397 JQ          | GF 830  | 62.0      | 7.1   | 23.0    | 0.3      |
|              | "                       | R 26    | 69.47     | 5.75  | 16.00   | 0.7      |
|              | Boschpoort 288 JQ       | R 24    | 67.23     | 9.19  | 14.85   | 0.5      |
|              | Rooiwal 285 JQ          | GF 805  | 62.8      | 6.8   | 18.8    | 0.8      |
|              | Wildebeestkuil 7 JQ     | FJC 448 | 43.03     | 13.15 | 18.40   | 1.04     |
|              | "                       | FJC 449 | 55.25     | 15.23 | 23.20   | 1.0      |
|              | Rooiwal 285 JQ          | GF 821  | 55.7      | 12.9  | 10.4    | 1.8      |
|              | "                       | GF 820  | 72.8      | 5.1   | 13.6    | 1.9      |
|              | "                       | GF 804  | 75.9      | 2.9   | 12.8    | 1.8      |
|              | "                       | R 2     | 70.27     | 5.75  | 12.60   | 1.1      |
| Lower bands  | Nooitgedacht 287 JQ     | GF 824  | 69.9      | 4.8   | 12.7    | 1.8      |
|              | "                       | GF 823  | 76.5      | 5.6   | 13.6    | 1.9      |
|              | "                       | GF 822  | 51.1      | 18.1  | 12.6    | 2.1      |
|              | Boschpoort 288 JQ       | GF 827  | 67.7      | 9.1   | 12.5    | 1.9      |
|              | "                       | GF 826  | 71.3      | 6.3   | 13.2    | 1.7      |
|              | "                       | GF 825  | 71.2      | 9.9   | 9.9     | 2.0      |
|              | Berseba 397 JQ          | GF 829  | 67.1      | 8.9   | 13.4    | 2.0      |
|              | "                       | GF 828  | 66.8      | 11.7  | 13.3    | 1.9      |
|              | Grootkuil 409 KQ        | FJC 439 | 67.55     | 3.59  | 19.20   | 1.6      |
|              | Spitskop 410 KQ         | FJC 440 | 62.11     | 9.34  | 17.60   | 1.81     |
|              | Syferkuil 9 JQ          | FJC 447 | 61.55     | 15.59 | 12.80   | 2.88     |
|              | Haakdoorn 6 JQ          | FJC 437 | 60.85     | 12.21 | 17.88   | 1.52     |
|              | "                       | FJC 438 | 63.50     | 5.96  | 20.28   | 1.44     |
|              | Rhenosterkraal 132 JP   | FJC 441 | 53.81     | 17.67 | 16.80   | 1.12     |
|              | "                       | FJC 451 | 58.68     | 17.89 | 12.60   | 2.80     |
|              | Wildebeestkuil 7 JQ     | FJC 450 | 64.67     | 6.47  | 19.76   | 1.44     |
| Pipes        | Goedgedacht 114 JQ      | R 22    | 55.10     | 14.37 | 24.09   | 0.2      |
|              | "                       | R 18    | 62.92     | 6.61  | 8.01    | 0.2      |
|              | "                       | R 15    | 46.31     | 24.43 | 21.32   | 0.5      |
|              | Bultfontein 259 JQ      | GF 807  | 44.6      | 15.5  | 25.9    | 1.1      |
|              | Vogelstruiskraal 400 KQ | FJC 442 | 57.17     | 16.38 | 18.92   | 1.12     |

R—Numbers: Schwellnus and Willemse, 1943, Table 1.

GF—Numbers: Samples collected by G. Fourie. Analysts: C.E.G. Schutte and C. Lessing, Division of Chemical Services, Pretoria.

FJC—numbers: Samples collected by author..Analyst: C.E.G. Schutte, Division of Chemical Services, Pretoria.

TABLE V  
Vanadium and Iron Content and Fe : V Ratios  
of Analysed Magnetite

|              |     | Percentage |                  |                  |                   |          |              | Variation   |
|--------------|-----|------------|------------------|------------------|-------------------|----------|--------------|-------------|
|              |     | No.        | V <sup>+++</sup> | Fe <sup>++</sup> | Fe <sup>+++</sup> | Total Fe | Fe : V ratio |             |
| Upper bands  | GF  | 806        | 0.34             | 3.73             | 48.02             | 51.75    | 152          | 134—<br>233 |
|              | GF  | 831        | 0.39             | 3.63             | 48.44             | 52.07    | 134          |             |
|              | R   | 14         | 0.22             | 7.14             | 41.42             | 48.56    | 221          |             |
|              | R   | 7          | 0.22             | 8.94             | 39.63             | 45.57    | 207          |             |
|              | R   | 4          | 0.22             | 7.03             | 44.32             | 51.35    | 233          |             |
| Middle bands | GF  | 830        | 0.17             | 5.52             | 43.34             | 48.86    | 289          | 69—<br>193  |
|              | R   | 26         | 0.39             | 4.47             | 48.36             | 52.83    | 135          |             |
|              | R   | 24         | 0.28             | 7.14             | 46.99             | 54.13    | 193          |             |
|              | GF  | 805        | 0.45             | 5.28             | 43.90             | 49.18    | 109          |             |
|              | FJC | 448        | 0.58             | 10.22            | 30.08             | 40.30    | 69           |             |
|              | FJC | 449        | 0.56             | 11.83            | 38.62             | 50.45    | 90           |             |
| Lower bands  | GF  | 821        | 1.01             | 10.02            | 38.93             | 48.95    | 49           | 34—<br>86   |
|              | GF  | 820        | 1.06             | 3.96             | 50.89             | 54.85    | 52           |             |
|              | GF  | 804        | 1.01             | 2.25             | 53.05             | 55.30    | 55           |             |
|              | R   | 2          | 0.62             | 4.47             | 49.12             | 53.59    | 86           |             |
|              | GF  | 824        | 1.01             | 3.73             | 48.86             | 52.59    | 52           |             |
|              | GF  | 823        | 1.06             | 4.35             | 53.47             | 57.82    | 55           |             |
|              | GF  | 822        | 1.18             | 14.06            | 35.72             | 49.78    | 42           |             |
|              | GF  | 827        | 1.06             | 7.07             | 47.32             | 54.39    | 51           |             |
|              | GF  | 826        | 0.95             | 4.90             | 49.84             | 54.74    | 58           |             |
|              | GF  | 825        | 1.12             | 7.69             | 49.77             | 57.46    | 51           |             |
|              | GF  | 829        | 1.12             | 6.92             | 46.90             | 53.82    | 48           |             |
|              | GF  | 828        | 1.06             | 9.09             | 46.69             | 55.78    | 53           |             |
|              | FJC | 439        | 0.90             | 2.79             | 47.22             | 50.01    | 56           |             |
|              | FJC | 440        | 1.01             | 7.26             | 43.42             | 50.68    | 50           |             |
|              | FJC | 447        | 1.61             | 12.11            | 43.02             | 55.13    | 34           |             |
|              | FJC | 437        | 0.85             | 9.49             | 42.53             | 53.02    | 62           |             |
|              | FJC | 438        | 0.81             | 4.63             | 44.39             | 49.02    | 61           |             |
|              | FJC | 441        | 0.63             | 13.73            | 37.61             | 51.34    | 81           |             |
|              | FJC | 451        | 1.57             | 13.90            | 40.47             | 54.37    | 35           |             |
|              | FJC | 450        | 0.81             | 5.03             | 45.20             | 50.23    | 62           |             |
| Pipes        | R   | 22         | 0.11             | 11.17            | 38.52             | 49.69    | 452          | 70—<br>452  |
|              | R   | 18         | 0.11             | 5.14             | 43.98             | 49.12    | 447          |             |
|              | R   | 15         | 0.28             | 18.98            | 32.37             | 51.35    | 148          |             |
|              | GF  | 807        | 0.62             | 12.04            | 31.18             | 43.22    | 70           |             |
|              | FJC | 442        | 0.63             | 12.73            | 39.96             | 52.69    | 82           |             |

It is clear that among the various bands, there are two distinct types of magnetite: the upper bands with an iron : vanadium ratio of 134 : 1 — 223 : 1 and the lower bands in which the ratio ranges from 34 : 1 — 86 : 1. The middle bands overlap in both directions with iron : vanadium ratios of 69 : 1 — 193 : 1. In the middle bands, GF 830 with a ratio of 289 : 1 is an exception, and this sample most probably belongs to either upper bands or to one of the pipe-like bodies. In the pipes the iron : vanadium ratio increases upwards in the sequence.

More or less similar ratios have previously been described for magnetite in the Eastern Bushveld Complex (Coertze, 1964, p. 47). The Fe : V ratios of the samples analysed show that, on the one hand, there exists very close constancy in the range 55 — 60 over the magnetite bands and pipes in the lower part of the ferrogabbro, whereas, on the other hand, a close constancy in the range 128 — 213 exists in the magnetite bands and pipes in the upper part of the ferrogabbro.

In Plate XXVIII a correlation between the percentage of vanadium and the percentage of iron is made. It seems that there exists, on an average, a sympathetic relationship between the iron and vanadium. A similar relationship for Fe : V in the chromitite is described by De Wet (1956, p. 461).

The lower magnetite bands on Krokodilkraal 426 JQ, Uitvalgrond 431 JQ, and Sjambok Syn Oude Kraal 258 JR, were investigated in detail and analysed for vanadium (Coertze, 1963 b, p. 1). These analyses are not shown in Table IV because analyses were only made for  $V_2O_5$ . There are two lower bands showing high vanadium values: an upper one, 90 to 120 centimetres thick and a lower one about 30 centimetres thick. The vanadium contents is higher in the lower band and ranges between approximately 1.90 and 1.99 per cent  $V_2O_5$ . In the higher band, it ranges between 1.37 and 1.86 per cent  $V_2O_5$ . It was also established that in the same band the  $V_2O_5$  value is higher in the lower part than in the upper part.

The significance of the differentiation phenomenon will be discussed later.

## VI. PETROGENESIS OF THE BASIC ROCKS

### A. Differentiation

According to the intrusive relations observed in the field, the basic rocks of the Bushveld Complex can be chronologically sub-divided into the following successive units: the basal norite unit, the harzburgite unit, the pyroxenite unit with chromitite seams, the anorthosite unit, the norite unit, the porphyritic pyroxenite unit, the gabbro unit, and the ferrogabbro unit in which the magnetitite seams mainly occur. Magnetitite dunite pipes may occur in any of the units mentioned and the magnetitite is considered to be one of the last intrusions.

In any attempt to discuss or explain the differentiation trend, the intrusive relations indicating the chronological order of emplacement and formation, should be kept in mind. Intrusive units which differ in average composition indicate some kind of "differentiation" before emplacement. According to Kuno (1968, p. 624), differentiation is a process by which a variety of rocks is produced from a single parental magma without incorporation of foreign material (assimilation). Fractional crystallization appears to be the principal cause of differentiation, but differentiation may take place by several different other mechanisms such as liquid immiscibility, thermodiffusion, and gaseous transfer. The differentiation trend can also be studied by means of the more important silicate minerals and by chemical analyses. Sudden changes in the trends of mineral composition and chemical composition are all confined to the contacts between successive units and never occur within one of the units.

In Plate XXIII the trends of the average compositions of clinopyroxene, orthopyroxene, plagioclase, and olivine, are shown. As far as the orthopyroxene and plagioclase are concerned, this plate must, however, not be studied without referring to Plate XVI where the trends of the compositions of the orthopyroxene and plagioclase in each one of the units are also shown. In Plate XXIII it is shown that the average composition of the clinopyroxene ranges from  $Wo_{38}En_{60}Fs_2$  in the quartz norite sub-unit and  $Wo_{34}En_{58}Fs_8$  in the marginal norite sub-unit to  $Wo_{37}En_{29}Fs_{34}$  in the ferrogabbro unit. As already mentioned, there is, however, an obvious shift towards the iron-rich member in this trend because the porphyritic pyroxenite unit follows immediately after the two sub-units mentioned instead of after the norite unit where it fits chronologically. The composition of the orthopyroxene ranges from  $Of_8$  in the harzburgite unit to

Of 41 in the ferrogabbro unit and that of the plagioclase from an average of An 80 in the first units to about An 55 in the last one. The composition of the olivine is generally close to Fo 90 in the harzburgite unit, but this mineral is not present in any quantity in the succeeding pyroxenite, norite, and gabbro units. Where it occurs in the ferrogabbro unit, its composition is close to Fo 45. Thus, discussing differentiation, it should be stressed that the compositions of the clinopyroxene, orthopyroxene, and olivine in general, become progressively more iron-rich higher up in the sequence or in the successive units and the composition of the plagioclase more sodic (Plate XXIII and Plate VI). Also in each separate unit the orthopyroxene becomes more iron-rich from base to top (Plate XVI').

In each one of these units, the compositional trend is, therefore, similar to that of the sequence as a whole. However, it is also illustrated (Plate XVI) that there are reversed shifts in the compositional trends of the orthopyroxene and plagioclase at the contacts between the successive units. The olivine in the harzburgite unit and the ferrogabbro unit also becomes more iron-rich from base to top in each one of the units. These trends indicate crystallization differentiation (crystal accumulation) after emplacement in each one of the separate units. The result of this general fractionation sequence is actually that the pyroxenes and olivines become more iron-rich and the plagioclase more sodic with increasing height in each one of the units and also in the Complex as a whole.

The chemical analyses shown in the MFA diagram (Plate XXIV), indicate that there is a general trend towards the FeO apex from the lower units to the higher ones. It is also indicated that, notwithstanding this trend, the different units are separately grouped together and that there are compositional differences between different units. Within each one of these units, a differentiation trend can be observed. The FeO : MgO ratio increases higher up except in the norite and anorthosite units where this ratio remains more or less constant, but the total alkalis increase.

The plotted Niggli values (Plate XXV and XXVI) indicate that on the whole *si* increases with decreasing *fm* and increasing *c* and *al*. However, sudden compositional shifts in the differentiation trend at the contacts between units, are also shown.

In the oxide variation diagrams (Plate XXVII) of the basic rocks of the Bushveld Complex, plotted against *SI* (Kuno's solidification index), some differentiation trends

in the units are indicated. It is known that in any fractionation trend plotted in an MFA diagram, the composition of the magma invariably changes so as to decrease the SI value as fractionation proceeds. The SI decreases more or less in the following order of units: harzburgite, pyroxenite, porphyritic pyroxenite, norite, gabbro, anorthosite, and ferrogabbro. This order does not represent the chronological order nor the normal sequence in the field. The basic magma could thus not have been a magma emplaced in one surge with subsequent fractionation to form the different units.

The  $\text{Al}_2\text{O}_3$  diagram (Plate XXVII) shows trends of increasing  $\text{Al}_2\text{O}_3$  with decreasing SI value in all the units. There is roughly one trend line from the harzburgite unit and the pyroxenite unit to the norite unit. The line in the porphyritic pyroxenite unit deviates from this one and those in the gabbro, anorthosite, and ferrogabbro units could not be tied up with any other line.

The CaO diagram shows that the trend line of increasing CaO with decreasing SI value in the harzburgite and pyroxenite units could not be tied up with that in the norite unit and the porphyritic pyroxenite units. In the MgO diagram on the other hand, there is a gap between the lines of decreasing MgO with decreasing SI value in the harzburgite and pyroxenite units. Even if in some of the oxide variation diagrams some fairly continuous trend lines are shown, such as in the  $\text{Na}_2\text{O}$  diagram, in others it is shown that there are interruptions or gaps in the trends.

Thus in each unit there is a differentiation trend (Plates XXIV, XXVII, and XVI) which, if considered cumulatively for all the units, roughly gives a general trend for the basic portion of the Bushveld Complex as a whole. This is in agreement with the intrusive nature of the separate units. That crystal fractionation took place in each one of the units, is shown by the trends in mineral composition already mentioned, and also by the fact that in the pyroxenite unit and the bands of the porphyritic pyroxenite unit (Bastard Reef for instance), the upper parts contain more plagioclase than the lower parts. Differentiation in place is also illustrated by the fact that feldspar crystals occur in the upper parts of some magnetitite bands, by magnetite-rich layers which occur at the base of the magnetitite anorthosite, and by higher vanadium values in the lower magnetitite bands or in the lower parts of these bands (Plate XXVIII).

So far one of two hypotheses of differentiation has been favoured by various authors. According to one school of thought, differentiation took place in depth and separate surges of magma of different composition were emplaced one after the other (Lombaard, 1934, p.32). According to the other school of thought, crystal fractionation after complete emplacement of the basic part of the Complex, gave rise to the various rock types (Hall, 1932, pp. 279–281).

Considering all the facts given above, it is clear that neither the one nor the other hypothesis alone can explain the diversity of rock units and rock types in the Bushveld Complex, especially in the light of what is known to-day of magma generation and emplacement.

### B. Existing Hypotheses on the Genesis of the Basic Rocks

The following is a short summary of ideas that have already been expressed on the genesis of the basic rocks.

#### 1. *Post-emplacement Differentiation in Situ*

Hall (1932, pp. 279–281) supports this hypothesis in the light of knowledge already accumulated in 1932. After the emplacement of the magma the great petrographical diversity of basic rocks was caused by differentiation *in situ* under the dominating, but not exclusive influence of gravity. Although he states that differentiation was essentially gravitative, he admits that it was not wholly so, otherwise the chromitite and magnetitite layers should be right at the bottom of the Complex.

This hypothesis, although in revised and much more detailed form, is still accepted by many workers such as Wager and Brown (1968, p. 404). They describe the history of this hypothesis, and use the term crystal fractionation (p. 1–7). Cooling of the magma would have initiated crystallization and the crystals would have sunk through the magma, aided by convection currents, sweeping crystals from the upper cooler zones to the deeper levels where the crystals would have accumulated on the floor. The process is described in detail for the Skaergaard intrusion (p. 219) which was also described by Wager and Deer in 1939 (pp. 262–289). They postulate that the significant convection currents in the magma are due to increase in density

of the magma on cooling. Cooling must have taken place mainly from the top and the cooled and partly crystallized magma along the top and walls would have had a higher specific gravity than the rest and would have sunk. Thus a convective circulation would be established in which currents descended along the walls, crossed the floor to about the centre, and then rose to the top where they would spread out to the walls again.

## 2. *Separate Intrusions*

As far back as 1927 Reuning (Hall, 1932, pp. 108–109), raised strong doubts on differentiation *in situ* and suggested the principle of successive intrusions. His conclusions are based mainly on analyses of the various rock types of the basic zone. In 1930 he stated (Hall, 1932, p. 121) that the norites, pyroxenites, and dunites belong to independent partial magmas, which must have already existed prior to their emplacement. Lombaard (1934, p. 32) is of the opinion that several heaves or influxes of magma from an intra- or subcrustal reservoir were intermittently emplaced. The magma continually changed its composition so that the successive heaves were of slightly different composition and each new heave was differentiated *in situ*.

According to Hess (1960, p. 155), differentiation in depth implies a magma chamber in depth, several times as large in volume as the basic portion of the Bushveld Complex and he considers this improbable. Willemse (1964, p. 117) thinks that evidence is still lacking to prove that the inflows of magma, at various times, differed considerably from one another.

## 3. *Extrusion*

Separate extrusive flows, one after the other, are suggested by Feringa (1959, p. 231) and supported by Cousins (1959b, p. 236). It is, however, considered that field evidence, including extensive metamorphism of the country rocks, is conclusive evidence for the intrusive nature of the layered igneous rocks. (Coertze 1959, p. 233, and 1960b, pp. 84–85). There are no signs of erosion surfaces on which extrusive magma was poured out and there are no aphanitic rocks as would have resulted from quick cooling in a surface flow.

#### 4. Transformation

Van Biljon (1949, pp. 1—175) suggests that the several basic rock types in the Bushveld Complex resulted from transformation of sediments of the Pretoria Series. He considers the Magaliesberg beds to have been transformed into pseudo-igneous rocks. Shales were transfused into norite and carbonate-rich layers into basic and ultrabasic rocks. Volatiles from lower levels converted carbonate bands into magnetite. According to him, the origin of the hydrothermal constituents is a problem, but it can be assumed that they came from the depths of the earth. The volume thereof was enhanced by  $\text{CO}_2$  from the limestone bands and the dolomite of the Transvaal System in depth.

However, detailed mapping on aerial photographs (Coertze, 1962b, pp. 67—70) and Plate I shows that the sedimentary layers differ in strike and dip from the igneous layers of the Complex north of Pretoria.

#### C. Current Ideas Regarding the Origin and Emplacement of Basaltic Magmas

The Mohorovicic discontinuity separates the crust of the earth from its mantle. It marks a major chemical discontinuity (Green, 1968, p. 839) with material of peridotitic character below. According to Kushiro and Kuno (1963, p. 76) there may be gabbro resting on this peridotitic material. Afanas'yev (1967, pp. 1513—1536) states that new data on velocities of elastic waves in rocks and minerals under pressures, anisotropism of elastic properties of monocrystals, oceanic volcanism, deep seismic profiles, isotopic composition of strontium, and distribution abundance of  $\text{Sr}^{87}$  in ancient and young rocks, tend to show that the Moho discontinuity is but an expression of the state of compaction of the rocks, devoid of any petrographic or geochemical connotations, and that the crust of the earth extends to depths exceeding 100 km (deeper than the Moho). He thinks the nature of the Moho is not known and may change from region to region and it is also unknown what exactly causes the changes in physical properties; be it change in the composition of the material or a change in the physical state of the material under the influence of pressure and temperature.

According to Smit, Hales, and Gough (1962, pp. 361–362), the most probable thickness of the crust in South Africa, calculated on the Bowie criterion and the Hales and Gough criterion, based on variance of anomalies, lies apparently between 29 and 42 km, which in general is consistent with seismic refraction results obtained by Gane and by Hales and Sacks.

Under the influence of radio-active heating, a selective melting takes place in the upper mantle (Belousov, 1964, pp. 3–5) and to-day it is believed that most basaltic magmas have originated in the upper mantle. Studies of the velocities of seismic waves in the upper mantle have shown that the velocities obtained are consistent with experimentally determined velocities for rocks ranging from peridotite to eclogite. According to Kushiro (1968, p. 619), peridotite or garnet peridotite, on the basis of petrological observations on inclusions in kimberlite and basaltic rocks, and also on peridotite in the Mid-Atlantic ridge, seems to constitute the greater part of the upper mantle. The peridotite consists probably of olivine, orthopyroxene, clinopyroxene, and garnet or spinel. It should be stressed that almost complete melting of the mantle would be required to produce basalt magma if it consisted of eclogite.

Basaltic magmas thus derive from the peridotitic upper mantle by partial melting yielding a basalt liquid and residual refractory dunite or harzburgite. There is evidence (Green, 1968, p. 839) that this possible mantle material is inhomogeneous in the proportions of major elements present. The occurrence of several equivalent mineral assemblages in mantle compositions intermediate between basalt and peridotite, means that in considering partial melting of the mantle, liquids of significantly different composition will probably be produced from the same parental material depending on the particular minerals that are present and involved in the melting (Green, 1968, pp. 850–851). The hypothesis of partial melting must recognize the existence of differing mineralogy at different depths in parental peridotite. Only future work may show whether small differences in mantle chemistry could give rise to basaltic liquids of different chemistry.

Green (1968, pp. 856–857) points out that differences in interpretation of the sequence of partial melting exemplify the speculative nature of mantle magma at the present time. Although it has been argued that basalts in general are not

derived from hydrous phases in the mantle, it is possible that small variations in water or oxygen pressure at the source of magmas could modify the course of fractional melting in ways not yet understood. It is apparent that there is little agreement on the nature of the mantle source rock which contribute directly to basaltic magma; the factors (variation in depth of melting or variation in degree of melting) that produce the varieties of basalt magmas; and the melting behaviour of individual minerals or mineral assemblage within the mantle. McGregor (1968, p. 3744) infers that different types of basaltic rock originate at different depths, the variety of compositions being brought about by changing physical conditions rather than by variations in the composition of the parental material. According to Sheynmann (1970, p. 152), different minerals pass into the liquid phase at different depths, while the composition of the same minerals changes with depth. It is unlikely that the liquid separated out in small quantities could have been separated from a magmatic slurry under the usual conditions. He states that the most likely magmas turn out to be (in the absence of water) at 7–12 kbar : aluminium-rich basalts; at 12–18 kbar : olivine tholeiite; and deeper : tholeiitic picrites.

According to Kushiro (1968, p. 631), magmas formed by the partial melting of the upper mantle, may change their compositions during the process of ascending. In the upper mantle, where magmas are generated, the temperature is close to that of the beginning of melting and fissures are not likely to exist. Zone melting would probably take place at the "ceiling" of the molten zone, since the temperature of complete melting is much higher than that of the beginning of melting. Unmelted crystals or blocks of the mantle peridotite would sink in the molten zone and accumulate at the bottom where crystallization also takes place. Kushiro calls this process of magma ascent "partial zone melting".

The composition of the magma in the molten zone would change during partial zone melting. Magmas formed at the ceiling of the molten zone will have compositions at or close to the isobaric invariant point where olivine and orthopyroxene are involved in systems. Since the position of the isobaric invariant point changes with pressure, the compositions of magmas formed at the top of the molten zone change while ascending. Pressure near the bottom is slightly higher

than that near the top, and, therefore, the compositions of the invariant points are slightly different between the top of the bottom of the molten zone.

According to Sheynmann (1970; p. 156), fusion produces a mixture of crystalline grains and liquid. However, the difference between the density of this slurry and the matrix rock is too small to create a strong upward push. If the liquid separated from the grains, much larger forces exist, the density difference can be as high as 0.3 units, and the liquid will tend to rise. He states that for a considerable amount of magma to be formed, some 30 to 40 per cent of the rock must be converted to liquid. McBirney (1970, p. 348) states that the great eruptions of basalts are related to large tensional features, but the thermodynamics of the magma generation are still not understood.

#### D. The Genesis and Emplacement of the Bushveld Magma

Since most of the Bushveld magmas were high-alumina tholeiites, whereas those from which the gabbro and ferrogabbro units formed were ordinary tholeiites, their genesis and emplacement must be considered in the framework of the origin of basaltic magmas as outlined above. Careful attention should also be paid, not only to the generation of basaltic magmas, but also to the structural setting and field relations and the differentiation already discussed.

##### *1. Structural Setting*

Visser (1957, p. xxi) states that after prolonged erosion subsequent to the Witwatersrand disturbance, the ancient geosynclinal area in the Central Transvaal became active once more. This implies that the crust had been warped downwards along an east-west axis as the formation of the Transvaal basin commenced. As sedimentation proceeded, the floor must have continued to subside and this brought about some tilting of the strata along the margins of the basin.

According to Belousov (1964, pp. 3–5), the geosyncline as a whole is probably connected with deeper processes going on in the upper mantle, although these processes are suppressed by intensive redistribution of the material in the crust. The loading of sediment in the Transvaal basin caused redistribution of

material lower down in the crust and, according to the principle of isostasy, the granite and older sedimentary areas around the basin were elevated accordingly. Although sedimentation frequently caught up with subsidence (Coertze, 1961, p. 60), the process continued and so weakened the sub-crust that volcanic outbursts took place (Visser, 1957, pp. xxxli–xxxiii), finally culminating in the magmatic activity of the Bushveld after the accumulation of more than 6000 metres of sediment and lava. According to Visser (p. xxxv), the emplacement of the basic portion can hardly be visualized as the result of a single act, but was probably a long continued and rhythmic process.

Truter (1955, p. 86) describes tensional stresses which were superseded by compression after the emplacement of the "critical zone" and, according to him, tensional conditions took over again. A description of how compression from the north and south resulted in the updoming of the older rocks before the emplacement of the ferrogabbro unit has been published (Coertze, 1958, p. 391). Feringa (1959, p. 232) states that "gentle folding" occurred in the formations which underlie the Merensky Reef. There is also evidence of folding in the basal norite unit which is not reflected in the higher pyroxenite unit and of folding in the Merensky Reef, north of Rustenburg, which is not reflected in the gabbro unit. It thus seems that rhythmically alternating conditions of tension and compression prevailed during the period of emplacement of the Bushveld Complex. Structures related to compression which are evident in certain rock units, are not present in succeeding units.

## 2. *Depth of Formation of Bushveld Magma and Time of Crystallization*

An attempt to quantitatively assess the depth of origin of the Bushveld tholeiite was made by using the theta index of Sugimura (1966, p. 341). Theta is computed according to the formula  $\Theta = \text{SiO}_2 - 47(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$ , where  $\text{SiO}_2$  is in weight per cent and the other oxides in molecular proportions. The magnitude of  $\Theta$  is an indication of depth of origin for a magma of a specific composition. This relation of Sugimura was actually used for tholeiites from volcanoes in Japan. If it also holds for the Bushveld magmas, it indicates that the original magmas of the lower units (pyroxenite, anorthosite, norite) originated at a depth range

of 41 to 49 km whereas that of the ferrogabbro unit could have been formed at about 35 km.

As it is believed that basaltic Bushveld magmas formed in the upper mantle below the Moho, the above figures seem to be in line with the figures of Smit, Hales, and Gough (1962, pp. 361–362) of between 29 and 42 km for the thickness of the crust. The shallower depth indicated for the younger ferrogabbro unit suggests that the mechanism of partial zone melting (Kushiro, 1968, p. 631) could probably have been active.

Irvine (1970, pp. 1034–1036) describes the crystallization in convecting magma and reviews in a qualitative way the relation between crystallization mechanisms and temperature in a magma body when crystal fractionation is a major process. According to his calculations (p. 1059), it would take 200,000 years to cumulate the whole layered series of the Bushveld. However, this period could have been longer if it is assumed that the magma was emplaced in more than one heave.

### 3. *Emplacement*

(a) *General* — According to Sheynmann (1970, pp. 158–159), energy flows which give rise to magmas are concentrated in relatively narrow zones above which geosynclines are located. Radio-active heating could have been the main heat source for partial fusion in the peridotitic upper mantle below the Transvaal basin. The theta index, already discussed, indicates probable melting according to the mechanism of partial zone melting, a process which started in the peridotitic upper mantle at a depth of between 41 and 49 km and continued upwards towards the crust.

Because the subcrust was already weakened owing to downwarping (Visser, 1957, p. xxxii), the magma could also have ascended because of increased magmatic pressure. This is, of course, in contrast to Wager and Brown's idea (1968, p. 204) that injection of magma to form the Skaergaard intrusion took place as a single, violent episode which filled the space, that is now the intrusion, with a uniform magma. The weakening of the subcrust could have been more pronounced where the big fault zones, such as the Rustenburg fault zone and the one trending from Brits towards the Crocodile River fragment, are located to-day. Feeders were probably guided by these zones and one could have been where the

Pilanesberg is to-day and another below the Crocodile River fragment.

During tensional conditions in the upper crust, the first of the Bushveld magmas arrived in the Transvaal basin and blocks of floor sediments, such as the Crocodile River fragment, could have been floated upwards (Verwoerd, 1963, pp. 49–66). At some stage the weight of the sediments overlying the feeders was overcome by the magma which then spread out laterally and so the path was paved for all succeeding heaves of magma to come. This level was on top of the Magaliesberg quartzite but, as can be expected with an intrusion, this quartzite was also transgressed in places. Some time later, compression took over and the inflow of magma was probably arrested and, according to structural evidence in the Complex, this rhythmic process of tension and compression was repeated several times. In the place occupied by the magma after emplacement, crystallization and crystal fractionation took place, also during the periods of compression when no new magma was added. In the meantime, however, differential fusion continued uninterrupted in the peridotitic upper mantle, but at progressively higher levels.

The mantle material could have been inhomogeneous in composition and liquids of slightly different composition could have been tapped from time to time, especially if the possibility of differing mineralogy at different depths in the parental peridotite is accepted (Green, 1968, pp. 850–851). Changing physical conditions, such as produced by different depths, could also have resulted in the formation of slightly different types of magma. Kuno (1965, pp. 317–336) draws schematic sections through central Japan and shows depths of magma production and also of magma reservoirs. He describes lateral variation of basalt magma, but states (p. 329) that different basalt magmas are produced independently and at different depths. It is believed that a combination of these factors prevailed during the formation of the Bushveld magma, but in general it is conceded that there are still differences in interpretation of the sequence of partial melting, and little agreement on the nature of minerals within the mantle source rock (Green, 1968, pp. 856–857).

The formation, emplacement, and differentiation of the magma or magmas was a process which continued for a long period with rhythmic pulses and the emplacement was regulated by conditions prevailing in the crust at the time. Intrusion of

magma actually implies the addition of new volumes of magma during which process the already accumulated portion may be disrupted in places and intrusive relations developed. Such an addition of magma also means the interruption of the existing cycle of fractional crystallization and the initiation of a new cycle as shown by mineral composition and chemistry and illustrated in the differentiation diagrams. It also implies an interruption and a possible reversal in an existing differentiation trend and the beginning of a new trend along the same lines.

Wager (1968, pp. 619–620) states that the Merensky Reef marks a strong reversal in cryptic variation, and it is believed that this is due to a major influx of new magma. Other units may have resulted from lesser influxes. Olivine is present in some layers and absent in others, especially in the western section of the Bushveld, and this may well prove to be due to a succession of influxes of new magma other than that at the Merensky Reef horizon.

The addition of new magma not only had to lift the roof of sedimentary rocks higher in order to make room, but it also spread out laterally farther than previous ones (Plate XIV and Plate I, inset).

#### (b) *Sequence*

(i) *Basal Norite Unit.* — In this unit contamination due to incorporation, mainly of Magaliesberg quartzite, took place. Its lower part actually incorporated much of the sediment in which it had been emplaced and is called the quartz norite sub-unit. In comparison with the rock units higher up, rocks of this unit are fine grained, a feature diagnostic of comparatively rapid cooling.

Apparently, a gabbroic magma was emplaced on top of the Magaliesberg quartzite and as soon as the first magma reached this “cool” environment, comparatively rapid crystallization took place, at the roof, along the walls, and on the floor, and a sheet, resembling the diabase sheets lower down in the Pretoria Series, was formed. Whether there was interruption in the emplacement of magma at this stage, is uncertain, but more magma of similar composition had been fed into the sediments at this horizon before compression took over. Under more quiet conditions and in a warmer environment, crystal fractionation started and the marginal norite sub-unit was formed. In this sub-unit, trends showing that the plagioclase

becomes more sodic and the orthopyroxene more iron-rich in ascending order, are clearly discernable (Plate XVI).

(ii) *Harzburgite and Pyroxenite Units*. — Rocks of the harzburgite unit occur only as "lenses" and "bands" in the pyroxenite unit and are actually of very limited extent. The thickest development (about 900 m) is in the far western extension where rocks of the pyroxenite unit actually invaded and disrupted rocks of the harzburgite unit. Very little magnesium-rich olivine crystallized in the basal norite unit and then only in the quartz norite sub-unit. In the marginal norite sub-unit, no olivine was formed. It thus seems that a new influx of magma was actually responsible for the formation of the harzburgite unit.

According to the MFA diagram (Plate XXIV), there could have been a normal differentiation trend from the harzburgite unit to the pyroxenite unit. On the other hand, the Niggli variation diagrams (Plates XXV and XXVI) indicate no continuity between the two units. In the Si variation diagrams (Plate XXVII), the trends in the  $\text{SiO}_2$  and MgO also indicate gaps between the two rock units.

Magnesium-rich olivines could have crystallized at depth in the feeders and this crystal mush was probably carried along in a pyroxenitic magma which followed the gabbroic magma when conditions again favoured emplacement. The olivine underwent rapid settling together with some bronzite crystals which started to form at the slight drop in temperature. As the inflow of pyroxenitic magma continued for some time, the harzburgite layers could have been disrupted and invaded in places by this magma. Kushiro (1968, pp. 632–633) states that magmas of pyroxene composition can be formed by the partial melting of the mantle peridotite and that a possible pressure range for producing magmas of the iron-free pyroxene composition is between several and 30 kb. Considering the reversal in the compositional trends of the plagioclase and the orthopyroxene (Plate XVI) at the contact between the basal norite unit and the pyroxenite unit, it indeed seems that the differentiation trend in the basal norite unit was not continued, but was interrupted by a new heave of magma of pyroxenitic composition.

Crystal fractionation continued in the pyroxenitic magma and mainly bronzite accumulated. Later plagioclase, also a cumulus mineral, crystallized from time to

time according to pressure and temperature conditions, resulting in the formation of the noritic layers in the pyroxenite unit. Finally, more and more cumulus chromite crystals were also formed and settled in layers alternating with bronzitite layers. Slumping of accumulated crystals could have disrupted some of the layers in places. Plagioclase increases at the top of this unit which is followed rather suddenly by the anorthosite unit.

(iii) *Anorthosite and Norite Units.* — Considering the intrusive relations between the anorthosite unit and the preceding pyroxenite unit, it seems as if an "anorthositic magma" must have invaded the pyroxenite unit. However, many of the inclusions in the anorthosite can be explained by other mechanisms such as slumping.

According to the composition of the plagioclase (Plates XVI and XXIII), there is a reversed shift in the compositional trend at the contact between the pyroxenite unit and the anorthosite unit. The Si variation diagram (Plate XXVII) as well as Niggli's variation diagrams (Plates XXV and XXVI) also indicates a gap. Apparently, during the last stages of crystallization of the pyroxenitic magma, when the remaining liquid was enriched in plagioclase, and chromite crystallized and accumulated on the floor, a minor influx of magma occurred. Although it shifted the compositional trend of the plagioclase towards the calcic end, it did not result in the crystallization of other minerals than plagioclase, chromite, and a little orthopyroxene. Such an influx together with accumulated crystals on the floor, could have accounted for most of the intrusive relations observed and crystal fractionation produced more chromitite bands in the anorthosite. Anorthosite can be a normal fractionation product of a gabbroic magma and could normally fit somewhere in the norite unit. However, the field relations between the norite unit, and especially the lower two bands of the anorthosite unit, lead to the mapping of the anorthosite bands as a separate unit.

Anorthosite with "interrupted" chromitite bands occurs below and on top of the norite unit (Plate III) and at both contacts the norite is intrusive into the anorthosite as already described.

The formation of the anorthosite represents the first cycle in the development

of the basic rocks in which plagioclase is the main cumulus mineral. Some plagioclase crystals accumulated on the floor, but others could have gathered at the roof or mats of the crystals could have formed at some level above the floor with magma above and below (Lauder, 1964, pp. 1100–1101). If this were possible, the intrusion of a new heave of gabbroic magma, from which the norite unit crystallized, along a level where there was still some magma left, could have resulted in identical anorthosites occurring below and above the norite unit. A mechanism such as this can account for the intrusive relations near the floor and near the roof of the norite unit where numerous inclusions of the anorthosite unit occur in the norite unit, but never norite inclusions in the anorthosite. Locally also the lower pyroxenite unit could have been invaded and inclusions of the pyroxenite unit could have been carried along. Retief (1959, pp. 78–79) explains the structures at the Dwars River bridge by the intrusion of a new magma between pyroxenite and chromitite. According to him, thin layers of chromitite were wedged from a main band. Movements before consolidation caused slumping.

If it is accepted that the anorthosite below and above was still in a plastic state during intrusion of the new magma (some interstitial liquid left between crystals), movement in the anorthosite due to the incoming magma could have disrupted chromitite bands and structures such as at Dwars River bridge (Plates VIII B and IX A) could have been formed. On the other hand, considering the heat flow, it is possible that the heat from a large volume of new magma could have remelted plagioclase at the roof, destroying the anorthosite. Going from the anorthosite unit up into the norite unit, the compositional trend in the plagioclase and orthopyroxene (Plate XVI) is, however, again shifted, indicating a possible new influx of magma.

(iv) *Porphyritic Pyroxenite Unit* — Cumulus olivine again makes its appearance in this unit. Cumulus magnesium-rich orthopyroxene with a little clinopyroxene are the other main minerals (Plate VII). There is a definite shift in the trend of the composition of the orthopyroxene at the contact between the norite unit and the porphyritic pyroxenite unit (Plates XVI and XXIII). Gaps are also indicated by the Niggli's variation diagrams (Plates XXV and XXVI) and by the two different trend lines in the SI diagram for  $Al_2O_3$  and MgO. Coupled with the large-scale and small-scale intrusive relations, the injection of a new pyroxenite magma

during tensional conditions, is suggested. It is difficult to establish whether all previous magma was already solidified or whether new magma was merely added to the remaining fluid. In places, however, thin sheets of this unit transgress older units and are indicative of sheet-like intrusions. Normal crystal fractionation followed

(v) *Gabbro Unit* — In this unit there is no clear and direct evidence of intrusion into the porphyritic pyroxenite unit or anorthosite unit below it, but there are inclusions in it of the much lower pyroxenite unit. On studying Plate XVI, it is also obvious that at the contact between the porphyritic pyroxenite unit and the gabbro unit, there is no reversed shift in the compositional trend lines for plagioclase and orthopyroxene. The An content of the plagioclase seems to decrease gradually from the porphyritic pyroxenite unit to the gabbro unit whereas the composition of the orthopyroxene actually shows a shift in the opposite direction towards iron enrichment. Apparently, the emplacement of the magma from which the gabbro unit crystallized, followed soon after that of the porphyritic pyroxenite unit without much of an interval between the two. The gabbro unit represents a long period of normal crystal fractionation.

(vi) *Ferrogabbro Unit* — Large-scale and small-scale intrusive relations between the ferrogabbro unit and the gabbro unit obviously suggest the emplacement of a large volume of new magma, probably derived from a higher level in the upper mantle. There is also a shift in mineral compositions (Plate XVI). The fractionation of the gabbro did not proceed so far that magnetite crystallized, but if there was still magma left, it should have been enriched in iron.

Interstitial magnetite occurs right from the base of the ferrogabbro unit. This in turn suggests that this magma was more or less saturated with the elements required for the crystallization of magnetite. Intermittent settling of this liquid caused the rhythmic occurrence of magnetite seams. It is also possible that the occurrence of magnetite could have been controlled by the oxygen fugacity. Grobler and Whitfield (1970, p. 226) suggest the accumulation of a residual liquid rich in iron, titanium, and phosphorus, from which the apatite-bearing

magnetitites of Villa Nora formed. According to them, this was promoted by a low oxygen fugacity of the magma. In a published discussion of the character of the magnetite "ore fluid" (Coertze 1966, pp. 44–47) the high temperature of 1591°C required to melt magnetite in the dry state is pointed out and also that it should have crystallized first, had it been in a molten form. Pressure and the presence of other silicates and vapour cause a considerable depression of the melting points and temperatures of crystallization and the magnetite was actually the last mineral to crystallize. The possibility that the iron was present as a hydrosol of ferrous hydroxide, as originally suggested by Shand, is also discussed. In connection with the apatite-rich magnetitite at Villa Nora, Cameron (Grobler and Whitfield, 1970, p. 227) stresses that Reinhard-Fisher found that in gabbroic melts containing phosphorus and fluorine, immiscibility gave rise to liquids rich in Fe or in Fe and Ti.

There is also intrusive magnetitite in the ferrogabbro, most of it in the form of pipe-like bodies. The liquid from which this magnetite crystallized, must have accumulated at lower levels and, owing to compression, must have been squirted elsewhere. The magnetitite south-west of Pilanesberg occurs along a fault-zone low down in the basic rocks. The only possible explanation for this is a body of the ferrogabbro unit somewhere in depth in which liquid accumulated from which magnetite crystallized. Perhaps there is another of the transgressive ferrograbbro structures which did not reach the surface. When the overlying rock was cut by the faults, magnetitite, apparently under conditions of compression, intruded along the fault zone.

(vii) *Basic and Ultrabasic Pipes* — The hortonolite dunite pipes and harzburgite-dunite pipes, such as the one near Brits (Plate XI), occur in all the layered units. Apart from three main groups of magma types, Sheynmann (1970, p. 156) also mentions a fourth possible group: dunite-harzburgite. He thinks that this can possibly be either the crystalline residue resulting from the melting of basic magmas or the most basic differentiate of the magma formed as result of the fusion in the mantle. There is indeed still room for experimental work because the magnesium-rich types may perhaps be explained in this way. The iron-rich types, although not part of the layered sequence, may perhaps represent a

residual liquid of the ferrogabbro unit.

### E. Conclusions

The emplacement of the Bushveld magmas took place in a series of intrusions or heaves. These magmas were probably formed in the upper mantle by partial zone melting and their emplacement was probably regulated by alternating conditions of tension and compression prevailing at the time in the crust. Emplacement took place through feeders guided by zones of weakness in the crust and two of the feeders were probably situated on the Rustenburg fault zone, where the Pilanesberg is today, and below the Crocodile River fragment.

Crystal fractionation took place in each one of the magmas and is responsible for the igneous layering. During intrusion, the incoming magma, not only lifted the roof higher, but also spread farther into the sediment resulting in a funnel-shaped structure consisting of a series of layered units with each successive one overlapping the previous one. Soon after solidification of the ferrogabbro unit, the central part was faulted downwards along the big Rustenburg fault and the sagging of the floor and tilting towards the centre of the Complex resulted in a tilted funnel-shaped structure.

Deep bore-holes through the Complex, presently planned by the Geological Survey, will make it possible to study mineral variations right across the Bushveld in uninterrupted sections. The cores of such bore-holes will also provide the opportunity for chemical analyses to indicate the possible average composition of the original magmas of each one of the units. The study of the structure of the Complex will also be facilitated by stratigraphical data from these bore-holes.

## SUMMARY

The basic portion of the western part of the Bushveld Complex, which is the main subject of this thesis, covers about 5,000 square kilometres. It is an arcuate body which actually constitutes the western outer edge of the Complex. It trends from the Crocodile River, south of Thabazimbi, in a southwesterly direction to fringe the Pilanesberg from where it swings in a southeasterly direction past Rustenburg and thins gradually towards Pretoria. From west of the Pilanesberg a lobe of the basic rocks extends towards the west up to and over the Transvaal border. Physiographically the Bushveld Complex exhibits the features of a basin : it represents a topographical unit rimmed by a girdle of relatively high ground which consists mainly of rocks of the Transvaal System.

Some 2,590 square kilometres were mapped during the period 1956–1965 and areas previously mapped by others were revised. On the basis of this mapping, a geological map of the main compartment was compiled on a scale of 1:100,000 (Plate I).

On the basis of field relations, the following eight rock units, forming the normal sequence, have been distinguished on the map: the basal norite unit, harzburgite unit, pyroxenite unit, anorthosite unit, norite unit, porphyritic pyroxenite unit, gabbro unit, and ferrogabbro unit. The first-mentioned unit is sub-divided into the quartz norite and marginal norite sub-units and the sixth unit into the porphyritic and pegmatitic sub-units.

The quartz norite sub-unit is well developed in the Rustenburg area but is absent or covered north of the Pilanesberg. The marginal norite sub-unit is followed by the pyroxenite unit with the chromitite bands of the lower group in its upper part. The pyroxenite unit does not form a continuous zone but is disrupted in six places, either by intrusive rock units or by faulting, and near Brits it disappears. The norite unit can be traced from the Crocodile River via the Pilanesberg towards Brits. The anorthosite unit occurs as bands on five horizons in and above the norite unit. The Merensky Reef, a member of the porphyritic pyroxenite unit, trends from the Crocodile River in the north to the Pilanesberg but is interrupted by the ferrogabbro unit in the northern sector. South of the Pilanesberg it is again traceable

past Rustenburg to south of Brits. A wide zone of the gabbro unit lies on top of the Merensky Reef (pegmatitic sub-unit) and associated rocks. It thins and terminates north of Pretoria. The ferrogabbro unit with the magnetite bands follows on the gabbro unit, but transgresses the lower rock units in two places north of the Pilanesberg and in the south it trends further eastwards than the gabbro unit. Pipes of magnetite-hornofite dunite and associated diallagite pegmatite are intrusive in all the layered rock units and the well-known nickel-copper sulphide pipes west of the Pilanesberg are intruded in the pyroxenite unit.

According to the floor relations the basic rocks apparently follow concordantly on the Magaliesberg quartzite of the Pretoria Series in the eastern part of the area but towards Rustenburg the basal norite unit invades this quartzite. The invasion of the Magaliesberg quartzite becomes more extensive north of Rustenburg and immediately southwest of the Pilanesberg the basal norite unit cuts through this quartzite down into the underlying shale. Quartzite and granite or granophyre are present on top of the basic rocks. The quartzite seems to grade into the granophyre but apparently the granite is intrusive into the ferrogabbro unit.

The sub-division of the basic rocks into these eight units is based on large-scale and small-scale intrusive relations. Large-scale intrusive relations are illustrated by the ferrogabbro unit north of the Pilanesberg where, in two places, it cuts across the whole sequence causing two "breaks" in which the ferrogabbro unit forms trough-like transgressive structures. North of the Pilanesberg a band of the porphyritic pyroxenite unit is found below the Merensky Reef. South of the Pilanesberg, and towards Rustenburg and Brits, a similar succession is found lower down, half way up in the norite unit, with the sequence below the Merensky Reef not developed. This phenomenon represents a transgression of the norite unit by the porphyritic pyroxenite unit. At three places the pyroxenite unit is interrupted by the norite unit so that the pyroxenite unit occurs as large "lenses" up to 16 km and more in length (Plate I). On the other hand, a large body of the porphyritic pyroxenite unit is intrusive into the basal norite unit southeast of Rustenburg.

Small-scale relations between the various units are mostly represented by inclusions of one unit in another and tongues of one cutting the other. In this way rocks of the harzburgite unit in the western extension of the Complex are includ-

ed and invaded by rocks of the pyroxenite unit. There are inclusions of the pyroxenite unit and the chromitite in the anorthosite unit and also many inclusions of the anorthosite unit in the form of flat tapering or irregular bodies in the norite unit. At many places there are inclusions of anorthosite, chromitite, and pyroxenite in the porphyritic pyroxenite unit. Pyroxenite inclusions also occur in the gabbro unit and the ferrogabbro unit contains numerous inclusions of the other rock units. Finally there are pipe-like intrusive bodies of magnetite-hortonolite dunite, in places associated with diallagite pegmatite, and the well known nickel-copper sulphide-bearing pipes which occur west of the Pilanesberg. These pipe-like bodies may occur in any of the rock units and are not part of the normal layered sequence.

Previously the structure of the Bushveld Complex was described as a lopolith. Later it was considered to consist of separate bodies associated with a series of intrusion centres. Still later, on the basis of gravity anomalies, two deep-seated curved troughs of basic rocks were postulated. The present investigation indicates that the basic portion of the western part of the Complex is a tilted funnel-shaped structure. After emplacement of all the units in the postulated funnel-shaped intrusion, with the units fitting like saucers one on another and each successive "saucer" overlapping the previous one, sagging of the floor and tilting towards the centre of the Complex resulted in a *tilted funnel-shaped structure*. Possible feeders existed where the Pilanesberg is today and below the Crocodile River fragment.

There are two major fault systems: the Rustenburg fault with its several branches, and the series of faults trending northwest past Brits. They are all normal faults and apparently represent weak zones in the crust along which movement took place in the past.

The petrography of the basic rocks is described. Published and newly determined compositions of plagioclase and orthopyroxene of the different rock units are listed. Volumetric mineralogical compositions indicate that there is more than one rock type in each one of the rock units. Compositions of the plagioclase, orthopyroxene, and clinopyroxene indicate that upwards in the sequence in each one of the units and also in the sequence as a whole the pyroxenes become more iron rich and the plagioclase more sodic. The iron content of the orthopyroxene ranges from Of 15–20 low down in the sequence in the marginal norite sub-unit to

Of 35–45 high up in the gabbro and ferrogabbro units whereas the anorthite content of the plagioclase decreases from an average of An 75–80 near the base of the marginal norite sub-unit to an average of about An 45 near the top of the ferrogabbro unit. There are, however, small displacements in the compositional trends between the succeeding units (Plates XVI and XXIII).

All available chemical analyses representing all the rock units, are listed. The ratio  $\text{MgO} : \text{FeO} : \text{total alkalies}$  is shown graphically in a MFA weight-per-cent diagram which furnishes a useful simplification of the trend of change in the magma. There is a line trending from the MgO corner towards the FeO apex and another towards the  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  corner (Plate XXIV). Fields representing the compositions of the different units are also shown. The harzburgite unit occurs near the MgO corner whereas the pyroxenite unit contains more FeO. The anorthosite unit falls near the  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  corner and the field of the norite unit extends from the pyroxenite unit towards the anorthosite unit. The gabbro unit shows more FeO which increases still further in the ferrogabbro unit. A comparison of the weight percentages of the normative minerals with the volumetric compositions of the rocks shows differences in certain respects such as normative orthoclase which was not identified microscopically. On the other hand there are also similar trends in a general way such as a lower anorthite content in the younger rock units. Niggli values, al, c, and fm are plotted against si. Tie lines link the points in the separate units to illustrate the possible differentiation trend in each one of the units. There are gaps between some of the units but more analytical data could reduce the gaps between these units. Available analyses show that there also exists, on an average, a sympathetic relationship between iron and vanadium in the magnetitite.

In any attempt to explain the differentiation trend the intrusive relations, indicating the chronological order of emplacement, should be kept in mind. Reversed shifts in the compositional trends of the plagioclase and orthopyroxene, and changes in chemical composition of rock units are confined to the contacts between successive units and never occur within one of the units. In the oxide variation diagrams plotted against SI (Kuno's solidification index), trends in the amounts of oxides such as  $\text{Al}_2\text{O}_3$ , FeO and MgO

in the units are indicated. Thus, in each unit there is a differentiation trend of increasing or decreasing oxide content, which, if considered cumulatively for all the units, roughly gives the general trend for the basic portion of the Complex as a whole. There are gaps in these trends between all units which seems to be in agreement with the intrusive nature of the separate units.

According to current ideas on the origin of basaltic magmas they are derived from the peridotitic upper mantle by partial melting. The theta index of Sugimura, who calculated depth of formation of tholeiites from volcanoes in Japan, was used on the high-alumina tholeiites and tholeiites of the Bushveld. According to this index the original magmas of the lower units (pyroxenite, anorthosite, norite) originated at a depth range of 41 to 49 km whereas that of the ferrogabbro unit could have been formed at a depth of about 35 km. The probable thickness of the crust in South Africa is between 29 and 42 km. It thus seems that the basaltic Bushveld magmas formed in the upper mantle below the Moho. Melting according to the mechanism of partial zone melting started in the peridotitic upper mantle at a depth of between 41 and 49 km and continued upwards towards the crust.

After the accumulation of more than 6,000 metres of sediment and lava in the Transvaal basin the Bushveld magmas arrived along feeders in the basin during tensional conditions. There is evidence of rhythmically alternating conditions of tension and compression which prevailed during the period of emplacement of the Complex and the magma was emplaced in several pulses. Intrusion of magma implies the addition of new volumes of magma during which process the already accumulated portion may be disrupted in places. The addition of fresh magma also means the interruption of an existing cycle of fractional crystallization and the initiation of a new cycle illustrated in the differentiation diagrams (Figs. XVI, XXV, XXVI, and XXVIII). It also implies an interruption and a possible reversal in an existing differentiation trend and the beginning of a new trend along the same lines. The addition of new magma not only lifted the roof of sedimentary rocks higher but also spread farther laterally than preceding flows.

The emplacement of the Bushveld magmas took place in a series of intrusions or heaves and feeders were guided by zones of weakness in the crust. The crystal fractionation which took place in each one of the magmas is responsible for the

igneous layering. Soon after solidification of the ferrogabbro unit, the central part of the Complex was faulted downwards along the large Rustenburg fault and the sagging of the floor and tilting towards the centre of the Complex resulted in the present tilted funnel-shaped structure.

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## APPENDIX 1.

## COMPOSITIONS OF PLAGIOCLASE AND ORTHOPYROXENE

| Rock and Stratigraphical Symbols            | Route Number (shown on plate I), Locality and/or Stratigraphical Position | Average percent-age An of Plagio-clase | Mol. per cent Of of ortho-pyroxene | Reference          |
|---------------------------------------------|---------------------------------------------------------------------------|----------------------------------------|------------------------------------|--------------------|
| Anorthosite (A1)                            | Kroondal 304 JQ                                                           | 78                                     |                                    | Fourie (1959)      |
| Anorthosite (A1)                            | "                                                                         | 80                                     |                                    |                    |
| Anorthosite (A1)                            | Klipfontein 300 JQ                                                        | 77                                     |                                    |                    |
| Anorthosite (A1)                            | Swartkop 369 KQ                                                           | 82                                     |                                    |                    |
| Anorthosite (A2)                            | Turffontein 262 JQ                                                        | 81                                     |                                    |                    |
| Anorthosite (A2)                            | Kroondal 304 JQ                                                           | 78                                     |                                    |                    |
| Anorthosite (A2)                            | Waterval 306 JQ                                                           | 79                                     |                                    |                    |
| Anorthosite (A2)                            | Brakspruit 299 JQ                                                         | 79                                     |                                    |                    |
| Anorthosite (A3)                            | Rustenburg Platinum Mine                                                  | 85                                     | 17                                 | Schmidt (1952)     |
| Anorthosite (A4)                            | "                                                                         | 76                                     |                                    |                    |
| Pegmatitic pyroxenite (Merensky Reef) (Pp3) | "                                                                         | 84-81                                  | 15                                 |                    |
| Porphyritic pyroxenite (P3)                 | "                                                                         | 84                                     | 14                                 |                    |
| Veins in Merensky Reef Anorthosite (A4)     | "                                                                         | 52                                     |                                    |                    |
|                                             | Rustenburg Platinum Mine                                                  | 79                                     |                                    | New determinations |
| Porphyritic pyroxenite (P <sub>3</sub> )    | "                                                                         | 78                                     | 17                                 |                    |
| Pegmatitic pyroxenite (Merensky Reef) (Pp3) | "                                                                         | 82                                     |                                    |                    |
| Anorthosite (A3)                            | "                                                                         | 80                                     | 19                                 |                    |
|                                             | <u>Vlakfontein borehole (below chromitite bands). 13 on Map</u>           |                                        |                                    | Schwell-nus (1939) |
| Pyroxenite (py)                             | At 105 feet depth                                                         | 77                                     | 13                                 |                    |
| "                                           | " 290 " "                                                                 | 73                                     | 13                                 |                    |
| Harzburgite (H)                             | " 620 " "                                                                 | 73                                     | 14                                 |                    |
| Contaminated rocks(Hy)                      | " 1050 " "                                                                | 78                                     | 21                                 |                    |
| "                                           | " 1200 " "                                                                | 81                                     | 33                                 |                    |
| "                                           | " 1390 " "                                                                | 72                                     | 25                                 |                    |
| "                                           | " 1680 " "                                                                | 63                                     | 23                                 |                    |
| "                                           | " 1810 " "                                                                | 69                                     | 22                                 |                    |
| "                                           | " 1990 " "                                                                | —                                      | —                                  |                    |
| Quartzite                                   | " 2000 " "                                                                | —                                      | —                                  |                    |
| Norite (N1) ?                               | " 2270 " "                                                                | 77                                     | 36                                 |                    |
| "                                           | " 2320 " "                                                                | 76                                     | 27                                 |                    |
| "                                           | " 2480 " "                                                                | 86                                     | 27                                 |                    |
| Pyroxenite (Py)                             | " 2820 " "                                                                | 79                                     | 14                                 |                    |
| "                                           | " 3050 " "                                                                | 80                                     | 14                                 |                    |

## APPENDIX 1 (continued)

| Rock and Stratigraphical Symbols          | Route Number (shown on plate I), Locality and/or Stratigraphical Position | Average percent-age An of Plagioclase | Mol. per cent Of of ortho-pyroxene | Reference                     |
|-------------------------------------------|---------------------------------------------------------------------------|---------------------------------------|------------------------------------|-------------------------------|
|                                           | <u><i>Bore-hole on Zwartklip 405 KQ (ZK 9)</i></u>                        |                                       |                                    |                               |
| Gabbro (noritic phase at base)            | At surface                                                                | 68                                    | 29                                 | Van Zyl (1960)                |
| "                                         | At 500 feet depth                                                         | 68                                    | 30                                 |                               |
| Gabbro (G)                                | " 1100 " "                                                                | 65                                    | 29                                 |                               |
| "                                         | " 1250 " "                                                                | 68                                    | 28                                 |                               |
| "                                         | " 1581 " "                                                                | 69                                    | 33                                 |                               |
| Anorthosite (A5)                          | " 1630 " "                                                                | 73                                    | —                                  |                               |
| "                                         | " 1750 " "                                                                | 78                                    | 21                                 |                               |
| "                                         | " 1794 " "                                                                | 75                                    | 19                                 |                               |
| Porphyritic pyroxenite (P4)               | " 1815 " "                                                                | 71                                    | 18                                 |                               |
| "                                         | " 1832 " "                                                                | 70                                    | 19                                 |                               |
| Anorthosite (A4)                          | " 1835 " "                                                                | 76                                    | 23                                 |                               |
| "                                         | " 1890 " "                                                                | 74                                    | 21                                 |                               |
| Porphyritic pyroxenite (P3)               | " 1912 " "                                                                | 71                                    | 19                                 |                               |
| Pegmatitic pyroxenite (Merensky Reef Pp3) | " 1940 " "                                                                | 78                                    | 19                                 |                               |
| Anorthosite (A3)                          | " 1941 " "                                                                | 78                                    | 25                                 |                               |
| "                                         | " 1998 " "                                                                | 76                                    | 19                                 |                               |
| Porphyritic pyroxenite (P2)               | " 2006 " "                                                                | 76                                    | 19                                 |                               |
| "                                         | " 2070 " "                                                                | 73                                    | 18                                 |                               |
| "                                         | " 2123 " "                                                                | 69                                    | 15                                 |                               |
| Anorthosite (A2)                          | " 2127 " "                                                                | 75                                    | 26                                 |                               |
| "                                         | " 2188 " "                                                                | 75                                    | 24                                 |                               |
| Norite (N3)                               | " 2350 " "                                                                | 73                                    | 22                                 |                               |
| "                                         | " 2500 " "                                                                | 72                                    | 19                                 |                               |
|                                           | <u><i>Route near Brits (not shown on plate I)</i></u>                     |                                       |                                    |                               |
| Ferrogabbro (F)                           | 2860' above main magnetite                                                | 48                                    |                                    | Lombaard (1934, p.29, fig. 4) |
| "                                         | 390' above main magnetite                                                 | 55                                    |                                    |                               |
| " ?                                       | 8450' above MR                                                            | 62                                    |                                    |                               |
| ?                                         | 7150' " "                                                                 | 50                                    |                                    |                               |
| ?                                         | 5850' " "                                                                 | 50                                    |                                    |                               |
| Gabbro (G)                                | 4550' " "                                                                 | 60                                    |                                    |                               |
| "                                         | 3510' " "                                                                 | 60                                    | 33                                 |                               |
| "                                         | 1950' " "                                                                 | 66                                    |                                    |                               |
| "                                         | 650' " "                                                                  | 70                                    |                                    |                               |
| Norite (N2 + N3)                          | 390' below "                                                              | 72                                    | 25                                 |                               |
| "                                         | 1560' " "                                                                 | 71                                    |                                    |                               |
| "                                         | 1950' " "                                                                 | 78                                    | 20                                 |                               |
| "                                         | 2600' " "                                                                 | 78                                    | 20                                 |                               |

## APPENDIX 1 (continued)

| Rock and Stratigraphical Symbols                                                                           | Route Number (shown on plate I), Locality and/or Stratigraphical Position | Average percentage An of Plagioclase | Mol. per cent Of orthopyroxene | Reference                  |
|------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|--------------------------------------|--------------------------------|----------------------------|
| Gabbro (G)<br>"<br>"<br>"<br>"<br>"<br>"<br>Norite (N1)<br>"<br>"<br>"<br>"                                | <u>Route 1: Bon Accord</u><br>17600' from quartzite                       | 60                                   | 40                             | Nel (1940, p.41 table III) |
|                                                                                                            | 16900' " "                                                                | 61                                   | 37                             |                            |
|                                                                                                            | 13700' " "                                                                | 66                                   | 37                             |                            |
|                                                                                                            | 12400' " "                                                                | 67                                   | 37                             |                            |
|                                                                                                            | 10200' " "                                                                | 69                                   | 37                             |                            |
|                                                                                                            | 9200' " "                                                                 | 55                                   | 40                             |                            |
|                                                                                                            | 7600' " "                                                                 | 78                                   | 49                             |                            |
|                                                                                                            | 4900' " "                                                                 | 70                                   | 24                             |                            |
|                                                                                                            | 4600' " "                                                                 | 76                                   | 22                             |                            |
|                                                                                                            | 4300' " "                                                                 | 72                                   | 18                             |                            |
|                                                                                                            | 3600' " "                                                                 | 81                                   | 19                             |                            |
|                                                                                                            | 2500' " "                                                                 | 79                                   | 21                             |                            |
| Gabbro (G)<br>"<br>"<br>"<br>"<br>Norite (N1)<br>"<br>"<br>"<br>"<br>"<br>"<br>"<br>"<br>"<br>"<br>"       | <u>Route 2: Sjambok 1</u><br>15800' from quartzite                        |                                      | 25                             | Nel (1940, p.41 table II)  |
|                                                                                                            | 14600' " "                                                                |                                      | 30                             |                            |
|                                                                                                            | 13500' " "                                                                |                                      | 34                             |                            |
|                                                                                                            | 12100' " "                                                                |                                      | 35                             |                            |
|                                                                                                            | 8400' " "                                                                 |                                      | 30                             |                            |
|                                                                                                            | 7400' " "                                                                 |                                      | 26                             |                            |
|                                                                                                            | 7000' " "                                                                 |                                      | 25                             |                            |
|                                                                                                            | 6500' " "                                                                 |                                      | 28                             |                            |
|                                                                                                            | 6200' " "                                                                 |                                      | 15                             |                            |
|                                                                                                            | 6100' " "                                                                 |                                      | 22                             |                            |
|                                                                                                            | 5900' " "                                                                 |                                      | 21                             |                            |
|                                                                                                            | 5600' " "                                                                 |                                      | 22                             |                            |
|                                                                                                            | 5200' " "                                                                 |                                      | 23                             |                            |
|                                                                                                            | 4000' " "                                                                 |                                      | 34                             |                            |
|                                                                                                            | 3700' " "                                                                 |                                      | 33                             |                            |
|                                                                                                            | 3000' " "                                                                 |                                      | 41                             |                            |
|                                                                                                            | 2600' " "                                                                 |                                      | 34                             |                            |
| Anorthosite (A3)<br>Norite (N2)<br>"<br>"<br>"<br>"<br>"<br>"<br>"<br>"<br>"<br>Norite (N1)<br>"<br>"<br>" | <u>Route 3: Sjambok II</u><br>16600' from quartzite                       | 82                                   | —                              | Nel (1940, p. 40 table, 1) |
|                                                                                                            | 15300' " "                                                                | 74                                   | 23                             |                            |
|                                                                                                            | 14400' " "                                                                | 75                                   | 30                             |                            |
|                                                                                                            | 14200' " "                                                                | 56                                   | 24                             |                            |
|                                                                                                            | 14000' " "                                                                | 55                                   | 40                             |                            |
|                                                                                                            | 13600' " "                                                                | —                                    | 28                             |                            |
|                                                                                                            | 13400' " "                                                                | 58                                   | 34                             |                            |
|                                                                                                            | 13000' " "                                                                | 80                                   | 28                             |                            |
|                                                                                                            | 11800' " "                                                                | 60                                   | 40                             |                            |
|                                                                                                            | 11500' " "                                                                | 65                                   | 40                             |                            |
|                                                                                                            | 8000' " "                                                                 | 62                                   | 40                             |                            |
|                                                                                                            | 5900' " "                                                                 | 67                                   | 26                             |                            |
|                                                                                                            | 5600' " "                                                                 | 77                                   | 21                             |                            |
|                                                                                                            | 5000' " "                                                                 | 72                                   | 24                             |                            |
|                                                                                                            | 1900' " "                                                                 | 68                                   | 40                             |                            |

## APPENDIX 1 (continued)

| Rock and Stratigraphical Symbols | Route Number (shown on plate 1), Locality and/or Stratigraphical Position | Average percent-<br>age An of<br>Plagioclase | Mol. per<br>cent Of<br>ortho-<br>pyroxene | Reference                  |
|----------------------------------|---------------------------------------------------------------------------|----------------------------------------------|-------------------------------------------|----------------------------|
|                                  | <u>Route 4</u>                                                            |                                              |                                           |                            |
| Gabbro (G)                       | 60000' north of MR                                                        | 58                                           | 42                                        | New<br>determin-<br>ations |
| "                                | 52000' " " "                                                              | 60                                           | 38                                        |                            |
| "                                | 37000' " " "                                                              | 66                                           | 35                                        |                            |
| "                                | 30000' " " "                                                              | 70                                           | 37                                        |                            |
| "                                | 23000' " " "                                                              | 65                                           | 36                                        |                            |
| "                                | 21000' " " "                                                              | 68                                           | 34                                        |                            |
| "                                | 16000' " " "                                                              | 69                                           | 30                                        |                            |
| "                                | 15000' " " "                                                              | 70                                           | 32                                        |                            |
| "                                | 13000' " " "                                                              | —                                            | 30                                        |                            |
| "                                | 10000' " " "                                                              | 75                                           | —                                         |                            |
| "                                | 9000' " " "                                                               | 64                                           | —                                         |                            |
| "                                | 6000' " " "                                                               | 65                                           | 29                                        |                            |
| "                                | 3000' " " "                                                               | 68                                           | —                                         |                            |
| Norite(N3)                       | 1000' south " "                                                           | 68                                           | 27                                        | Schwellnus<br>(1939)       |
| Norite (N2)                      | 6500' " " "                                                               | 85                                           | 18                                        |                            |
| Marginal Norite (N1)             | 15000 " " "                                                               | 75                                           | 23                                        |                            |
|                                  | <u>Route 5: Kroondal</u>                                                  |                                              |                                           |                            |
| Anorthosite (A4)                 |                                                                           | 79                                           | 22                                        | Schwellnus<br>(1939)       |
| Porphyritic pyroxenite(P3)       |                                                                           | 79                                           | —                                         |                            |
| Pegmatitic pyroxenite(Pp3)       |                                                                           | 75                                           | 18                                        |                            |
| Anorthosite (A3)                 |                                                                           | 79                                           | 23                                        |                            |
| Norite N3)                       |                                                                           | 80                                           | 18                                        |                            |
| Anorthosite (A2)                 |                                                                           | 83                                           | 21                                        |                            |
| Norite (N2)                      |                                                                           | 81                                           | 18                                        |                            |
|                                  | <u>Route 6: Rustenburg</u>                                                |                                              |                                           |                            |
| Ferrogabbro (F)                  | Just below main mag-<br>netitite                                          | 66                                           | 35                                        | Schwellnus<br>(1939)       |
| "                                | 9200' above MR                                                            | 74                                           | 25                                        |                            |
| Gabbro (G)                       | 8300' " "                                                                 | 57                                           | 37                                        |                            |
| "                                | 7420' " "                                                                 | 61                                           | 34                                        |                            |
| "                                | 6580' " "                                                                 | 61                                           | —                                         |                            |
| "                                | 5580' " "                                                                 | 63                                           | 29                                        |                            |
| "                                | 4540' " "                                                                 | 63                                           | 29                                        |                            |
| "                                | 3790' " "                                                                 | 64                                           | —                                         |                            |
| "                                | 2875' " "                                                                 | 71                                           | 28                                        |                            |
| "                                | 2200' " "                                                                 | 72                                           | 26                                        |                            |
| "                                | 1200' " "                                                                 | 68                                           | 28                                        |                            |
| "                                | 750' " "                                                                  | 68                                           | 28                                        |                            |

## APPENDIX 1 (continued)

| Rock and Stratigraphical Symbols | Route Number (shown on plate 1), Locality and/or Stratigraphical Position | Average percentage An of Plagioclase | Mol. per cent Of orthopyroxene | Reference                      |
|----------------------------------|---------------------------------------------------------------------------|--------------------------------------|--------------------------------|--------------------------------|
| Norite (N2)                      | <u>Route 7: Section III</u>                                               | 75                                   | 23                             | Fourie (1945, figs. 13 and 15) |
| "                                |                                                                           | 76                                   | 25                             |                                |
| "                                |                                                                           | 80                                   | 23                             |                                |
| Contaminated rock (Hy)           |                                                                           | —                                    | 37                             |                                |
| " "                              |                                                                           | 60                                   | 42                             |                                |
| " "                              |                                                                           | 65                                   | 32                             |                                |
| " "                              |                                                                           | 52                                   | 30                             |                                |
| " "                              |                                                                           | 51                                   | 15                             |                                |
| " "                              |                                                                           | 48                                   | 38                             |                                |
| " "                              |                                                                           | —                                    | 19                             |                                |
| " "                              |                                                                           | 63                                   | 40                             |                                |
| " "                              |                                                                           | 47                                   | 44                             |                                |
| " "                              |                                                                           | 54                                   | 47                             |                                |
| " "                              |                                                                           | 57                                   | 37                             |                                |
| Norite (N2)                      | <u>Route 8: Section II</u>                                                | 62                                   | 38                             | Fourie (1945, figs. 11 and 12) |
| "                                |                                                                           | 86                                   | 29                             |                                |
| "                                |                                                                           | 77                                   | 26                             |                                |
| "                                |                                                                           | 78                                   | 25                             |                                |
| Contaminated rock (Hy)           |                                                                           | 60                                   | 42                             |                                |
| " "                              |                                                                           | 56                                   | 41                             |                                |
| " "                              |                                                                           | 66                                   | 37                             |                                |
| " "                              |                                                                           | 55                                   | 42                             |                                |
| " "                              |                                                                           | 47                                   | 40                             |                                |
| " "                              |                                                                           | 79                                   | 44                             |                                |
| " "                              |                                                                           | 77                                   | 24                             |                                |
| " "                              |                                                                           | 78                                   | 18                             |                                |
| " "                              |                                                                           | 48                                   | 41                             |                                |
| " "                              |                                                                           | 48                                   | 34                             |                                |
| " "                              |                                                                           | 53                                   | 44                             |                                |
| " "                              |                                                                           | 52                                   | 39                             |                                |
| " "                              |                                                                           | 45                                   | 39                             |                                |
| Pyroxenite (Py)                  | <u>Route 9: Section I</u>                                                 | 77                                   | 18                             | Fourie (1945, p. 13, table II) |
| "                                |                                                                           | 83                                   | 22                             |                                |
| Contaminated rock (Hy)           |                                                                           | 78                                   | 29                             |                                |
| " "                              |                                                                           | 86                                   | —                              |                                |
| " "                              |                                                                           | 52                                   | 39                             |                                |
| " "                              |                                                                           | 80                                   | 47                             |                                |
| " "                              |                                                                           | 67                                   | 34                             |                                |
| " "                              |                                                                           | 51                                   | 22                             |                                |
| " "                              |                                                                           | 43                                   | 18                             |                                |

## APPENDIX 1 (continued)

| Rock and Stratigraphical Symbols | Route Number (shown on plate 1), Locality and/or Stratigraphical Position | Average percentage An of Plagioclase | Mol. per cent Of of orthopyroxene | Reference          |
|----------------------------------|---------------------------------------------------------------------------|--------------------------------------|-----------------------------------|--------------------|
| Pyroxenite (Py)                  | <u>Route 10: Tweelaagte</u>                                               |                                      |                                   |                    |
| "                                | 1100' above chromitite                                                    | 79                                   | 17                                |                    |
| "                                | 500' " "                                                                  | 81                                   | 15                                |                    |
| "                                | 200' " "                                                                  | 82                                   | 14                                |                    |
| "                                | 800' below "                                                              | 81                                   | 15                                | Schwellnus (1939)  |
| "                                | 1200' " "                                                                 | 83                                   | 14                                |                    |
| "                                | 2000' " "                                                                 | 79                                   | 15                                |                    |
| Pyroxenite (Py)                  | <u>Route 11: Groenfontein</u>                                             |                                      |                                   |                    |
| "                                |                                                                           |                                      | 20                                |                    |
| "                                |                                                                           |                                      | 20                                |                    |
| "                                |                                                                           |                                      | 18                                |                    |
| "                                |                                                                           |                                      | 15                                | Schwellnus (1939)  |
| "                                |                                                                           |                                      | 15                                |                    |
| "                                |                                                                           |                                      | 15                                |                    |
| "                                |                                                                           |                                      | 14                                |                    |
| "                                |                                                                           |                                      | 14                                |                    |
| Pyroxenite (Py)                  | <u>Route 12</u>                                                           |                                      |                                   |                    |
| Norite (N3)                      | Swartkop 369 KQ                                                           | 72                                   | 23                                |                    |
| Gabbro (G)                       | Near top of pyroxenite                                                    |                                      |                                   |                    |
| Ferrogabbro (F)                  | Schilpadnest 385 KQ                                                       | 75                                   | 28                                |                    |
|                                  | Near top of norite                                                        |                                      |                                   |                    |
|                                  | Schilpadnest 385 KQ.                                                      | 68                                   | 31                                | New determinations |
|                                  | Noritic phase of gabbro                                                   |                                      |                                   |                    |
|                                  | Kopje Alleen 422 KQ                                                       | 60                                   | 40                                |                    |
|                                  | Ferrogabbro between base and first magnetite                              |                                      |                                   |                    |
| Ferrogabbro (F)                  | Doornpoort 295JR: 18 on map                                               | 53                                   | 46                                |                    |
| "                                | Zeekoegat 296 JR: 17 on map                                               | 50                                   | —                                 |                    |
| "                                | Zeekoegat 296 JR; 17 on map                                               | 50                                   | 43                                |                    |
| "                                | Sjambok Zyn Oude Kraal 258 JR : 15 on map                                 | 57                                   | 40                                | New determinations |
| "                                | Rhenosterfontein 86 JQ : 14 on map                                        | —                                    | 44                                |                    |
| "                                | Rhenosterfontein 86 JQ: 14 on map                                         | 58                                   | 42                                |                    |
| "                                | Waterval 273 JR : 16 on map                                               | 42                                   | —                                 |                    |

## CHEMICAL ANALYSES, C.I.P.W. NORMS AND NIGGLI VALUES OF ROCK UNITS

A. 1. *Chemical Analyses of Harzburgite and Serpentinite*

| No.                            | 1      | 2      | 3      |
|--------------------------------|--------|--------|--------|
| SiO <sub>2</sub>               | 41.40  | 41.20  | 37.70  |
| Al <sub>2</sub> O <sub>3</sub> | 0.13   | 1.20   | 1.05   |
| Fe <sub>2</sub> O <sub>3</sub> | 4.71   | 4.00   | 10.90  |
| FeO                            | 7.41   | 8.20   | 1.30   |
| MgO                            | 42.15  | 34.40  | 35.90  |
| CaO                            | 1.32   | 1.35   | —      |
| K <sub>2</sub> O               | 0.04   | 0.30   | trace  |
| Na <sub>2</sub> O              | 0.03   | 0.20   | 1.10   |
| TiO <sub>2</sub>               | 0.80   | 0.25   | 0.05   |
| Cr <sub>2</sub> O <sub>3</sub> | 0.84   | 3.20   | 1.60   |
| MnO                            | 0.18   | 0.10   | trace  |
| P <sub>2</sub> O <sub>5</sub>  | —      | —      | 0.10   |
| NiO                            | 0.27   | 0.35   | trace  |
| Cu                             | 0.03   | —      | —      |
| S                              | 0.30   | 0.05   | —      |
| H <sub>2</sub> O <sup>+</sup>  | 0.06   | 0.25   | 0.80   |
| H <sub>2</sub> O <sup>—</sup>  | 1.24   | 5.20   | 11.15  |
| Totaal                         | 100.19 | 100.25 | 100.65 |

1. Harzburgite, Vlaktefontein 207 JP (Schwellnus, 1939, p. 14, no. 11)
2. Harzburgite, Vlaktefontein 207 JP (Wagner, 1924, p. 49, no. 1)
3. Serpentinite, Vlaktefontein 207 JP (Wagner, 1924, p. 53, no. 1)

B. 1. *Chemical Analyses of Pyroxenite*

| No.                            | 1     | 2     | 3      | 4      | 5      | 6      |
|--------------------------------|-------|-------|--------|--------|--------|--------|
| SiO <sub>2</sub>               | 53.00 | 52.00 | 55.30  | 52.86  | 54.49  | 54.05  |
| Al <sub>2</sub> O <sub>3</sub> | 5.98  | 10.02 | 2.20   | 7.41   | 1.12   | 2.84   |
| Fe <sub>2</sub> O <sub>3</sub> | 2.56  | 0.93  | 0.45   | 0.95   | 1.09   | 1.20   |
| FeO                            | 8.62  | 7.50  | 10.05  | 8.05   | 8.65   | 9.12   |
| MgO                            | 24.41 | 20.60 | 29.80  | 20.88  | 30.50  | 28.20  |
| CaO                            | 4.21  | 6.05  | 1.80   | 6.28   | 2.13   | 2.60   |
| K <sub>2</sub> O               | —     | 0.08  | trace  | 0.12   | —      | —      |
| Na <sub>2</sub> O              | 0.31  | 0.56  | 0.30   | 1.00   | 0.10   | 0.36   |
| TiO <sub>2</sub>               | 0.30  | 0.18  | 0.10   | 0.40   | 0.99   | 0.88   |
| Cr <sub>2</sub> O <sub>3</sub> | —     | —     | —      | 0.04   | 0.25   | 0.20   |
| MnO                            | 0.20  | —     | 0.15   | 0.17   | 0.14   | 0.14   |
| P <sub>2</sub> O <sub>5</sub>  | —     | —     | 0.20   | trace  | 0.02   | 0.02   |
| NiO                            | —     | —     | 0.20   | —      | —      | —      |
| CO <sub>2</sub>                | —     | —     | —      | 0.136  | —      | —      |
| H <sub>2</sub> O <sup>+</sup>  | 0.28  | —     | —      | 0.61   | 0.62   | 0.94   |
| H <sub>2</sub> O <sup>-</sup>  | 0.11  | 1.21  | 0.10   | 0.07   | —      | 0.04   |
| Total                          | 99.98 | 99.13 | 100.65 | 100.20 | 100.10 | 100.59 |

1. West of Bokfontein 448 JQ (Van Biljon, 1949, p. 137)
2. Kroondal 304 JQ (Liebenberg, 1961, pp. 66–67)
3. Vlakfontein 207 JP (Wagner, 1924, p. 44)
4. Derdepoort 326 JR (Van Biljon, 1949, p. 137)
5. Davidskuil 167 JP (Schwellnus, 1939, p. 28)
6. Tweelaagte 175 JP (Schwellnus, 1939, p. 28)

C. 1. *Chemical analyses of Anorthosite*

| No.                            | 1     | 2      | 3      | 4      | 5     |
|--------------------------------|-------|--------|--------|--------|-------|
| SiO <sub>2</sub>               | 45.72 | 47.75  | 48.61  | 48.33  | 47.33 |
| Al <sub>2</sub> O <sub>3</sub> | 34.51 | 30.24  | 32.45  | 30.87  | 32.01 |
| Fe <sub>2</sub> O <sub>3</sub> | 0.70  | 2.40   | 0.65   | 0.89   | 0.10  |
| FeO                            | 0.08  | 0.42   | 0.54   | 0.93   | 0.69  |
| MgO                            | 0.79  | 1.51   | 1.03   | 1.78   | 0.58  |
| CaO                            | 15.40 | 14.85  | 14.90  | 14.95  | 14.96 |
| K <sub>2</sub> O               | 0.12  | 0.16   | 0.68   | 0.13   | 0.74  |
| Na <sub>2</sub> O              | 1.64  | 2.28   | 2.33   | 2.04   | 1.93  |
| TiO <sub>2</sub>               | 0.04  | 0.10   | —      | 0.53   | 0.17  |
| Cr <sub>2</sub> O <sub>3</sub> | —     | —      | 0.10   | 0.10   | —     |
| MnO                            | —     | —      | trace  | trace  | 0.03  |
| P <sub>2</sub> O <sub>5</sub>  | —     | —      | 0.02   | 0.03   | 0.12  |
| F                              | —     | —      | 0.10   | —      | —     |
| CO <sub>2</sub>                | —     | —      | —      | —      | 0.20  |
| H <sub>2</sub> O <sup>+</sup>  |       |        | 0.39   | 0.55   | 0.70  |
|                                | 0.55  | 0.52   |        |        |       |
| H <sub>2</sub> O <sup>-</sup>  |       |        | 0.04   | 0.10   | 0.04  |
| Total                          | 99.55 | 100.23 | 101.74 | 100.83 | 99.60 |

1. Kroondal 304 JQ (Liebenberg, 1961, p. 68–69)
2. Turffontein 262 JQ (Liebenberg, , 1961, p. 68–69)
3. Vogelstruisnek 173 JP (Van Biljon, 1949, p. 152)
4. " " " " " " "
5. Zwartklip 405 KQ (Van Zyl, 1960, p. 79)

D. 1. *Chemical Analyses of Norite*

| No.                            | 1     | 2      | 3      | 4     | 5      | 6     |
|--------------------------------|-------|--------|--------|-------|--------|-------|
| SiO <sub>2</sub>               | 50.70 | 54.10  | 52.62  | 49.97 | 51.27  | 52.07 |
| Al <sub>2</sub> O <sub>3</sub> | 17.90 | 3.43   | 12.52  | 22.17 | 17.47  | 14.07 |
| Fe <sub>2</sub> O <sub>3</sub> | 1.30  | 0.79   | 0.96   | 1.06  | 1.27   | 1.86  |
| FeO                            | 5.80  | 11.57  | 7.87   | 3.04  | 5.80   | 5.58  |
| MgO                            | 10.40 | 25.25  | 17.44  | 6.10  | 11.50  | 13.64 |
| CaO                            | 9.80  | 3.19   | 6.50   | 13.64 | 10.10  | 7.68  |
| K <sub>2</sub> O               | 0.30  | 0.05   | 0.14   | 1.11  | 0.10   | 0.68  |
| Na <sub>2</sub> O              | 2.00  | 0.43   | 1.11   | 1.71  | 1.30   | 1.56  |
| TiO <sub>2</sub>               | 0.20  | 1.03   | 0.77   | 0.47  | 0.40   | 0.69  |
| Cr <sub>2</sub> O <sub>3</sub> | —     | 0.15   | 0.35   | —     | —      | —     |
| MnO                            | —     | 0.14   | 0.10   | 0.11  | 0.14   | 0.13  |
| P <sub>2</sub> O <sub>5</sub>  | 0.05  | 0.02   | 0.03   | 0.12  | 0.04   | 0.06  |
| CO <sub>2</sub>                | —     | —      | —      | 0.34  | —      | 0.36  |
| H <sub>2</sub> O <sup>+</sup>  | 1.00  | 0.35   | 0.25   | 0.10  | 0.50   | 1.10  |
| H <sub>2</sub> O <sup>-</sup>  | 0.03  | —      | 0.10   | 0.02  | 0.06   | 0.01  |
| Total                          | 99.48 | 100.50 | 100.76 | 99.96 | 100.22 | 99.49 |

1. Palmietfontein 208 JP (Hall, 1932, p. 304, no. III)
3. Vogelstruisnek 173 JP (Schwellnus, 1939, p. 29, no. XVIII)
3. Vogelstruisnek 173 JP (Schwellnus, 1939, p. 29, no. XIX)
4. Zwartklip 405 KQ (Van Zyl, 1961, p. 78, table 10, no. Z165)
5. Marginal norite, Wolhuterskop, Boschfontein 458 JQ (Van Biljon, 1949, p.124.
6. Marginal norite, Wildebeesthoek 310 JR (Nel, 1940, p. 45, no. a)

E. 1. *Chemical Analyses of Pegmatitic Pyroxenite and Porphyritic Pyroxenite*

| No.                            | 1      | 2      | 3      | 4      | 5      |
|--------------------------------|--------|--------|--------|--------|--------|
| SiO <sub>2</sub>               | 49.55  | 46.16  | 36.35  | 52.18  | 52.75  |
| Al <sub>2</sub> O <sub>3</sub> | 8.04   | 7.25   | 4.01   | 7.31   | 4.69   |
| Fe <sub>2</sub> O <sub>3</sub> | 8.87   | 2.17   | 7.44   | 3.31   | 4.26   |
| FeO                            | 2.47   | 10.42  | 6.32   | 6.79   | 6.40   |
| MgO                            | 17.40  | 26.15  | 30.18  | 21.96  | 26.10  |
| CaO                            | 6.30   | 4.15   | 2.52   | 5.24   | 3.60   |
| K <sub>2</sub> O               | 1.30   | 0.66   | 0.80   | 1.49   | 1.09   |
| Na <sub>2</sub> O              |        | 0.68   | 0.65   | 0.65   | 0.26   |
| TiO <sub>2</sub>               | 0.36   | 0.34   | 0.24   | 0.55   | 0.50   |
| Cr <sub>2</sub> O <sub>3</sub> | 1.50   |        |        |        |        |
| MnO                            | 0.20   | 0.16   | 0.19   | 0.23   | 0.22   |
| P <sub>2</sub> O <sub>5</sub>  | 1.40   | 0.20   | 0.16   | 0.12   | 0.11   |
| CO <sub>2</sub>                | 1.35   | 0.97   | 0.89   | 0.41   | 0.34   |
| S                              | 0.63   |        |        |        |        |
| As                             | 0.06   |        |        |        |        |
| Sb                             | 0.10   |        |        |        |        |
| Ni                             | 0.30   |        |        |        |        |
| Cu                             | 0.20   |        |        |        |        |
| H <sub>2</sub> O <sup>+</sup>  | —      | 0.65   | 10.24  | 0.15   | 0.22   |
| H <sub>2</sub> O <sup>-</sup>  | —      | 0.05   | 0.28   | 0.01   | 0.02   |
| Total                          | 100.03 | 100.01 | 100.45 | 100.40 | 100.56 |

1. Pegmatitic pyroxenite, Merensky Reef, Klipfontein (Wagner, 1929, p. 119)
2. " " " " , Swartklip (Van Zyl, 1960, p. 78, table 10, no. Z1046).
3. Pegmatitic pyroxenite 69 ft. below Merensky Reef, Swartklip (Van Zyl, 1960, p. 78, table 10, no. Z295).
4. Porphyritic pyroxenite, immediately above Merensky Reef, Swartklip (Van Zyl, 1960, p. 78, table 10, no. Z280)
5. Porphyritic pyroxenite, Bastard Reef, Swartklip (Van Zyl, 1960, p. 78, table 10, no. Z257)

## F. 1. Chemical Analyses of Gabbro and Ferrogabbro

| No.                            | 1      | 2     | 3     | 4      | 5      | 6      |
|--------------------------------|--------|-------|-------|--------|--------|--------|
| SiO <sub>2</sub>               | 52.48  | 52.70 | 51.03 | 50.45  | 39.91  | 47.08  |
| Al <sub>2</sub> O <sub>3</sub> | 16.95  | 21.05 | 15.79 | 27.40  | 16.40  | 13.07  |
| Fe <sub>2</sub> O <sub>3</sub> | 1.62   | 0.50  | 2.16  | 1.10   | 9.76   | 4.83   |
| FeO                            | 6.68   | 5.80  | 7.04  | 1.55   | 12.53  | 11.84  |
| MgO                            | 7.50   | 4.20  | 7.18  | 0.15   | 5.47   | 6.48   |
| CaO                            | 11.06  | 12.60 | 11.55 | 12.90  | 9.21   | 11.47  |
| K <sub>2</sub> O               | 0.30   | 0.30  | 0.56  | 0.50   | 0.49   | 0.27   |
| Na <sub>2</sub> O              | 2.50   | 2.10  | 1.93  | 3.83   | 2.33   | 2.22   |
| TiO <sub>2</sub>               | 0.56   | 0.15  | 0.84  | 0.10   | 2.53   | 1.93   |
| Cr <sub>2</sub> O <sub>3</sub> | —      | —     | 0.01  | —      | 0.02   | 0.02   |
| MnO                            | 0.22   | —     | 0.20  | 0.20   | 0.16   | 0.22   |
| P <sub>2</sub> O <sub>5</sub>  | 0.10   | 0.20  | 0.07  | 0.05   | 0.03   | 0.17   |
| CO <sub>2</sub>                | —      | trace | —     | —      | 0.05   | 0.08   |
| H <sub>2</sub> O <sup>+</sup>  | 0.30   | 0.05  | 1.12  | 2.10   | 1.22   | 0.62   |
| H <sub>2</sub> O <sup>-</sup>  | 0.07   | —     | —     | 0.55   | 0.05   | 0.03   |
| Total                          | 100.34 | 99.65 | 99.48 | 100.90 | 100.16 | 100.33 |

1. Gabbro, Bon Accord (Lombaard, 1932, p. 165)
2. Gabbro, Bon Accord (Hall, 1932, p. 304, no. 1)
3. Gabbro, Doornpoort 295 JR (Van Biljon, 1949, p. 131, no. 7)
4. Anorthositic ferrogabbro, immediately below magnetitite, Mamagalies Kraal (Hall, 1932, p.334.)
5. Ferrogabbro, F.J.C. 681, Rhenosterfontein 86 JQ ) Analyst: C.E. Austen,  
Government Metallurgical Laboratory
6. Ferrogabbro, F.J.C. 682, Rhenosterfontein 86 JQ )

## G.1. Chemical Analyses of Hortonolite Dunite

| No.                            | 1     | 2     | 3     |
|--------------------------------|-------|-------|-------|
| SiO <sub>2</sub>               | 27.45 | 32.50 | 32.16 |
| Al <sub>2</sub> O <sub>3</sub> | 1.32  | 1.00  | 4.17  |
| Fe <sub>2</sub> O <sub>3</sub> | 9.50  | 7.40  | 4.80  |
| FeO                            | 42.15 | 36.80 | 38.75 |
| MgO                            | 13.20 | 12.90 | 15.36 |
| CaO                            | 0.83  | 3.84  | 1.96  |
| K <sub>2</sub> O               | 0.01  | 0.01  | —     |
| Na <sub>2</sub> O              | 0.06  | 0.08  | 1.25  |
| TiO <sub>2</sub>               | 3.97  | 3.18  | 0.95  |
| Cr <sub>2</sub> O <sub>3</sub> | —     | —     | —     |
| MnO                            | —     | —     | 0.37  |
| P <sub>2</sub> O <sub>5</sub>  | —     | —     | —     |
| S                              | —     | —     | —     |
| CO <sub>2</sub>                | —     | —     | —     |
| H <sub>2</sub> O <sup>+</sup>  | —     | —     | —     |
| H <sub>2</sub> O <sup>-</sup>  | 0.50  | 1.42  | —     |
| Total                          | 98.99 | 99.13 | 99.77 |

1. Bultfontein 259 JQ (Liebenberg, 1961, pp. 72–73)
2. Vaalkop 275 JQ (Liebenberg, 1961, pp. 72–73).
3. Middellaagte 382 KQ (De Bruyn, 1944, p. 92)

## A.2. C.I.P.W. Norms of Harzburgite and Serpentinite

| No.              | 1      | 2      | 3      |
|------------------|--------|--------|--------|
| Orthoclase       | 0.236  | 1.771  | 0.0    |
| Albite           | 0.254  | 1.691  | 5.396  |
| Anorthite        | 0.102  | 1.489  | 0.0    |
| Diopside         | 5.058  | 4.098  | 0.0    |
| Hypersthene      | 16.114 | 30.161 | 18.198 |
| Olivine          | 66.587 | 44.480 | 49.899 |
| Acmite           | 0.0    | 0.0    | 3.441  |
| Magnetite        | 6.842  | 5.811  | 1.611  |
| Ilmenite         | 1.622  | 0.507  | 0.101  |
| Hematite         | 0.0    | 0.0    | 8.618  |
| Apatite          | 0.0    | 0.0    | 0.219  |
| H <sub>2</sub> O | 1.300  | 5.450  | 11.950 |
| Pyrite           | 0.561  | 0.094  | 0.0    |
| Total            | 98.675 | 95.551 | 99.433 |

## B.2. C.I.P.W. Norms of Pyroxenite

| No.              | 1       | 2       | 3       | 4      | 5      | 6       |
|------------------|---------|---------|---------|--------|--------|---------|
| Quartz           | 0.892   | 0.154   | 0.0     | 0.0    | 0.0    | 0.0     |
| Orthoclase       | 0.0     | 0.472   | 0.0     | 0.708  | 0.0    | 0.0     |
| Albite           | 2.621   | 4.734   | 2.536   | 8.454  | 0.845  | 3.043   |
| Anorthite        | 14.914  | 24.572  | 4.653   | 15.364 | 2.605  | 6.129   |
| Diopside         | 4.738   | 4.319   | 2.467   | 12.581 | 6.210  | 5.277   |
| Hypersthene      | 72.130  | 61.953  | 84.619  | 56.859 | 84.797 | 79.643  |
| Olivine          | 0.0     | 0.0     | 4.984   | 1.979  | 1.149  | 1.763   |
| Magnetite        | 3.719   | 1.351   | 0.654   | 1.380  | 1.583  | 1.743   |
| Ilmenite         | 0.608   | 0.365   | 0.203   | 0.811  | 2.007  | 1.784   |
| Apatite          | 0.0     | 0.0     | 0.437   | 0.0    | 0.044  | 0.044   |
| H <sub>2</sub> O | 0.390   | 2.420   | 0.100   | 0.680  | 0.620  | 0.980   |
| Total            | 100.013 | 100.341 | 100.652 | 98.816 | 99.861 | 100.406 |

*C.2. C.I.P.W. Norms of Anorthosite*

| No.              | 1       | 2       | 3       | 4       | 5      |
|------------------|---------|---------|---------|---------|--------|
| Quartz           | 1.539   | 0.203   | 0.0     | 1.345   | 0.215  |
| Orthoclase       | 0.708   | 0.944   | 4.014   | 0.767   | 4.368  |
| Albite           | 13.865  | 19.275  | 19.698  | 17.246  | 16.316 |
| Anorthite        | 76.341  | 71.753  | 73.013  | 73.934  | 73.455 |
| Corundum         | 3.685   | 0.0     | 1.103   | 0.257   | 1.094  |
| Diopside         | 0.0     | 1.450   | 0.0     | 0.0     | 0.0    |
| Hypersthene      | 1.967   | 3.088   | 0.135   | 4.443   | 2.404  |
| Olivine          | 0.0     | 0.0     | 1.986   | 0.0     | 0.0    |
| Magnetite        | 0.142   | 1.066   | 0.944   | 1.293   | 0.145  |
| Ilmenite         | 0.081   | 0.203   | 0.0     | 1.075   | 0.345  |
| Hematite         | 0.603   | 1.669   | 0.0     | 0.0     | 0.0    |
| Apatite          | 0.0     | 0.0     | 0.047   | 0.066   | 0.262  |
| H <sub>2</sub> O | 1.100   | 1.040   | 0.430   | 0.650   | 0.740  |
| Fluorite         | 0.0     | 0.0     | 0.202   | 0.0     | 0.0    |
| Total            | 100.032 | 100.692 | 101.572 | 101.076 | 99.344 |

D.2. *C.I.P.W. Norms of Norite*

| No.              | 1      | 2       | 3       | 4      | 5      | 6      |
|------------------|--------|---------|---------|--------|--------|--------|
| Quartz           | 0.0    | 0.147   | 0.907   | 0.0    | 2.249  | 2.005  |
| Orthoclase       | 1.771  | 0.295   | 0.826   | 6.552  | 0.590  | 4.014  |
| Albite           | 16.908 | 3.635   | 9.384   | 14.456 | 10.990 | 13.188 |
| Anorthite        | 38.950 | 7.276   | 28.745  | 49.502 | 41.507 | 29.359 |
| Diopside         | 7.500  | 6.738   | 2.638   | 13.901 | 6.672  | 6.654  |
| Hypersthene      | 26.987 | 78.684  | 54.442  | 11.423 | 34.647 | 38.620 |
| Olivine          | 3.281  | 0.0     | 0.0     | 0.914  | 0.0    | 0.0    |
| Magnetite        | 1.889  | 1.148   | 1.395   | 1.540  | 1.845  | 2.702  |
| Ilmenite         | 0.406  | 2.088   | 1.561   | 0.953  | 0.811  | 1.399  |
| Apatite          | 0.109  | 0.044   | 0.066   | 0.262  | 0.087  | 0.131  |
| H <sub>2</sub> O | 1.030  | 0.350   | 0.350   | 0.120  | 0.560  | 1.110  |
| Total            | 98.831 | 100.405 | 100.313 | 99.624 | 99.960 | 99.182 |

**E.2. C.I.P.W. Norms of Pegmatitic Pyroxenite and Porphyritic Pyroxenite**

| No.              | 1         | 2      | 3      | 4       | 5       |
|------------------|-----------|--------|--------|---------|---------|
| Orthoclase       | Not       | 3.896  | 4.722  | 8.794   | 6.434   |
| Abite            | calculat- | 5.749  | 5.495  | 5.495   | 2.198   |
| Anorthite        | ed        | 14.770 | 5.657  | 12.619  | 8.405   |
| Diopside         |           | 3.692  | 4.627  | 10.021  | 6.936   |
| Hypersthene      |           | 29.603 | 4.850  | 50.777  | 66.377  |
| Olivine          |           | 36.381 | 51.903 | 5.996   | 2.250   |
| Magnetite        |           | 3.152  | 10.808 | 4.809   | 6.189   |
| Ilmenite         |           | 0.689  | 0.487  | 1.115   | 1.014   |
| Apatite          |           | 0.437  | 0.350  | 0.262   | 0.240   |
| H <sub>2</sub> O |           | 0.700  | 10.520 | 0.160   | 0.240   |
| Total            |           | 99.070 | 99.419 | 100.047 | 100.282 |

F.2. *C.I.P.W. Norms of Gabbro and Ferrogabbro*

| No.              | 1       | 2      | 3      | 4       | 5       | 6       |
|------------------|---------|--------|--------|---------|---------|---------|
| Quartz           | 1.769   | 5.094  | 2.982  | 0.0     | 0.0     | 0.0     |
| Orthoclase       | 1.771   | 1.771  | 3.305  | 2.951   | 2.892   | 1.594   |
| Albite           | 21.135  | 17.754 | 16.316 | 30.555  | 18.819  | 18.768  |
| Anorthite        | 34.117  | 47.090 | 32.743 | 55.964  | 32.819  | 24.882  |
| Nepheline        | 0.0     | 0.0    | 0.0    | 1.080   | 0.476   | 0.0     |
| Diopside         | 16.356  | 11.737 | 19.599 | 4.838   | 10.411  | 25.587  |
| Hypersthene      | 21.142  | 14.644 | 18.472 | 0.0     | 0.0     | 15.475  |
| Wollastonite     | 0.0     | 0.0    | 0.0    | 0.892   | 0.0     | 0.0     |
| Olivine          | 0.0     | 0.0    | 0.0    | 0.0     | 14.326  | 2.189   |
| Magnetite        | 2.353   | 0.726  | 3.138  | 1.598   | 14.179  | 7.017   |
| Ilmenite         | 1.135   | 0.304  | 1.703  | 0.203   | 5.130   | 3.913   |
| Apatite          | 0.219   | 0.437  | 0.153  | 0.109   | 0.066   | 0.371   |
| H <sub>2</sub> O | 0.370   | 0.050  | 1.120  | 2.650   | 1.270   | 0.650   |
| Total            | 100.368 | 99.607 | 99.532 | 100.841 | 100.387 | 100.445 |

G.2. C.I.P.W. Norms of Hortonolite Dunite

| No.              | 1       | 2       | 3      |
|------------------|---------|---------|--------|
| Orthoclase       | 0.059   | 0.059   | 0.0    |
| Albite           | 0.507   | 0.676   | 0.0    |
| Anorthite        | 3.300   | 2.338   | 5.763  |
| Nepheline        | 0.0     | 0.0     | 5.727  |
| Diopside         | 0.689   | 14.090  | 1.060  |
| Hypersthene      | 4.719   | 12.450  | 0.0    |
| Olivine          | 67.898  | 51.325  | 77.618 |
| Magnetite        | 13.801  | 10.750  | 6.973  |
| Ilmenite         | 8.049   | 6.448   | 1.926  |
| H <sub>2</sub> O | 1.000   | 2.840   | 0.0    |
| Total            | 100.023 | 100.976 | 99.068 |

A.3. | *Niggli values of Harzburgite and Serpentinite*

| No.                           | 1       | 2       | 3       |
|-------------------------------|---------|---------|---------|
| si                            | 54.406  | 64.618  | 58.470  |
| sil                           | 100.294 | 102.417 | 104.533 |
| al                            | 0.103   | 1.109   | 0.960   |
| fm                            | 97.919  | 96.018  | 97.386  |
| c                             | 1.905   | 2.269   | 0.0     |
| alk                           | 0.074   | 0.604   | 1.654   |
| mg                            | 0.864   | 0.837   | 0.852   |
| c/fm                          | 0.019   | 0.024   | 0.0     |
| K                             | 0.467   | 0.497   | 0.0     |
| TiO <sub>2</sub>              | 0.810   | 0.295   | 0.058   |
| P <sub>2</sub> O <sub>5</sub> | 0.0     | 0.0     | 0.066   |
| H <sub>2</sub> O              | 0.269   | 1.308   | 4.137   |
| S                             | 0.757   | 0.147   | 0.0     |
| qz                            | -45.888 | -37.799 | -46.063 |

B.3. *Niggli Values of Pyroxenite*

| No.                           | 1       | 2       | 3       | 4       | 5       | 6       |
|-------------------------------|---------|---------|---------|---------|---------|---------|
| si                            | 98.112  | 102.656 | 97.361  | 103.950 | 96.158  | 97.414  |
| sil                           | 102.225 | 104.690 | 102.048 | 108.228 | 100.684 | 102.516 |
| al                            | 6.524   | 11.658  | 2.283   | 8.588   | 1.165   | 3.017   |
| fm                            | 84.569  | 74.372  | 93.809  | 76.122  | 94.637  | 91.333  |
| c                             | 8.351   | 12.798  | 3.396   | 13.233  | 4.028   | 5.021   |
| alk                           | 0.556   | 1.173   | 0.512   | 2.057   | 0.171   | 0.629   |
| mg                            | 0.796   | 0.815   | 0.834   | 0.804   | 0.848   | 0.829   |
| c/fm                          | 0.099   | 0.172   | 0.036   | 0.174   | 0.043   | 0.055   |
| K                             | 0.0     | 0.086   | 0.0     | 0.073   | 0.0     | 0.0     |
| TiO <sub>2</sub>              | 0.418   | 0.267   | 0.132   | 0.592   | 1.314   | 1.193   |
| P <sub>2</sub> O <sub>5</sub> | 0.0     | 0.0     | 0.149   | 0.0     | 0.015   | 0.015   |
| H <sub>2</sub> O              | 1.728   | 7.965   | 0.0     | 4.000   | 3.648   | 5.649   |
| CO <sub>2</sub>               | 0.0     | 0.0     | 0.0     | 0.376   | 0.0     | 0.0     |
| qz                            | -4.113  | -2.035  | -4.687  | -4.278  | -4.527  | -5.102  |

C.3. *Niggli Values of Anorthosite*

| No. .                         | 1       | 2       | 3       | 4       | 5       |
|-------------------------------|---------|---------|---------|---------|---------|
| si                            | 113.514 | 118.035 | 120.745 | 119.708 | 122.047 |
| sil                           | 116.550 | 122.865 | 126.754 | 120.416 | 124.168 |
| al                            | 50.496  | 44.055  | 47.504  | 45.063  | 48.646  |
| fm                            | 4.397   | 10.896  | 6.150   | 10.156  | 3.977   |
| c                             | 40.969  | 39.333  | 39.658  | 39.677  | 41.335  |
| alk                           | 4.138   | 5.716   | 6.688   | 5.104   | 6.042   |
| mg                            | 0.665   | 0.511   | 0.620   | 0.647   | 0.561   |
| c/fm                          | 9.317   | 3.610   | 6.449   | 3.907   | 10.395  |
| K                             | 0.046   | 0.044   | 0.161   | 0.040   | 0.201   |
| TiO <sub>2</sub>              | 0.075   | 0.186   | 0.0     | 0.987   | 0.330   |
| P <sub>2</sub> O <sub>5</sub> | 0.0     | 0.0     | 0.021   | 0.031   | 0.131   |
| H <sub>2</sub> O              | 4.554   | 4.286   | 3.230   | 4.543   | 6.019   |
| CO <sub>2</sub>               | 0.0     | 0.0     | 0.0     | 0.0     | 0.704   |
| qz                            | -3.037  | -4.830  | -6.008  | -0.708  | -2.121  |

D.3. *Niggli Values of Norite*

| No.                           | 1       | 2       | 3       | 4       | 5       | 6       |
|-------------------------------|---------|---------|---------|---------|---------|---------|
| si                            | 112.495 | 100.355 | 107.631 | 117.379 | 112.666 | 115.783 |
| sil                           | 119.145 | 103.330 | 109.535 | 122.230 | 111.639 | 117.310 |
| al                            | 23.702  | 3.750   | 15.093  | 30.692  | 22.625  | 18.438  |
| fm                            | 47.919  | 89.077  | 68.278  | 29.420  | 50.683  | 58.936  |
| c                             | 23.593  | 6.341   | 14.246  | 34.331  | 23.782  | 18.298  |
| alk                           | 4.786   | 0.832   | 2.384   | 5.557   | 2.910   | 4.327   |
| mg                            | 0.727   | 0.784   | 0.779   | 0.726   | 0.743   | 0.767   |
| c/fm                          | 0.492   | 0.071   | 0.209   | 1.167   | 0.469   | 0.310   |
| K                             | 0.090   | 0.071   | 0.077   | 0.299   | 0.048   | 0.223   |
| TiO <sub>2</sub>              | 0.338   | 1.437   | 1.184   | 0.830   | 0.661   | 1.154   |
| P <sub>2</sub> O <sub>5</sub> | 0.048   | 0.016   | 0.026   | 0.119   | 0.037   | 0.056   |
| H <sub>2</sub> O              | 7.492   | 2.165   | 1.705   | 0.783   | 3.664   | 8.156   |
| CO <sub>2</sub>               | 0.0     | 0.0     | 0.0     | 1.090   | 0.0     | 1.093   |
| qz                            | -6.651  | -2.975  | -1.904  | -4.850  | -1.028  | -1.527  |

E.3. *Niggli Values of Pegmatitic Pyroxenite and Porphyritic Pyroxenite*

| No.                           | 1         | 2       | 3       | 4       | 5       |
|-------------------------------|-----------|---------|---------|---------|---------|
| si                            | Not       | 77.901  | 58.415  | 99.210  | 95.543  |
| sil                           | calculat- | 107.292 | 107.331 | 112.021 | 106.864 |
| al                            | ed        | 7.211   | 3.798   | 8.191   | 5.006   |
| fm                            |           | 83.462  | 90.030  | 78.128  | 86.291  |
| c                             |           | 7.504   | 4.339   | 10.675  | 6.987   |
| alk                           |           | 1.823   | 1.833   | 3.005   | 1.716   |
| mg                            |           | 0.788   | 0.803   | 0.796   | 0.816   |
| c/fm                          |           | 0.090   | 0.048   | 0.137   | 0.081   |
| K                             |           | 0.390   | 0.447   | 0.601   | 0.734   |
| TiO <sub>2</sub>              |           | 0.432   | 0.290   | 0.786   | 0.681   |
| P <sub>2</sub> O <sub>5</sub> |           | 0.143   | 0.109   | 0.097   | 0.084   |
| H <sub>2</sub> O              |           | 3.658   | 54.874  | 0.951   | 1.329   |
| CO <sub>2</sub>               |           | 2.235   | 1.953   | 1.064   | 0.841   |
| qz                            |           | -29.392 | -48.916 | -12.811 | -11.321 |

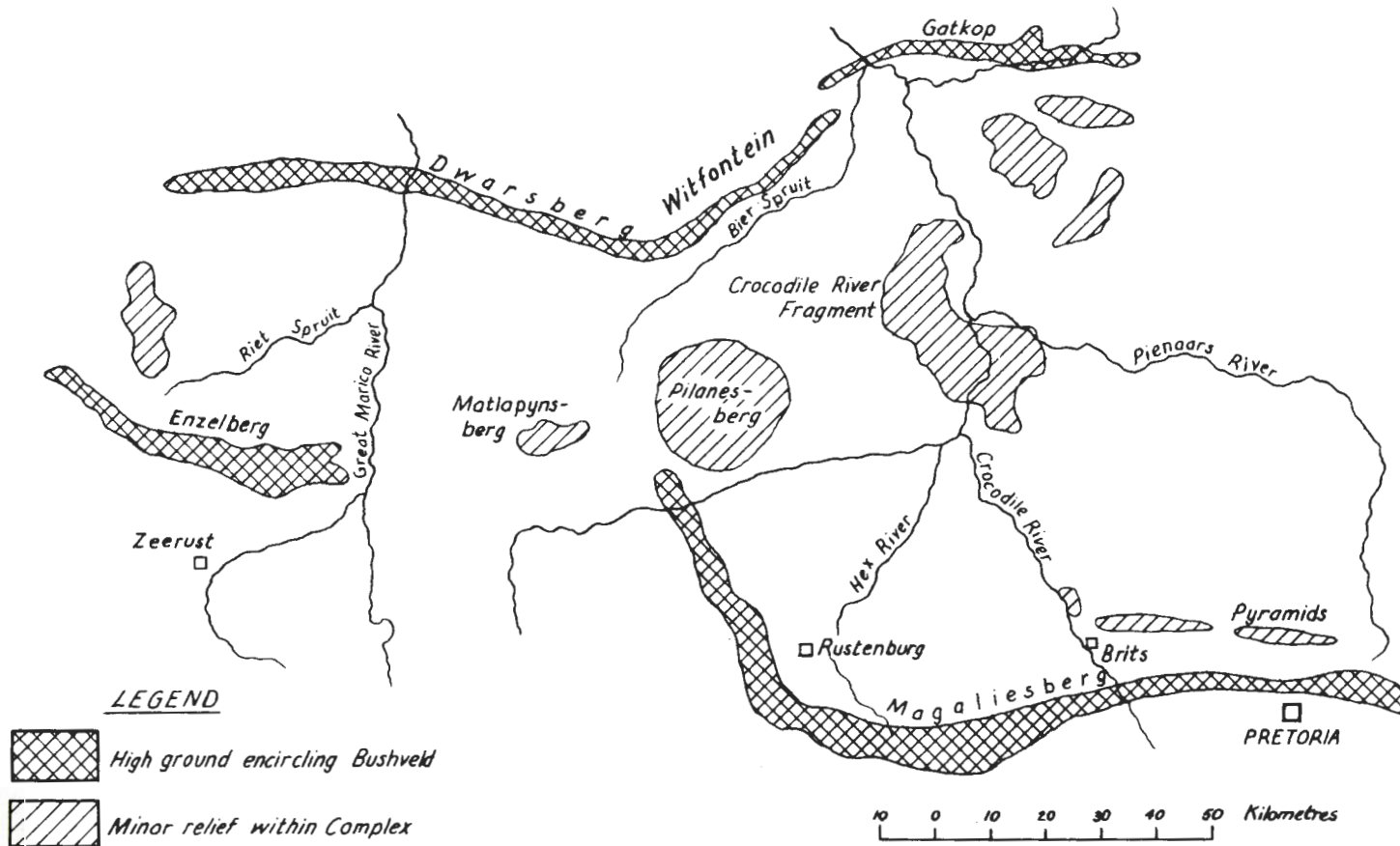
F.3. *Niggli Values of Gabbro and Ferrogabbro*

| No.                           | 1       | 2       | 3       | 4       | 5       | 6       |
|-------------------------------|---------|---------|---------|---------|---------|---------|
| si                            | 123.120 | 133.012 | 120.658 | 138.071 | 82.772  | 103.024 |
| sil                           | 124.540 | 122.486 | 121.075 | 144.352 | 121.332 | 120.346 |
| al                            | 23.436  | 31.312  | 22.003  | 44.194  | 20.046  | 16.856  |
| fm                            | 42.627  | 28.991  | 43.466  | 6.889   | 54.154  | 51.163  |
| c                             | 27.803  | 34.076  | 29.262  | 37.829  | 20.467  | 26.894  |
| alk                           | 6.135   | 5.622   | 5.269   | 11.088  | 5.333   | 5.087   |
| mg                            | 0.615   | 0.545   | 0.582   | 0.089   | 0.312   | 0.413   |
| c/fm                          | 0.652   | 1.175   | 0.673   | 5.492   | 0.378   | 0.526   |
| K                             | 0.073   | 0.086   | 0.160   | 0.079   | 0.122   | 0.074   |
| TiO <sub>2</sub>              | 0.988   | 0.285   | 1.494   | 0.206   | 3.946   | 3.176   |
| P <sub>2</sub> O <sub>5</sub> | 0.099   | 0.214   | 0.070   | 0.058   | 0.026   | 0.157   |
| H <sub>2</sub> O              | 2.347   | 0.421   | 8.831   | 19.165  | 8.437   | 4.524   |
| CO <sub>2</sub>               | 0.0     | 0.0     | 0.0     | 0.0     | 0.142   | 0.239   |
| qz                            | -1.420  | 10.526  | -0.417  | -6.280  | -38.560 | -17.322 |

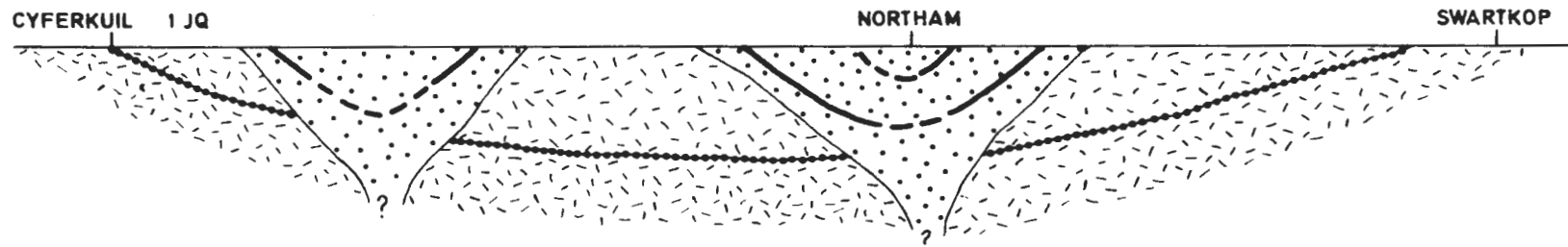
## G.3. Niggli Values of Hortonolite Dunite

| No.                           | 1       | 2       | 3       |
|-------------------------------|---------|---------|---------|
| si                            | 43.022  | 53.845  | 49.481  |
| sil                           | 100.405 | 100.556 | 107.458 |
| al                            | 1.219   | 0.976   | 3.781   |
| fm                            | 97.286  | 92.068  | 91.123  |
| c                             | 1.394   | 6.817   | 3.231   |
| alk                           | 0.101   | 0.139   | 1.865   |
| mg                            | 0.317   | 0.346   | 0.387   |
| c/fm                          | 0.014   | 0.074   | 0.035   |
| K                             | 0.099   | 0.076   | 0.0     |
| TiO <sub>2</sub>              | 4.679   | 3.962   | 1.099   |
| P <sub>2</sub> O <sub>5</sub> | 0.0     | 0.0     | 0.0     |
| H <sub>2</sub> O              | 2.613   | 7.845   | 0.0     |
| qz                            | -57.382 | -46.711 | -57.977 |

DIAGRAMMATIC SKETCH PLAN OF MAIN PHYSIOGRAPHIC FEATURES  
OF WESTERN BUSHVELD



SCHEMATIC SECTION OF TROUGH-LIKE TRANSGRESSIVE STRUCTURES  
NORTH OF PILANESBERG

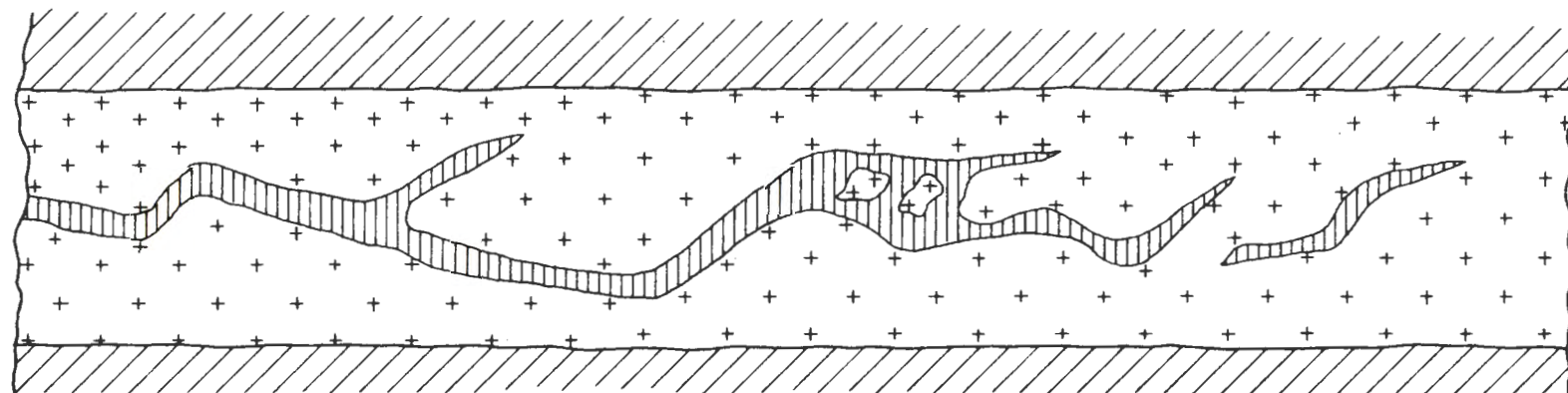


LEGEND

- |                                                                                     |                  |                                                                                       |               |
|-------------------------------------------------------------------------------------|------------------|---------------------------------------------------------------------------------------|---------------|
|   | Ferrogabbro unit |   | Magnetitite   |
|  | Older units      |  | Merensky Reef |

5 0 5 10 15 Kilometres

SERPENTINITE INCLUSIONS IN CHROMITITE NEAR NIETVERDIEND



0  $\frac{1}{2}$  1 Metre

LEGEND

-  Pyroxenite
-  Chromitite
-  Serpentinite

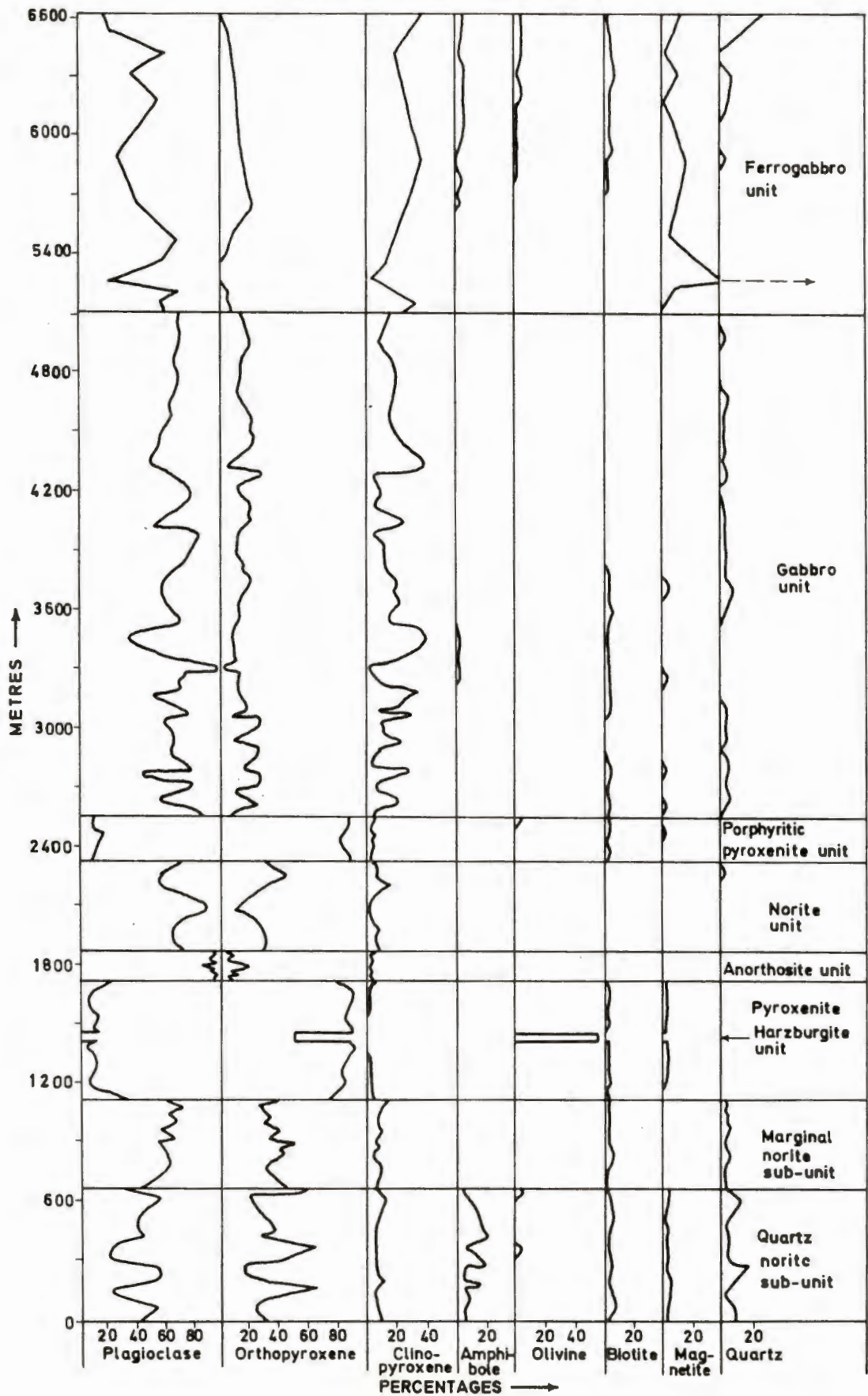


**A. Igneous layering in pyroxenite on Ruighoek 169 JP.**



**B. Wedge-like intrusion of anorthosite into chromitite,  
Schilpadnest 385 KQ.**

VOLUMETRIC COMPOSITIONS





A. Rhythmic layering in pyroxenite, Ruighoek 169 JP.



B. Chromitite bands in anorthosite, Dwars River, Eastern Transvaal.



A. Chromitite in anorthosite near Brits.



B. Flat tapering body of anorthosite in norite, Schilpadnest  
385 KQ.

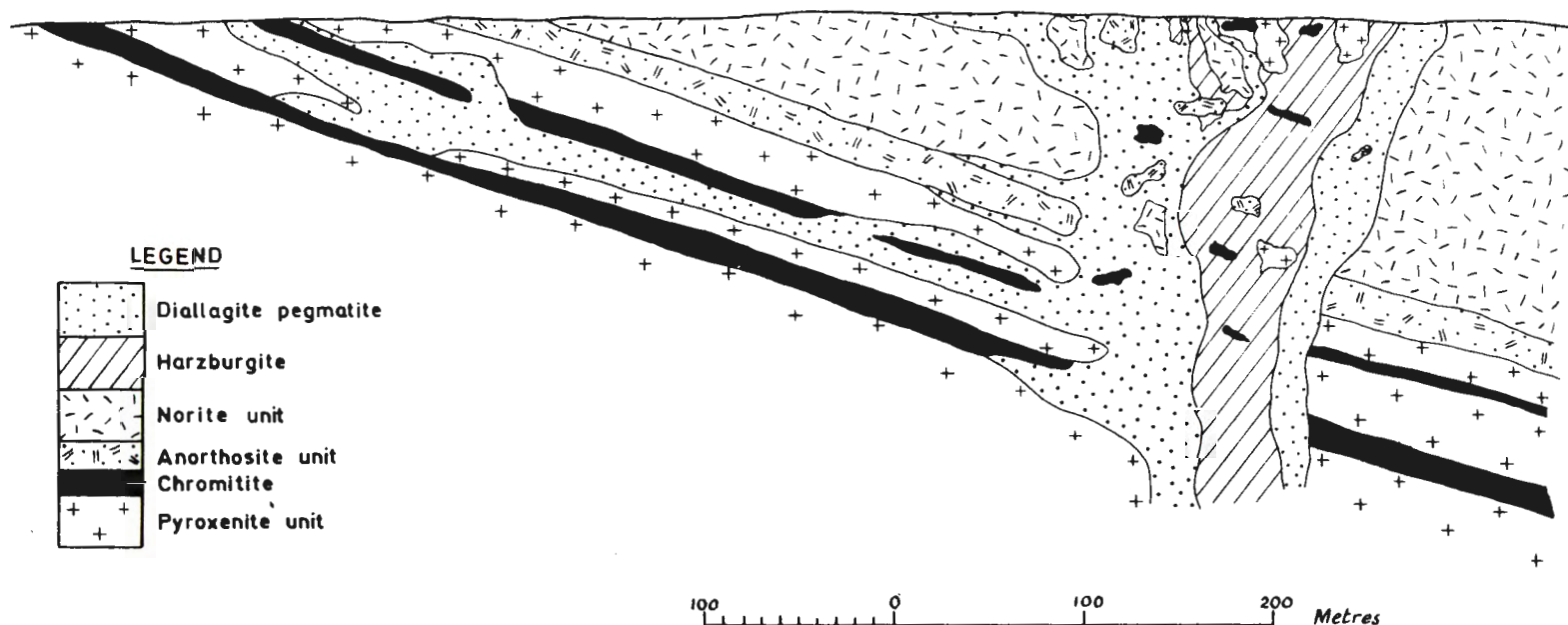


A. Irregular anorthosite inclusions in norite, Ruighoek 169 JP.  
(Igneous layering parallel to hammer head,)



B. Upper contact of Bastard Reef with anorthosite,  
Rustenburg Platinum Mine.

SCHEMATIC SECTION: PIPE SOUTH OF BRITS



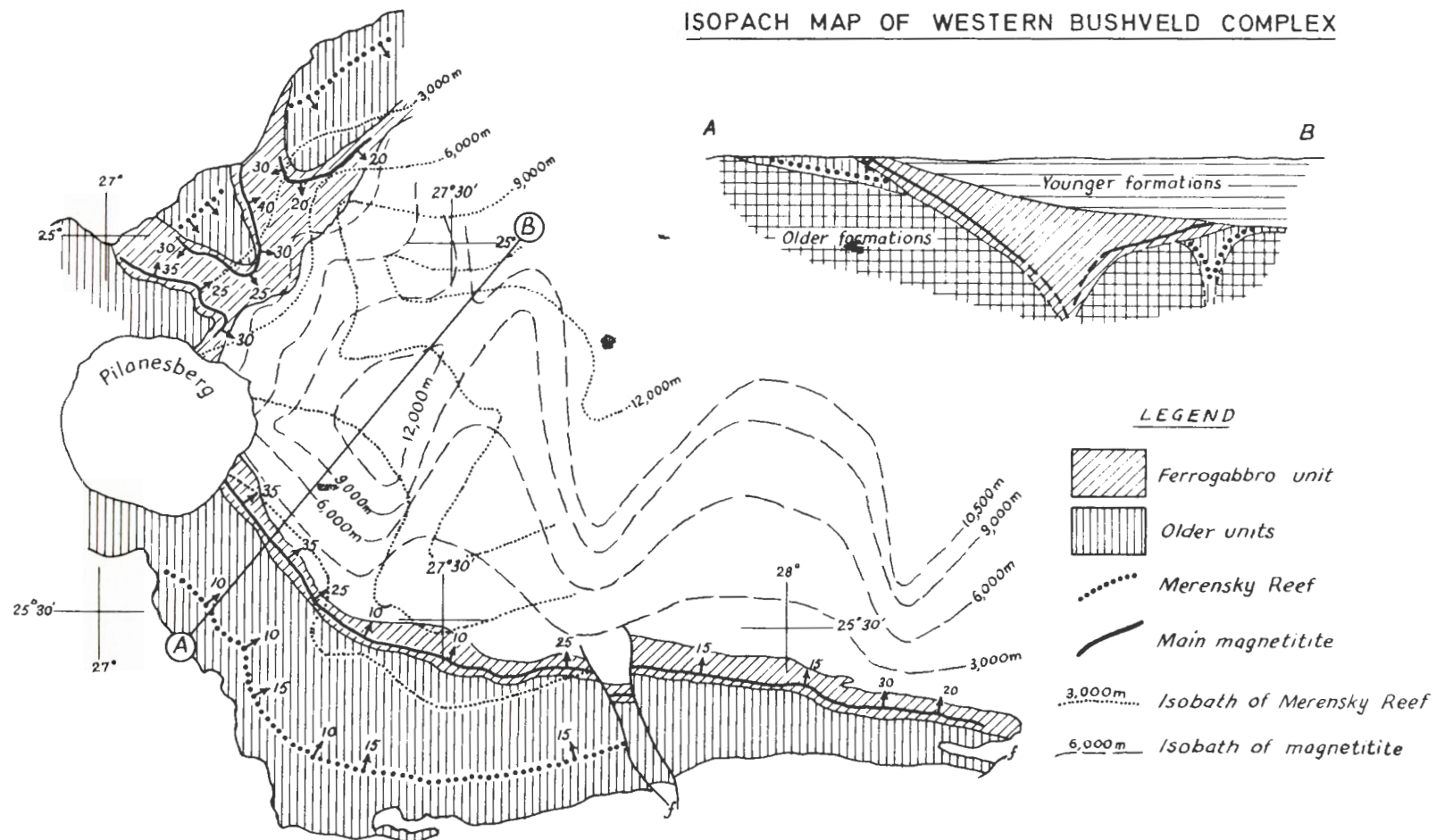


A. Hortonolite dunite pipe on Boschkoppie 104 JQ.



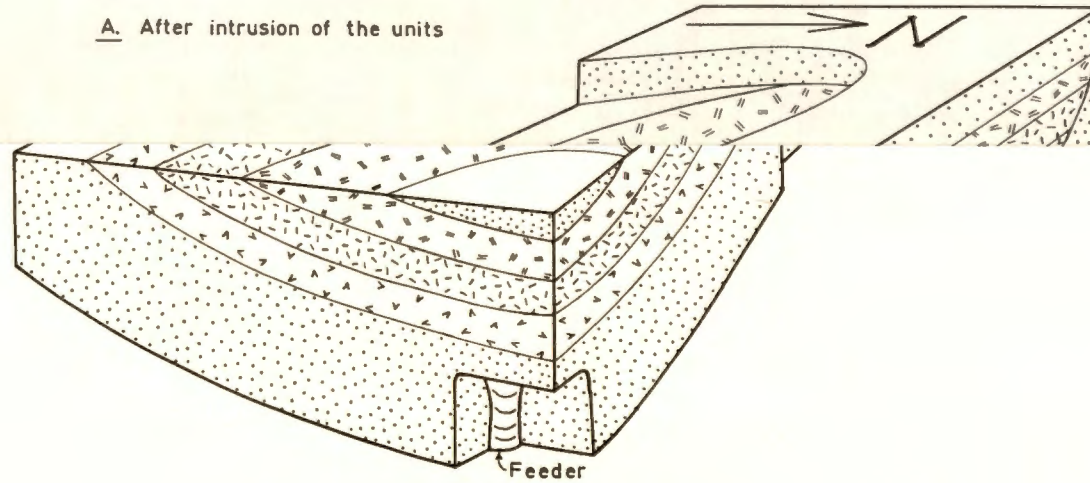
B. Chromitite inclusion in dunite on De Kroon 44 JQ.

ISOPACH MAP OF WESTERN BUSHVELD COMPLEX



SCHEMATIC SECTIONS SHOWING STRUCTURAL DEVELOPMENT  
OF WESTERN PART OF THE COMPLEX

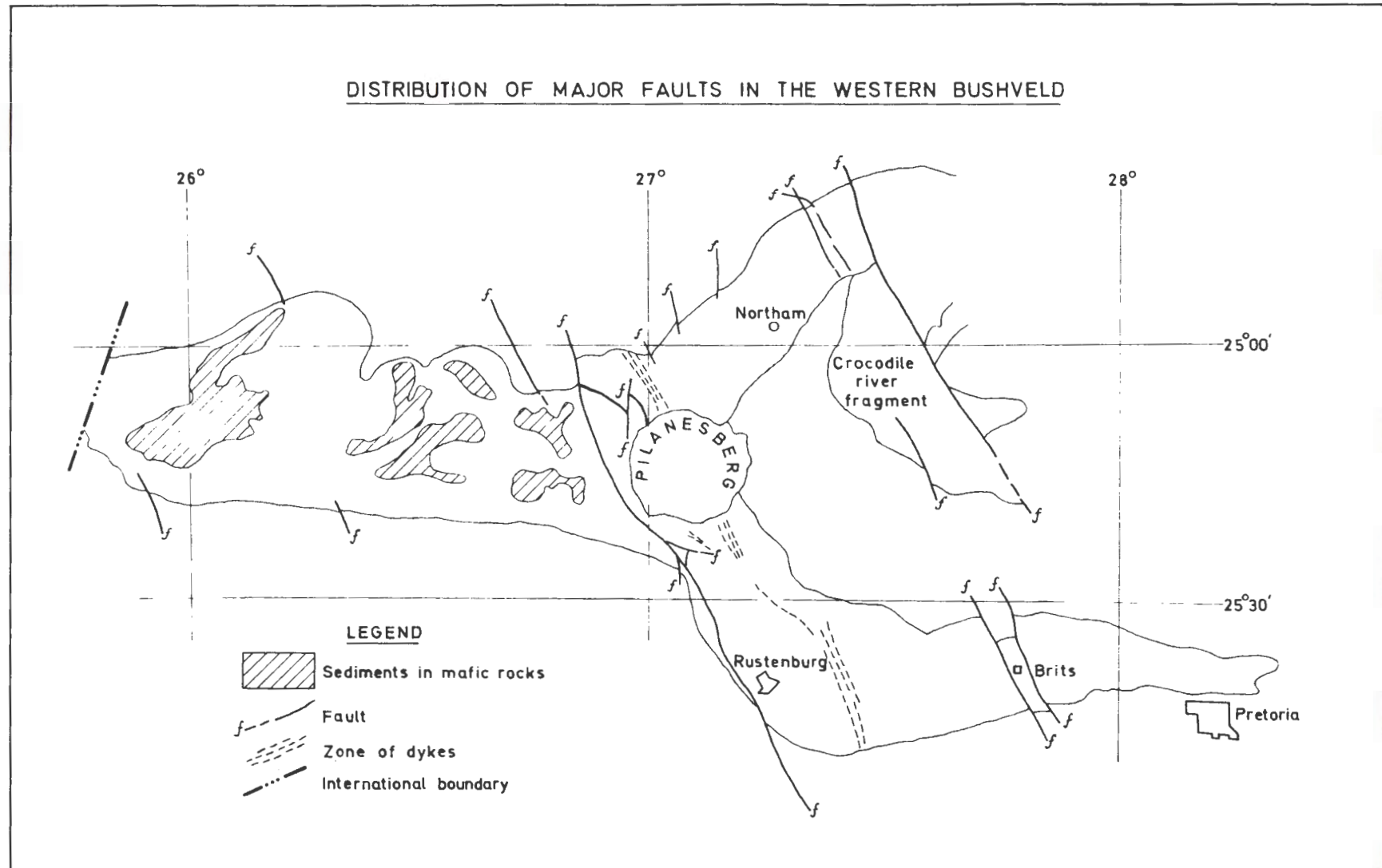
A. After intrusion of the units

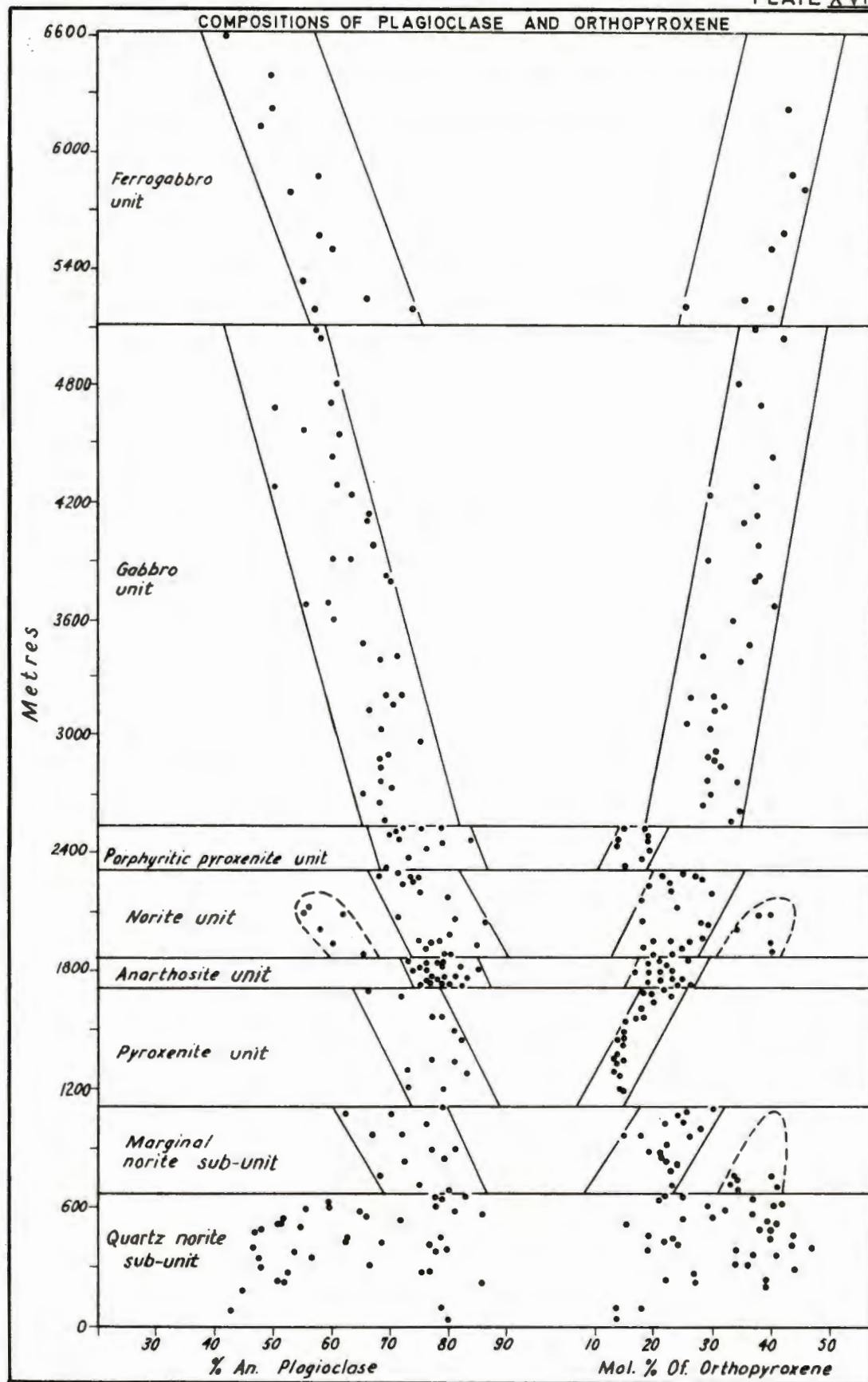


LEGEND

|                                                                                   |                  |                                                                                     |                 |
|-----------------------------------------------------------------------------------|------------------|-------------------------------------------------------------------------------------|-----------------|
|  | Upper rock unit  |  | Lower rock unit |
|  | Middle rock unit |  | Sediments       |

DISTRIBUTION OF MAJOR FAULTS IN THE WESTERN BUSHVELD

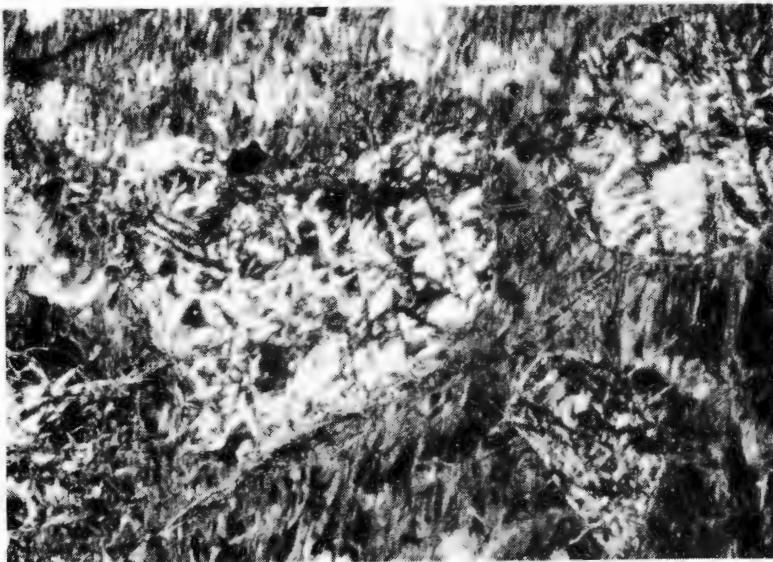






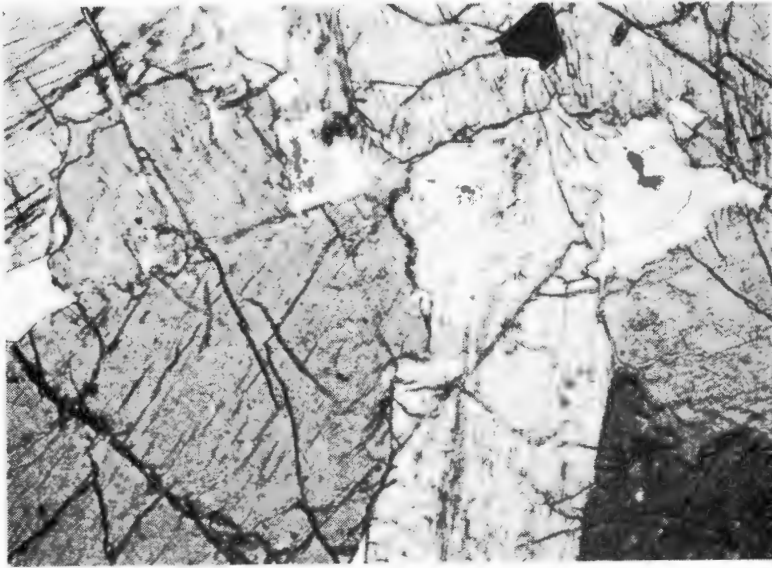
1 mm

- A. Quartz norite.  
 Lower part: Pyroxene partly altered to biotite (dark mineral lower left corner) followed by amphibole (lighter colour) and plagioclase.  
 Higher up: Pyroxene, in various stages of alteration, and quartz (upper left corner towards right centre). Crossed nicols.



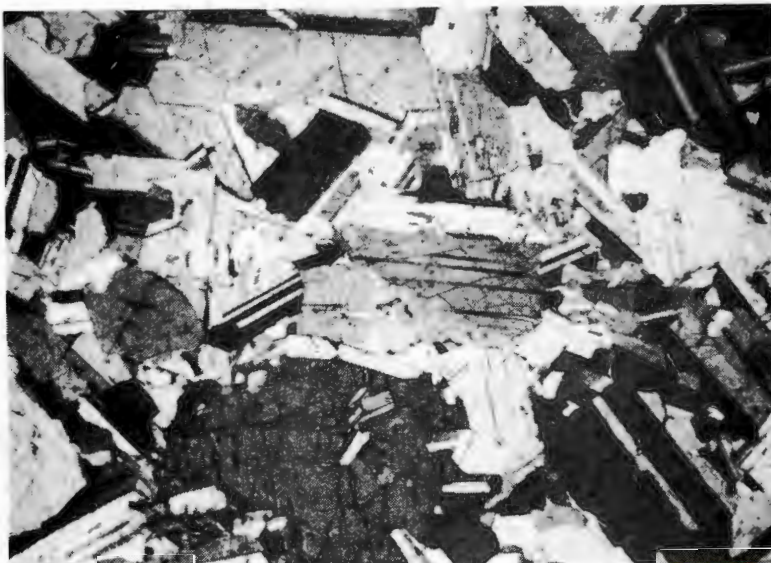
1 mm

- B. Serpentinized harzburgite.  
 Outlines of original olivine crystals still recognizable.  
 Crossed nicols.



1 mm

A. Bronzitite.  
Bronzite crystals with plagioclase and chromite grain  
(upper right).



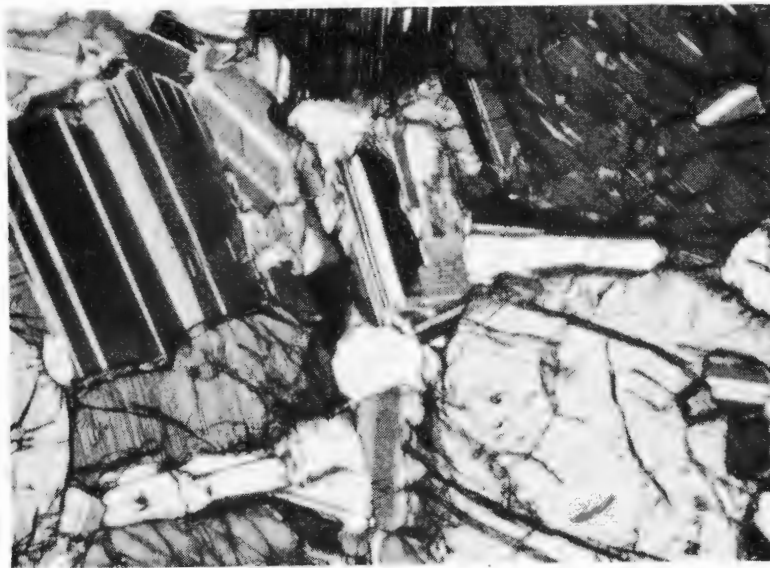
2 mm

B. Spotted anorthosite  
Large orthopyroxene crystal and plagioclase.  
Crossed nicols.



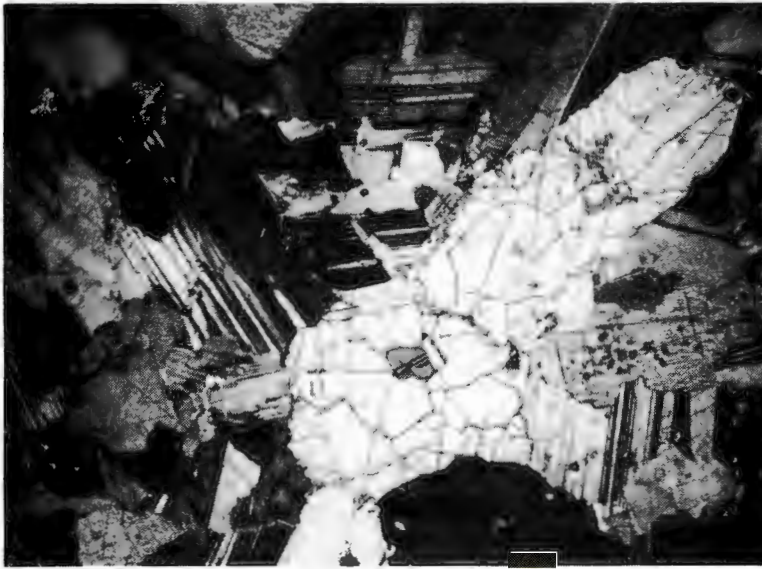
1 mm

- A. Mottled anorthosite.  
Plagioclase and interstitial clinopyroxene (upper left.)  
Crossed nicols.



1 mm

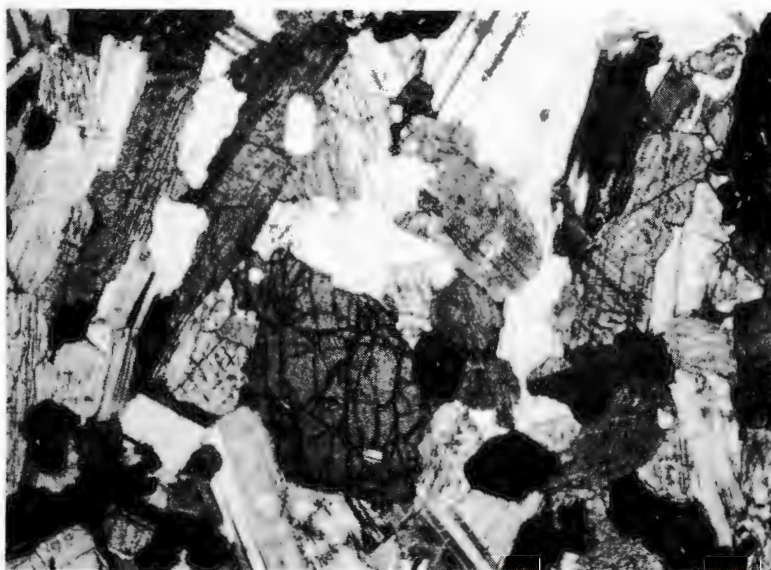
- B. Norite.  
Plagioclase crystals (upper left) and orthopyroxene  
crystals. Crossed nicols.



A. Porphyritic pyroxenite.  
Orthopyroxene and plagioclase. Few dark chromitite grains.  
Crossed nicols.



B. Pegmatitic pyroxenite.  
Two large orthopyroxene crystals in large continuous  
plagioclase (centre). Crossed nicols.



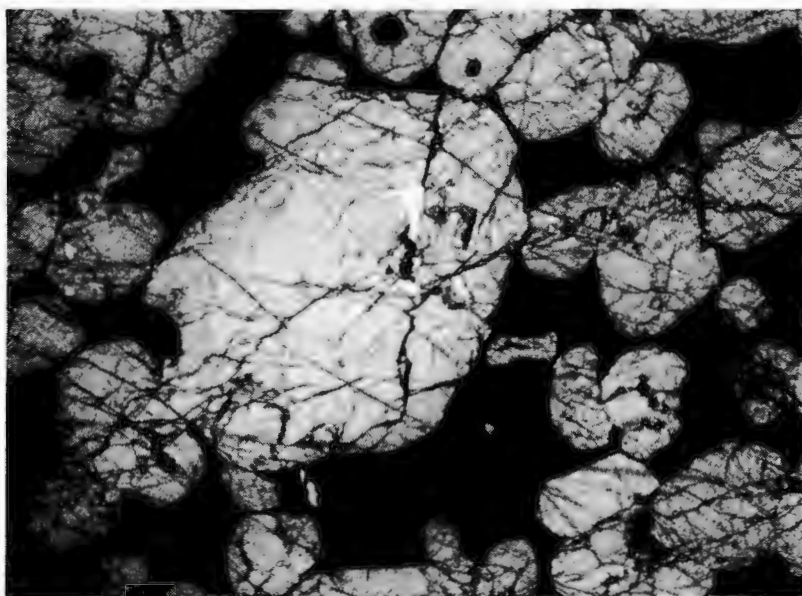
5 mm

- A. Gabbro.  
Clinopyroxene (centre and right), orthopyroxene (left)  
and plagioclase. Crossed nicols.



1 mm

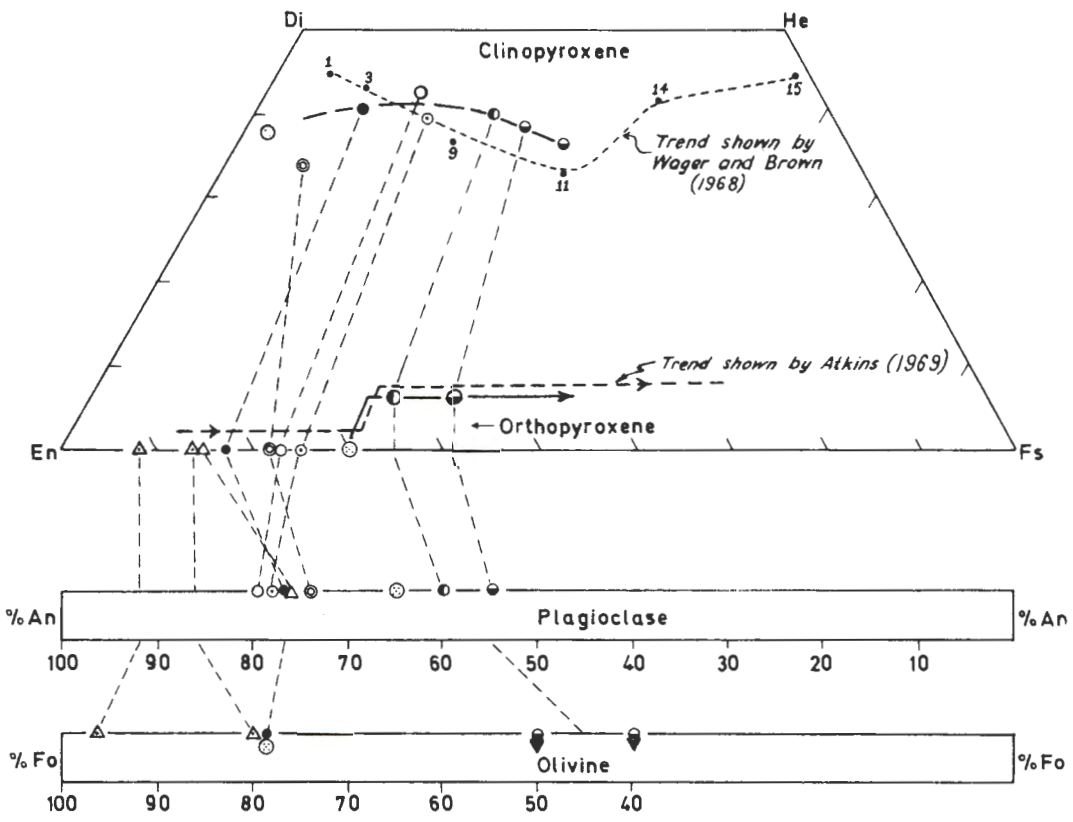
- B. Ferrogabbro.  
Plagioclase (top, right). Large orthopyroxene with ex-  
solution lamellae of clinopyroxene and clinopyroxene  
(lower left) and magnetite (black, upper left).  
Crossed nicols.



5 mm

Hortonolite dunite.  
Olivine crystals with interstitial magnetite (black). Crossed nicols.

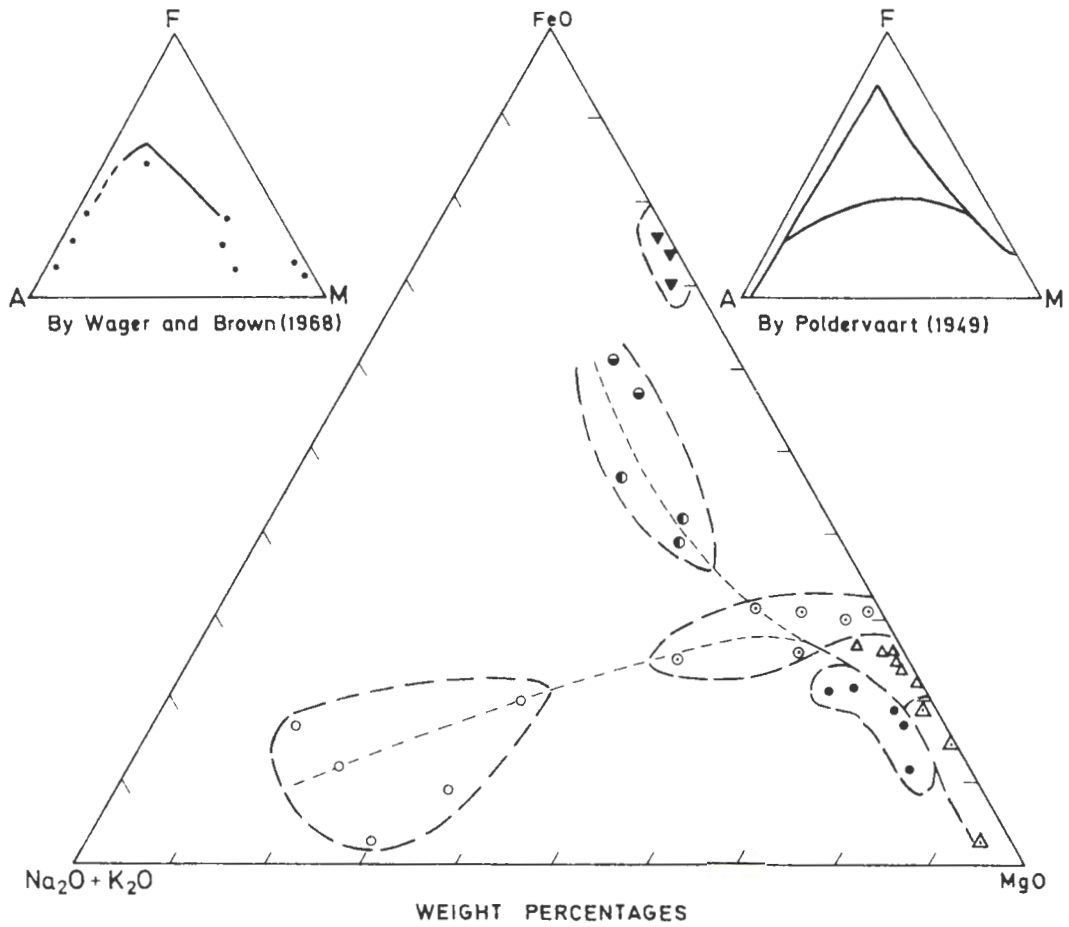
COMPOSITIONS OF CO-EXISTING PYROXENE, PLAGIOCLASE AND OLIVINE



LEGEND

- ▼ Hortonolite dunite
- Ferrogabbro unit
- Gabbro unit
- Porphyritic pyroxenite unit
- Norite unit
- Anorthosite unit
- △ Pyroxenite unit
- △ Harzburgite unit
- Marginal norite sub-unit
- ⊙ Quartz norite sub-unit

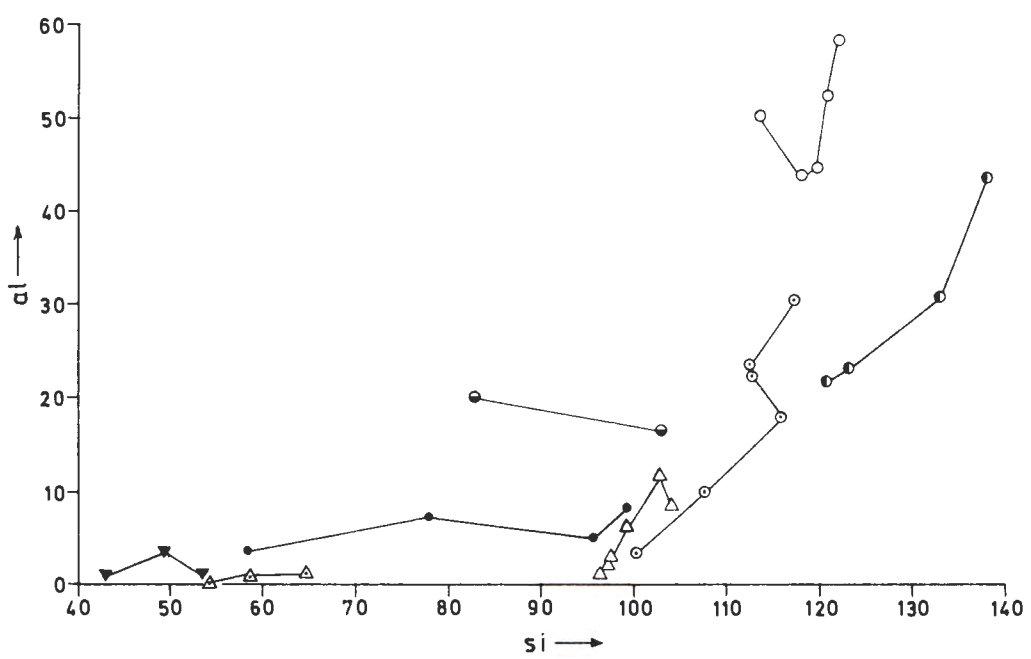
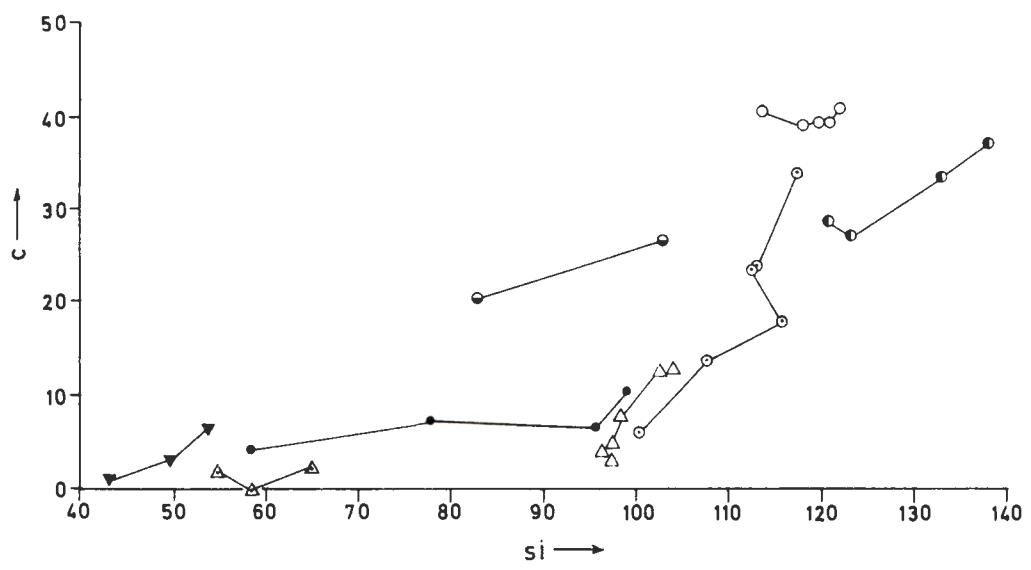
M F A DIAGRAM



LEGEND

- ▼ Hortonolite dunite
- Ferrogabbro unit
- Gabbro unit
- Porphyritic pyroxenite unit
- Norite unit
- Anorthosite unit
- △ Pyroxenite unit
- △ Harzburgite unit

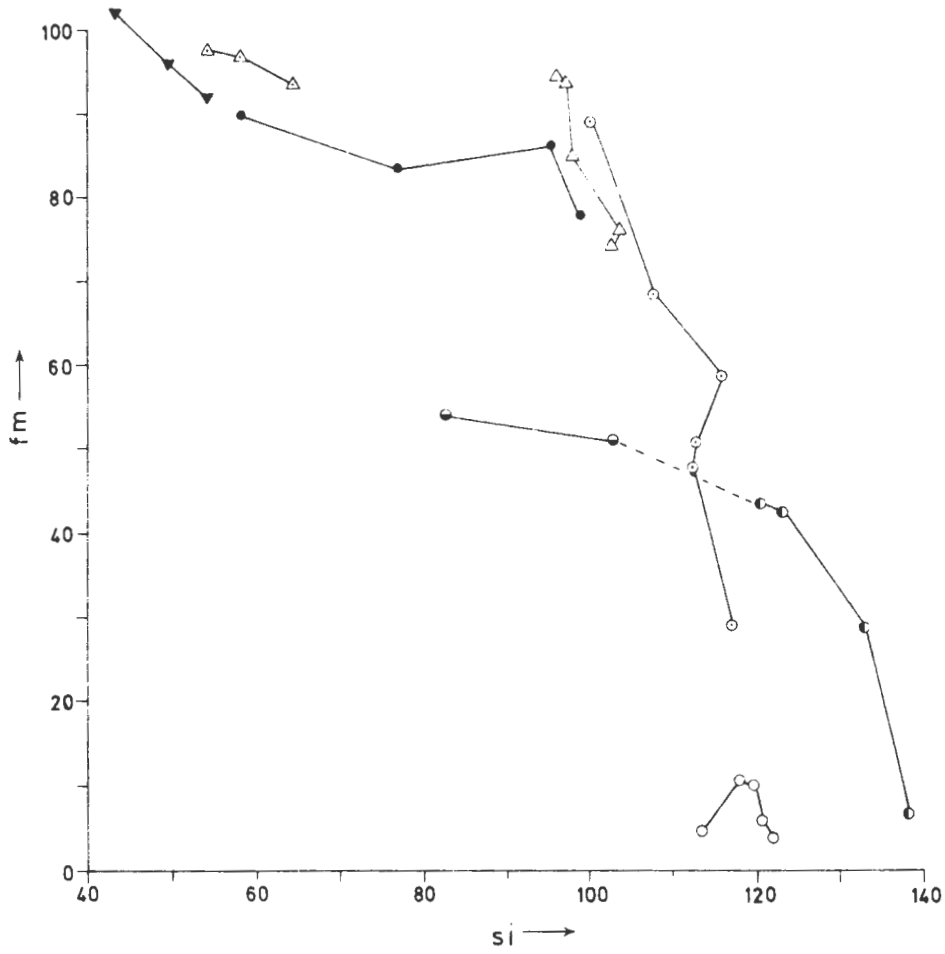
DIFFERENTIATION DIAGRAM  $si:al$  AND  $si:c$



LEGEND

- |                               |                    |
|-------------------------------|--------------------|
| ▼ Hortonolite dunite          | ○ Norite unit      |
| ● Ferrogabbro unit            | ○ Anorthosite unit |
| ○ Gabbro unit                 | △ Pyroxenite unit  |
| • Porphyritic pyroxenite unit | △ Harzburgite unit |

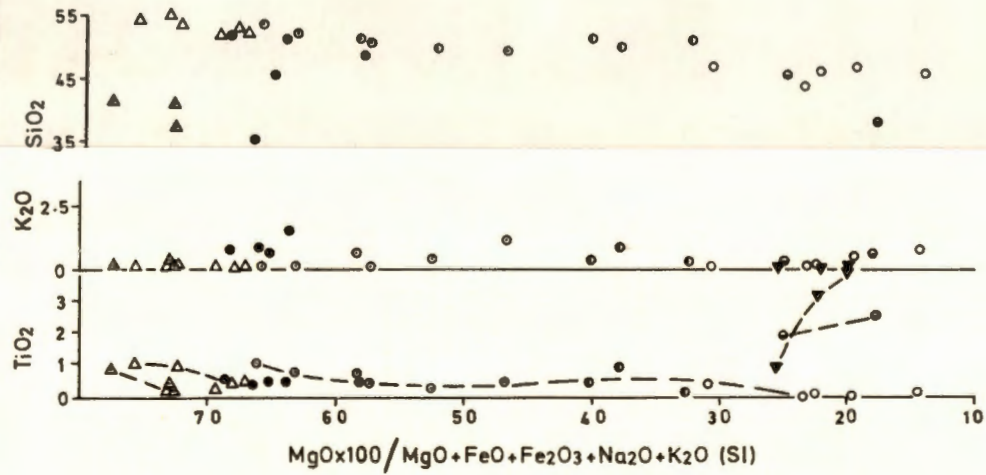
DIFFERENTIATION DIAGRAM si:fm



LEGEND

- ▼ Hortonolite dunite
- Ferrogabbro unit
- Gabbro unit
- Porphyritic pyroxenite unit
- Norite unit
- Anorthosite unit
- △ Pyroxenite unit
- △ Harzburgite unit

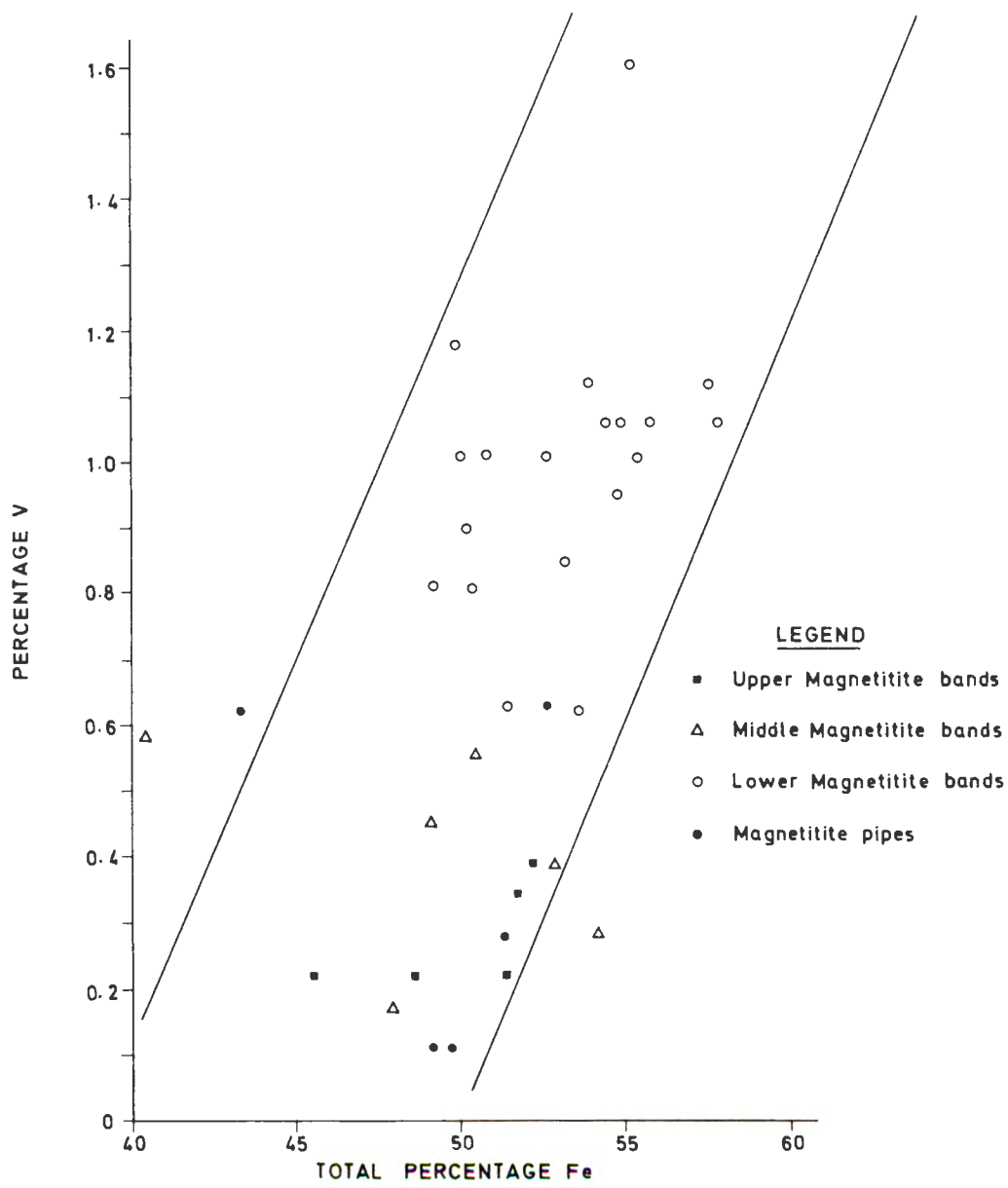
OXIDE VARIATION DIAGRAMS OF THE BASIC ROCKS  
OF THE BUSHVELD COMPLEX PLOTTED AGAINST SI



LEGEND

- |                               |                    |
|-------------------------------|--------------------|
| ▼ Hortonolite dunite          | ● Norite unit      |
| ○ Ferrogabbro unit            | ○ Anorthosite unit |
| ○ Gabbro unit                 | △ Pyroxenite unit  |
| ● Porphyritic pyroxenite unit | △ Harzburgite unit |

VANADIUM:IRON RATIOS OF MAGNETITITE ANALYSED



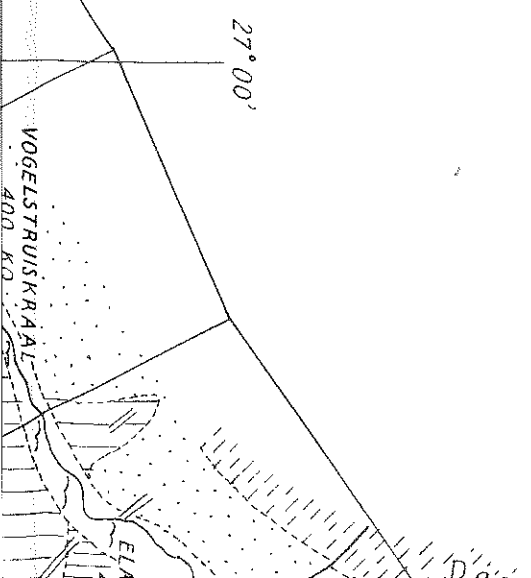
# GEOLOGICAL MAP

OF THE

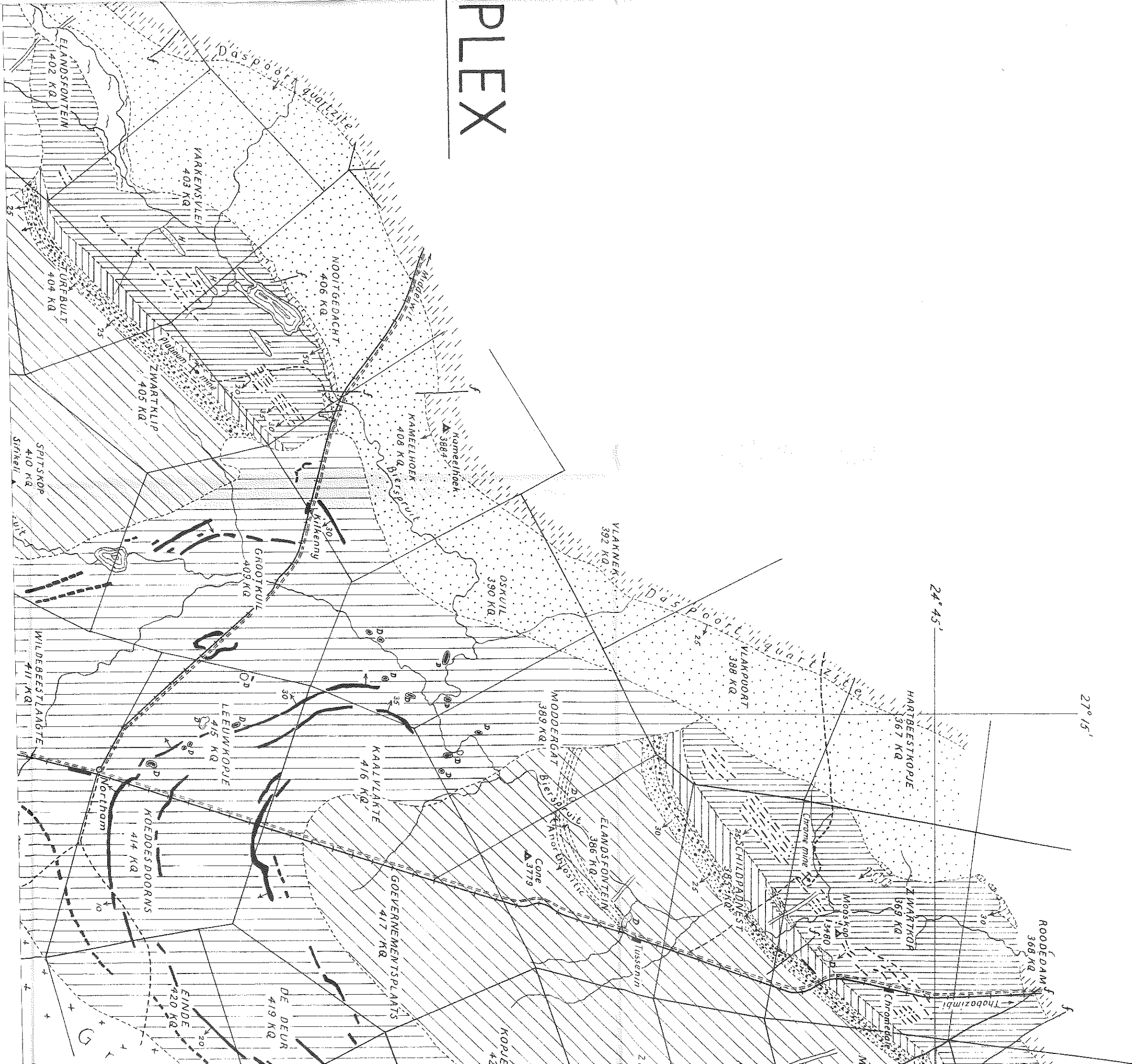
BASIC PORTION

OF THE

WESTERN BUSHVELD COMPL

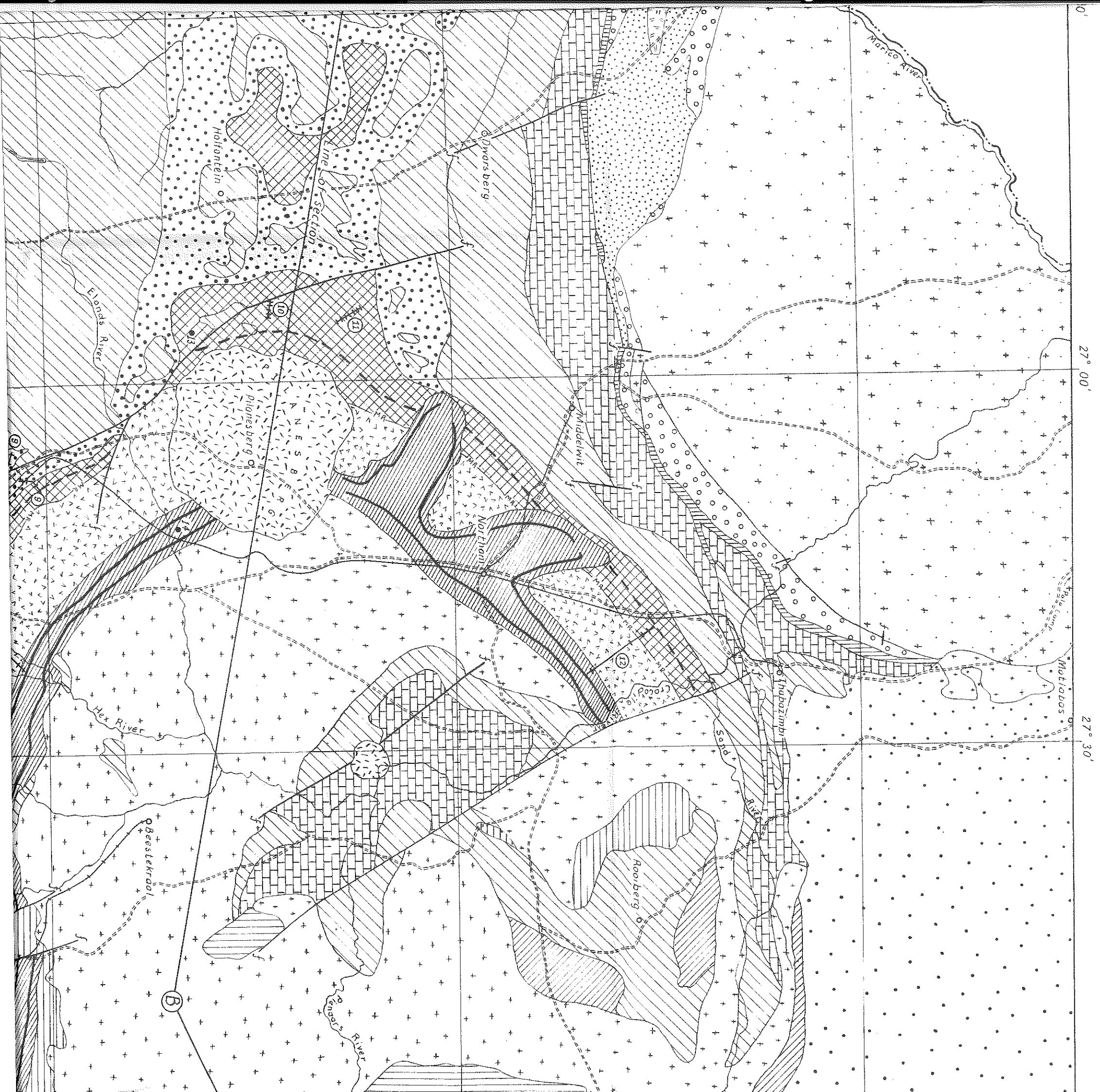


# PLEX

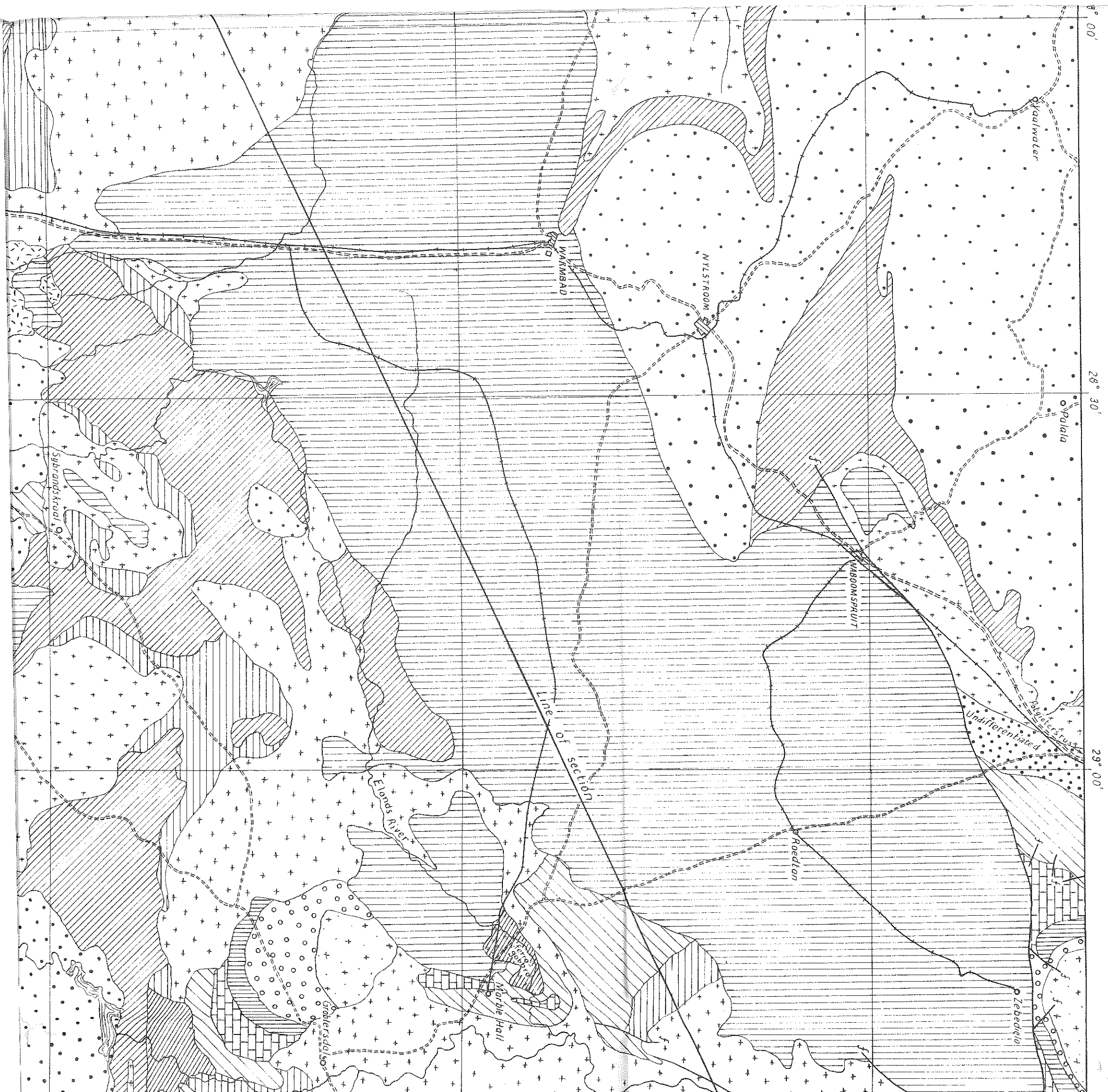


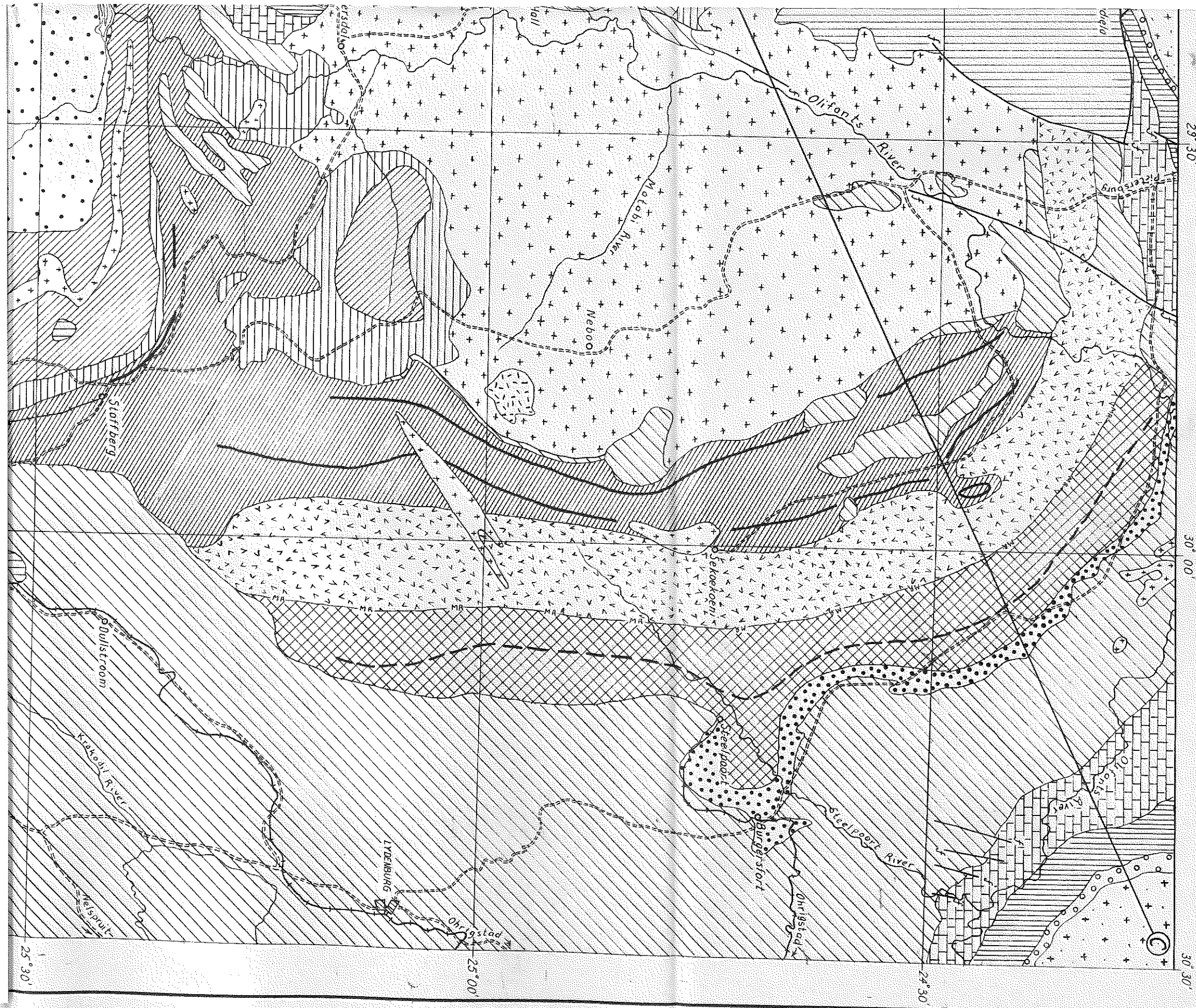


GENERALISED MAP OF THE BU



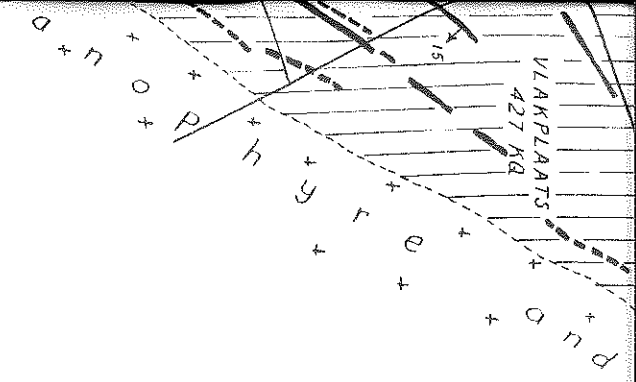
SHVELD COMPLEX IN TRANSVAAL

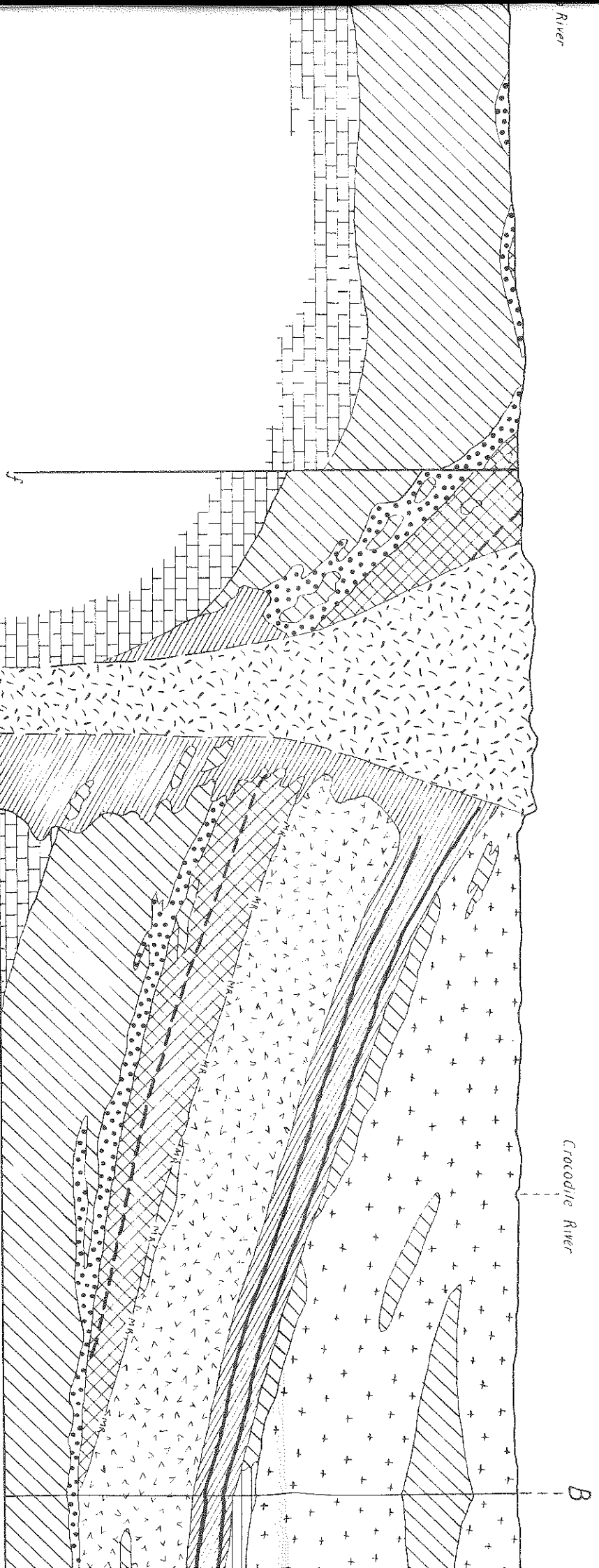
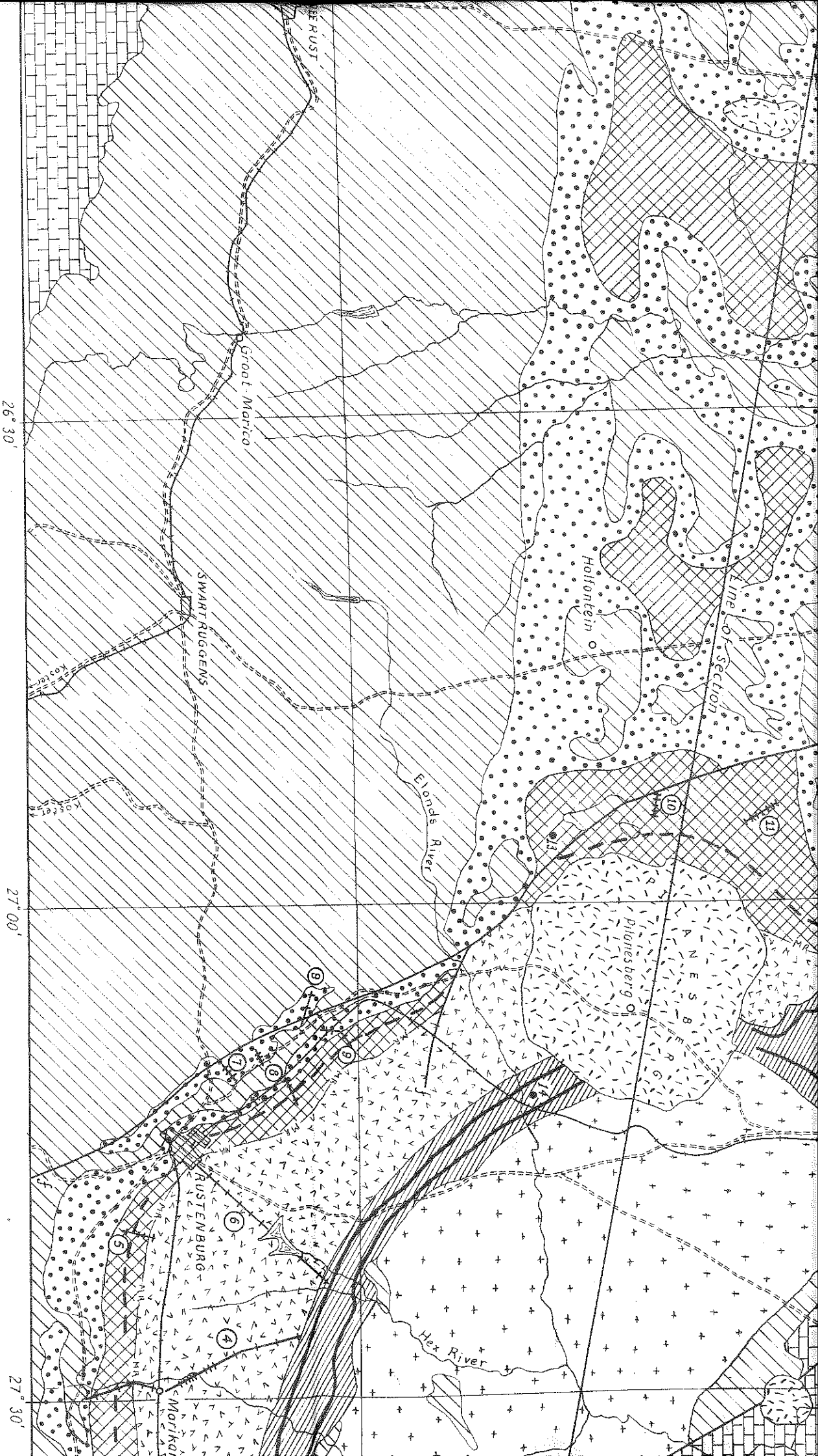












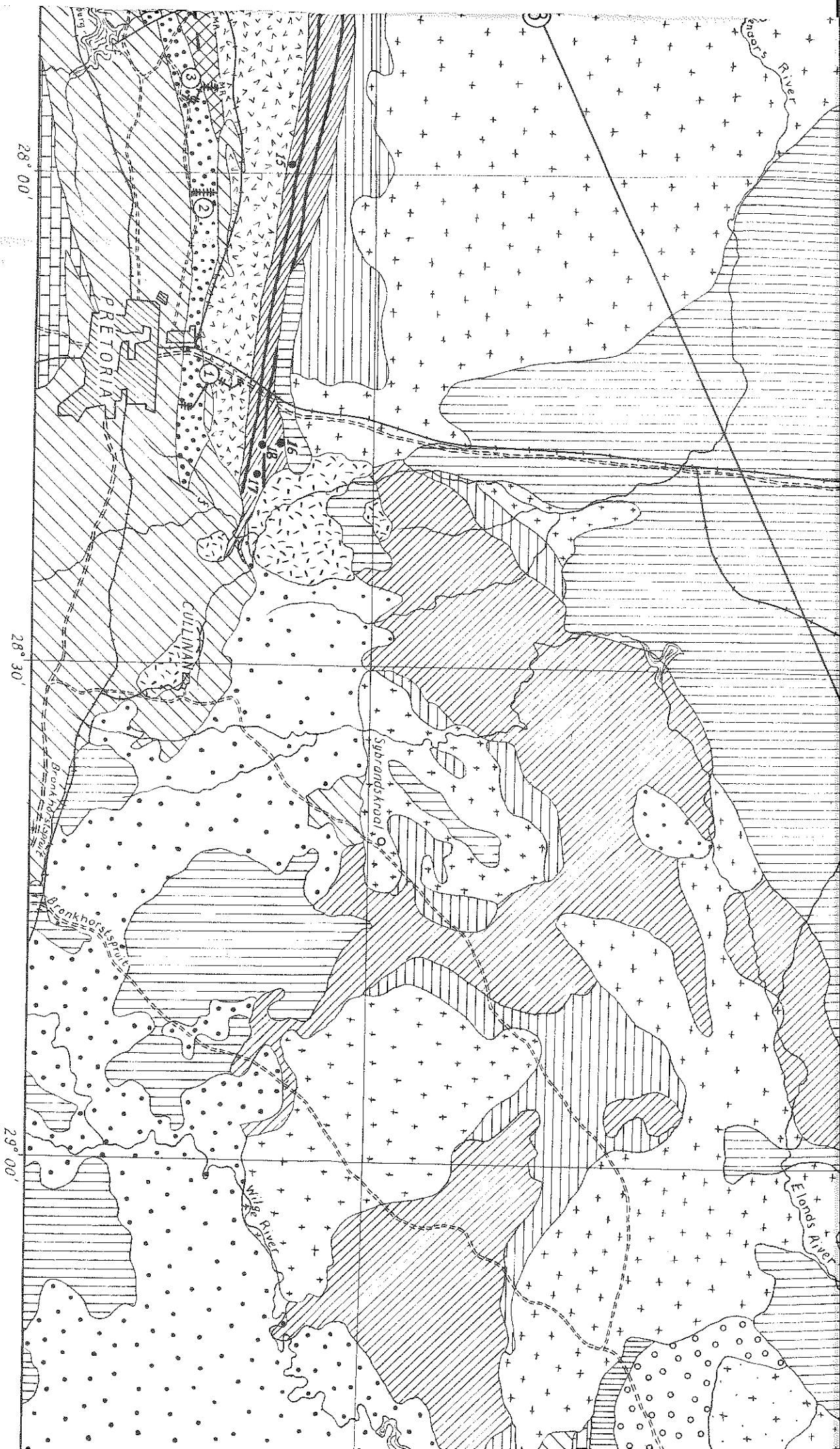
} Kurroo System  
 } Planesberg and other Complexes  
 } Waterberg System



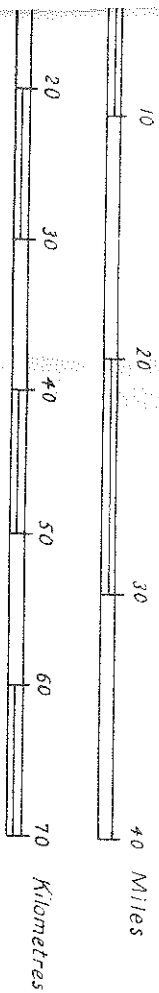
Granite  
 Granophyre  
 Ferragabbro Unit with magnetitite bands (—)  
 Gabbro Unit  
 Merensky Reef  
 Pyroxenite and Norite Units with chromitite bands (— — —)  
 Basal Norite Unit  
 Felsite

Acid Rocks  
 Basic Rocks  
 Extrusive Acid Rocks

Bushveld Comp

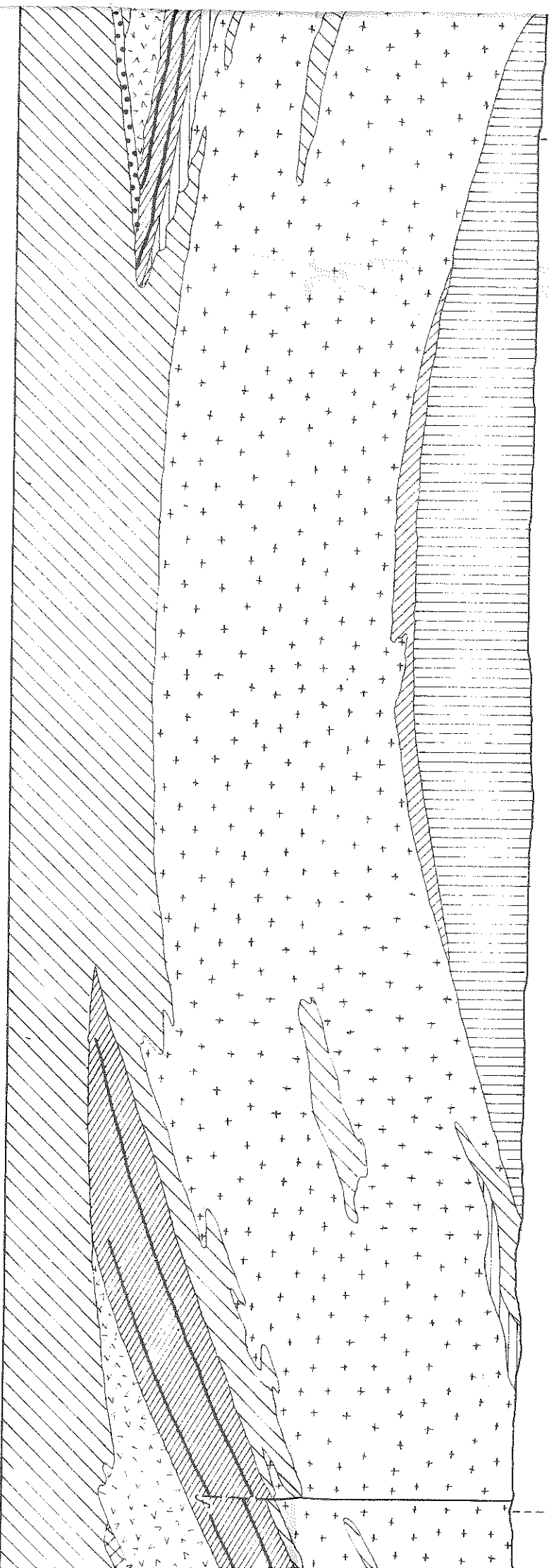


SCALE 1:500,000



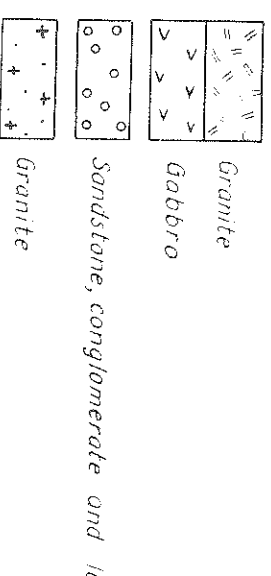
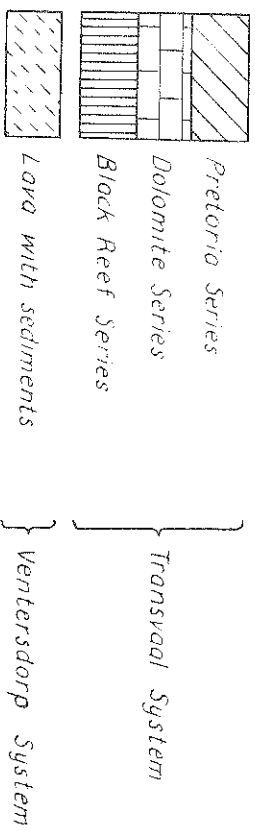
Pretorius River

Olifants River

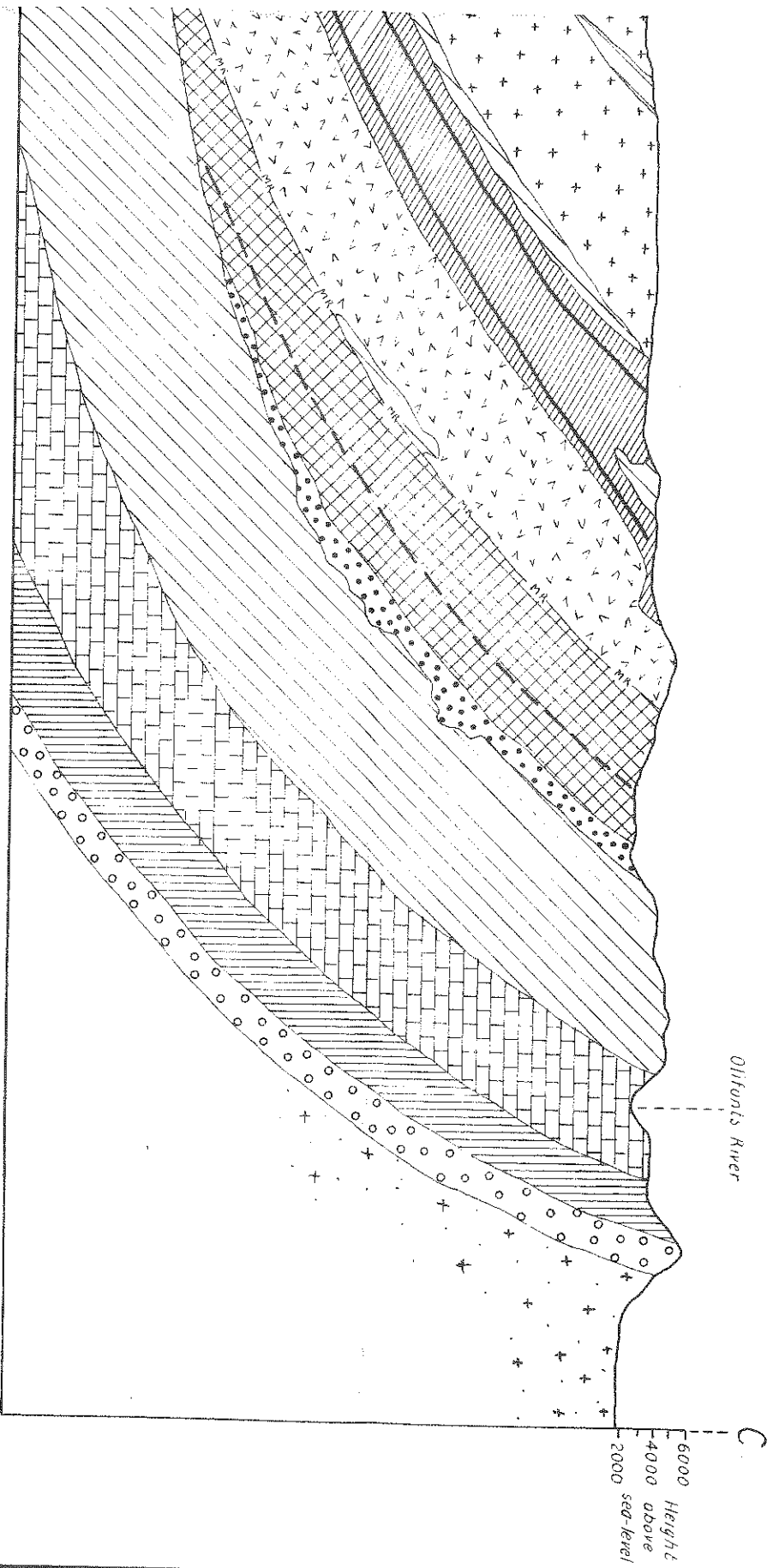
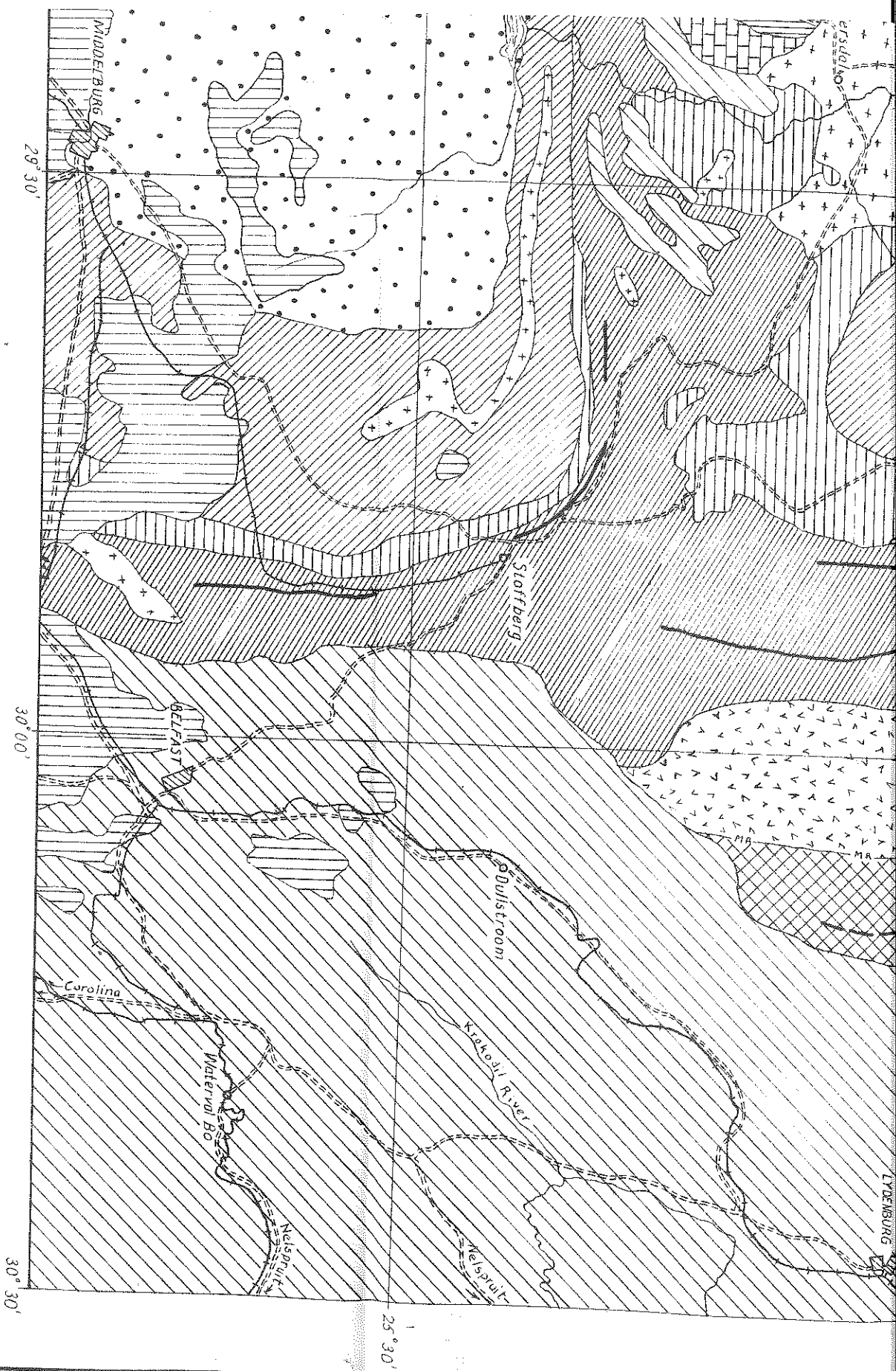


Geological Section A-B-C

Geological Legend



Fault



- ⑦ Sampling route and number of route  
 • 14 Locality of sample not along route

Dominion Reef System  
 Archaean Complex

# DETAILED SUCCESSIONS OF THE BASIC ROCKS

(NOT DRAWN TO SCALE)

IN THE VICINITIES OF SWARTKLIP, BOSHOEK AND RUSTENBURG

Thickness in metres

