IV. THE LAYERED SEQUENCE OF THE BUSHVELD COMPLEX

1. General

The portion of the Layered Sequence of the Bushveld Complex investigated includes the Main and Upper Zones. The lower portion of the Main Zone was not included in this mapping project as it had recently been undertaken by P. Roux (1968). However, the generous assistance of Rand Mines, who kindly provided core from a bore-hole 1300m deep, drilled on the farm Pietersburg 44 JT (Folder I), made it possible to investigate rocks of the complete succession of the Main Zone.

In subdividing the rocks of these two zones, the author adhered to the scheme as proposed by Molyneux (1970, Plate II), except for the division between the lower two subzones of the Upper Zone which is taken at the base of the Main Magnetitite Seam. The thicknesses of the various zones and subzones are given in Table II and these are also compared with those given by Molyneux (1970, p. 14) from the area north of the Steelpoort River. A more detailed schematic profile of the various subzones and the characteristic rock types is given in Folder II.

In the general descriptions of the field characteristics of the various rock types, the cumulus terminology of Wager et al. (1960, p. 73) and/or Jackson (1967, p. 22 and 1970, p. 392) cannot be used, as it is extremely difficult to distinguish the various cumulus phases in hand-specimen. For the same reason, subdivision of rocks into gabbro, hypersthene gabbro, hyperite and norite (Raal, 1965, p. 3) cannot be made in the field. Rocks are therefore generally referred to as gabbros in the Main Zone and magnetite gabbros in the Upper Zone. Where reference is made to specific horizons in the Layered Sequence, descriptive rock names such as fine-grained norite, norite, mottled anorthosite, spotted anorthosite, porphyritic norite etc. are used. For a general description of the last three terms, see Willemse (1969a, p. 14).

Names, according to relative abundances of pyroxenes (illustrated diagrammatically by Raal, 1964, p. 3) are given in Appendix I for rocks on which modal analyses were made. Cumulus phases, where evident, are indicated by an asterisk next to the volumetric percentage of the particular mineral.

2. The Main Zone

The Main Zone extends from Roossenekal in the west to the Dwars River

TABLE II SUBDIVISION AND THICKNESS OF THE UPPER AND MAIN ZONES IN THE ROOSSENEKAL AREA

Zone	Subzone	Rock types	Thickness in metres	Magnet Heights (Molyneux 1970 p. 14)
UPPER ZONE	Subzone D	Magnetitite Seams 15-21, olivine diorite, anorthosite, diorite	990	650
		Appearance of cumulus apatite		
	Subzone C	Magnetitite Seams 8-14, troctolite, magnetite gabbro, olivine gabbro, anorthosite	600	500
		Appearance of olivine (Sisal Marker)		
	Subzone B	Magnetitite Seams 1-7 above the Main Magnetitite Seam, anorthosite, magnetite gabbro, feldspathic pyroxenite	540	450
		Main Magnetitite Seam		
	Subzone A	Lower Magnetitite Seams 1-3, anorthosite, magnetite gabbro	140	190
		Appearance of magnetite		
		Thickness of Upper Zone	2270	1790
MAIN ZONE	Subzone C	Pyroxenite, anorthosite, gabbroic rocks	690	660
		Pyroxenite Marker		
	Subzone B	Homogeneous gabbroic rocks, fine-grained norite	1985	1000
		Upper Mottled Anorthosite		
	Subzone A	Pyroxenite, noritic and gabbroic rocks, mottled and spotted anorthosite	1265	1200
		Merensky Reef		
		Thickness of Main Zone	3940	2860
		Total thickness	6210	4650

in the east. It occupies a rugged, mountainous region which can be regarded as the southern continuation of the Leolo Mountains. The thickness was calculated as being 3940m, which is about 1000m more than that calculated by Molyneux north of the Steelpoort River and may in part be due to possible strike-faults in Subzone B of this zone. This faulting is extremely difficult to evaluate as the rocks of this subzone are very homogenous in appearance and also show very little variation in composition of the cumulus phases (Folder III).

a) Subzone A

All the specimens investigated from this subzone are from a bore-hole drilled by Rand Mines on the farm Pietersburg 44 JT. The top of this subzone is taken at the so-called "Upper Mottled Anorthosite" which could be followed for some distance along strike close to the eastern boundary of the area mapped. Only in the extreme north-eastern corner are rocks below this horizon present on the farm Hebron 5 JT (Folder I).

No specimens were available from the Merensky Reef, but this reef has been described in some detail by several authors from various localities of the Bushveld (Cousins, 1964, p. 227-229, and 1969, p. 239; Van Zyl, 1970, p. 91-93; Liebenberg, 1970, p. 181-189) as well as by Roux (1968, p. 69-74) east of this area.

Thirty-five metres above the Merensky Reef is the well known Bastard Reef, which is a feldspathic pyroxenite (orthopyroxene-plagioclase cumulate). It is separated from the Merensky Reef by alternating mottled anorthosite and spotted noritic to anorthositic rocks. The most common rock type for 100m above the Bastard Reef is mottled anorthosite which in turn is succeeded, after some normal gabbroic rocks, by the prominent "porphyritic norite". These porphyritic rocks are about 200m thick and contain large crystals of orthopyroxene which constitute on an average about 20 per cent by volume of the rock and are characterized by numerous small inclusions of plagioclase laths. Directly underlying this porphyritic norite is a fine-grained plagioclase-orthopyroxene cumulate, some 20m thick, which corresponds to the height of the needle-norite in other localities. Although no typical needles of orthopyroxene as described by Willemse (1969a, p. 15) were found in these rocks, some of these crystals tend to have a pronounced prismatic habit.

The Main Mottled Anorthosite of Subzone A is approximately 50m thick, 700m above the Merensky Reef. It forms a prominent exposure on the face of a cliff on Hebron 4 JT in the extreme north-eastern corner of the area. Mottled anorthosite is however developed intermittently in the overlying 80m and the underlying 60m and consequently this whole zone of 200m is often referred to as the Main Mottled Anorthosite (Molyneux, 1970, p. 15).

The top 400m of this subzone consists of fairly uniform gabbroic rocks which contain a few thin layers of spotted and porphyritic rocks as well as three layers of mottled anorthosite at the top. The upper two of these are about 10m apart (Upper Mottled Anorthosite) and mark the top of Subzone A of the Main Zone. Apart from separating the variable rock-types of Subzone A from the fairly uniform overlying gabbroic rocks, this anorthosite is situated in the sequence close to the first appearance of inverted pigeonite and also close to a small compositional break of the cumulus phases in the sequence (Folder III).

b) Subzone B

Practically the whole of Subzone B consits of monotonous gabbroic rocks which show hardly any variation from top to bottom. This subzone is close to 2000m thick in this area, although two faults may possibly have caused duplication of parts of the sequence. The most characteristic textural feature of the rocks of this subzone, is that the orthopyroxene is optically continuous over large areas with the result that, in hand-specimen, cleavage planes reflect the sunlight over large areas (Fig. 35).

At the top of this subzone is a fine-grained norite, about 100m thick, which could be followed for 20km along strike directly underlying the Pyroxenite Marker at the base of the next subzone. In the south, these fine-grained rocks contain large quantities of cumulus magnetite and also more cumulus clinopyroxene than in the north (G453 and G450). Rocks of the same stratigraphical horizon, east of Stoffberg and also farther south, contain, apart from magnetite, dark gray to black plagioclase crystals, the colour of which is caused by numerous inclusions of tiny rods of magnetite, (Groeneveld, 1970, p. 39). These dark gabbroic rocks are not developed in the Roossenekal area. This lateral change in composition of the rock types in one correlated layer suggests that the composition of the magma was not uniform throughout the chamber and that it was probably more iron-rich in the south than in the north.

In the west of the area, on the farm Buffelsvallei 170 JS gabbroic rocks of the Main Zone outcrop south of the Blood River. The highest exposed rocks contain small amounts of magnetite and these rocks are therefore correlated with the top of Subzone B east of Roossenekal.

c) Subzone C

The base of Subzone C is taken at the contact between the fine-grained rocks of the previous subzone and the overlying Pyroxenite Marker of the Main Zone. This pyroxenite, first described by Lombaard (1934, p. 7) was found to be an excellent marker and was followed for more than 80km along strike by Molyneux (1970, p. 22) and the author, north and south of the Steelpoort Park Granite respectively. The Pyroxenite Marker does not seem to be present in the area to the south, but Groeneveld (1970, Fig. 1, p. 38) recorded a compositional break of the cumulus phases in the sequence above the black gabbroic rocks.

The thickness of the Pyroxenite Marker could not be determined in the field. It usually outcrops as a few boulders in a slight depression between parallel dipslopes east of Roossenekal. On the northern portions of Mapochsgronde 500 JS and on the adjoining farms a slightly coarser-grained pyroxenite is developed, a few metres below or sometimes directly below the Pyroxenite Marker. No sulphides were found to be present in this pyroxenite.

The rocks of the lower half of Subzone C can easily be recognized in the field in that they contain primary cumulus orthopyroxene in contrast with the large units of similarly orientated grains of this mineral in the over- and underlying rocks. In appearance they are similar to the rocks of Subzone A. Spotted varieties are characteristic owing to large crystals (up to 5mm in diameter) of orthopyroxene. Some of the "porphyritic" rocks of this subzone differ, however, from those of Subzone A as they contain larger amounts of clinopyroxene which is present as long needles orientated parallel to the plane of layering. The character and appearance of these clinopyroxene needles (up to 8mm long and 1mm wide) is very similar to that of the orthopyroxene in the needle-norite described by Willemse (1969a, p. 15) from Subzone A.

Two layers of mottled anorthosite are present about halfway up in this subzone, the upper one of which could be followed for some distance along the strike to the west of and parallel to the road to Steelpoort Park. Above this anorthosite, the rocks are very similar to those of Subzone B.

3. The Upper Zone

This zone, 2270m thick, occupies the area from Roossenekal in the east to the foot of the Sekhukhune Plateau in the west, as well as the low-lying region south and west of Tauteshoogte. The division between the Upper and the Main

Zone is taken at the appearance of magnetite in the rocks. This is generally in a fairly prominent mottled anorthosite in which some of the mottles are caused by intercumulus magnetite (Molyneux, 1970, p. 22).

a) Subzone A

The top of this subzone is taken at the base of the Main Magnetitite Seam in contrast to the subdivision by Molyneux (1970, p. 24) who considers the boundary to be at the base of an olivine gabbro some 50m below the Main Seam. This olivine gabbro was not found in the Roossenekal area, but may possibly be concealed by the large amount of magnetitite rubble up-dip from the Main Seam. Because of the large amount of magnetitite rubble (Folder I), the author has resorted to river-sections to determine the sequence of this subzone. In most cases, however, it was found that where rivers traverse the massive and resistant Main Magnetitite Seam, the courses follow lines of weakness in the rocks, i.e. where faults and folds are developed. This, together with the low dips of the rocks, made mapping and reconstruction of the sequence difficult, and consequently some uncertainty still exists about the succession of rock types of this subzone.

Above the mottled anorthosite, which forms the base of the Upper Zone, follows some magnetite gabbro which contains the first of the lower magnetitite seams. About 30m above Lower Seam 1 is a mottled anorthosite, about 1,5m thick which contains disseminated sulphides. This is overlain by Lower Seam 2. Lower Seam 3 follows only a few metres above and was only observed on Zwartkop 142 JS.

The magnetite gabbros above these two seams are succeeded after a short distance by a very fine-grained magnetite-bearing gabbroic rock. At its upper contact, big xenoliths of the latter were found in the overlying magnetite gabbro (Fig. 14) in an outcrop in a tributary of the Mapochs River, north-east of the Mapochs Mine. This magnetite gabbro is fairly homogeneous, about 60m thick, and contains two layers of mottled anorthosite in which a few specks of intercumulus sulphides were observed. At the base of the Main Seam is the well-known mineralized anorthosite which was found to be about 3m thick in this area.

In an effort to obtain a clearer picture of the sequence of rocks in Subzone A, the author investigated outcrops in a tributary of the Mapochs River near the southern boundary of Zwartkop 142 JS. It was, however, found that the sequence differs in several respects from that to the south, e. g. :

i) The mottled anorthosite at the base of this subzone contains very little or no magnetite. The contact with the underlying gabbro of the Main Zone is irregular and large inclusions of the one are often encountered in the other.

ii) The first magnetitite seam is followed by about 6-7m of magnetite gabbro and is overlain by 12m of mottled anorthosite which seems to cut across the lower horizons in places.

iii) The mottled anorthosite below Lower Seam 2 is exceptionally rich in sulphides in this locality.

iv) Above the very fine-grained gabbro is a prominent mottled anorthosite, about 3m thick.

(v) A magnetitite plug is situated below these fine-grained rocks. This plug is surrounded by anorthositic rocks which contain little veinlets and nodules of magnetitite (Hammerbeck, 1970, p. 308).

The sequence of rocks in this river section is by no means clear. The abundance of anorthositic rocks which seem to cut across the normal layering, the presence of a magnetitite plug and shearing, seems to indicate that considerable disturbance took place during and after consolidation of the rocks. Much more detailed mapping in this area is necessary to unravel these complex relationships.

b) Subzone B

The Main Magnetitite Seam at the base of this subzone differs very little in appearance from that in the Magnet Heights area, as described by Molyneux (1964, p. 58). Only Upper Seams 1 and 2 were found in this area, directly above the Main Seam, because of poor exposures of the greater part of Subzone B. In the valley of the Mapochs River, at the boundary between Mapochsgronde 500 JS and Zwartkop 142 JS, two mottled anorthosites are developed above these seams. The lower one of these two is slightly more than 1,5m thick and could be followed for some distance along strike (Folder I). This anorthosite is correlated with the one directly underlying Seam 3 in the Magnet Heights area (Molyneux, 1964, p. 67). In the same valley, fairly good exposures of the overlying magnetite gabbros as well as Magnetitite Seams 6 and 7 are present. The only outcrop of the feldspathic pyroxenite some distance below Seam 6 is present east of the Erts Railway Station, close to the vermiculite-bearing pegmatoid (Folder I).

Owing to poor exposures, the sequence of rocks at the top of this subzone is not quite clear. The appearance of olivine is generally taken as being the beginning of Subzone C. These olivine-bearing rocks usually form a fairly prominent ridge west of, and parallel to, the main road from Middelburg to Steelpoort. However, one specimen collected some distance below this ridge (G658) was found to contain some olivine, whereas some of the rocks from this scarp contain very little (G365, G351) and sometimes no olivine at all. Underlying this scarp there seem to be some magnetite gabbro and anorthosite which outcrop intermittently along strike and the presence of magnetitite rubble associated with these rocks seems to indicate the presence of an additional magnetitite seam at the top of Subzone B.

c) Subzone C

The basal 150m of this subzone seems to consist of alternating layers of olivine gabbro, magnetite gabbro, anorthosite and troctolite. The Sisal Marker, a magnetite-bearing troctolite about 30m thick, was taken by Molyneux as the base of this subzone, but it is developed about 40m above the first olivine-bearing rocks in this area. The top of this olivine-rich basal unit of Subzone C is taken at a characteristically fine-grained norite which contains, apart from large amounts of cumulus inverted pigeonite, also a few cumulus crystals of olivine (G314). On Onverwacht 148 JS two layers of these fine-grained rocks are developed.

Magnetitite Seam 8 follows directly on this olivine-bearing norite and marks the appearance of seven seams which succeed each other at short distances at the base but at greater intervals higher up. Interlayered rocks are magnetite gabbro, which tend to be anorthositic at the base of the seams, and two thin layers of olivine gabbro above and below Seam 11. Seam 13 is followed by a prominent mottled anorthosite some 5m thick, which is characterized in that the lower 1,5m contains smaller mottles than the upper 3,5m. Owing to differential weathering of the alternating rock-types in this subzone the layering is clearly visible in the field (Fig. 15).

d) Subzone D

The rocks of this subzone contain andesine and consequently most authors (Boshoff, 1942, p. 24; Wager and Brown, 1968, p. 376; Willemse, 1969, p. 10; Groeneveld, 1970, p. 40, and Molyneux, 1970, p. 26) have termed these rocks either olivine diorite or ferrodiorite. If olivine is present in these rocks, it

Fig. 14. Large inclusion of very fine-grained magnetite gabbro in ordinary magnetite gabbro. Subzone A of the Upper Zone, Mapochsgronde 500 JS

Fig. 15. Layering of the rocks of Subzone C of the Upper Zone. Luipershoek 149 JS.

should be more iron-rich than about Fo_{40} according to the definition of ferrodiorite (Wager and Brown, 1968, p. 78) and for the Bushveld, the usage of this term is therefore justified. It must however, be borne in mind that the majority of olivine diorites contain fair amounts of cumulus apatite (Folder IV), usually between 4 and 8 per cent by volume, which indicates that the magma was still rich in Ca and would probably have precipitated labradorite if the concentration of phosphorus did not reach saturation at the level where andesine appears in the sequence. Furthermore, where apatite is not present in these rocks, as for instance between Seams 17 and 21, the Ca-content of the plagioclase increases noticeably and attains values of above An_{50} (Folder III). The appearance of all these rocks is very similar to the magnetite gabbros from lower horizons and for the same reason Wager and Deer (Wager and Brown, 1968, p. 78) originally decided to refer to the ferrodiorite of Skaergaard as ferrogabbro. For the above reasons the author would favour the term olivine gabbro, but in order to avoid further confusion in terminology, the name olivine diorite (ferrodiorite) is retained for the majority of rocks in this part of the sequence.

The term "diorite" is used in this treatise for the topmost 100m of the intrusion, because of the large amount of hornblende present in these rocks. Olivine is very subordinate, but as it has an extremely iron-rich nature, the term "fayalite diorite" is often used by other authors (Boshoff, 1942, p. 29, and Groeneveld, 1970, p. 41). The name "granodiorite" (Molyneux, 1970, p. 26) for rocks which constitute the uppermost part of the Layered Sequence, is not recommended as this term defines more closely the hybrid rocks which are associated with the overlying acid roof of the complex.

Olivine diorite is the most common rock type of Subzone D and constitutes about 70 per cent of this sequence. Olivine-free rocks are characteristically developed where magnetitite seams are present (Folder IV). The first of these olivine-free rocks are developed above and below Seam 15 and consist of mottled anorthosite which underlies this seam and magnetite gabbro which overlies it. Directly above this magnetite gabbro is the ovicular olivine diorite, characterized by the presence of numerous elongated inclusions which consist exclusively of plagioclase (Fig. 16). The rocks between Seams 17 and 21 are mostly olivine-free "anorthositic diorites" alternating with magnetitite seams and thin layers of olivine diorite. A peculiar rock which contains numerous perfectly spheroidal

Fig. 16. The ovicular olivine diorite, Subzone D of the Upper Zone. Onverwacht 148 JS.

Fig. 17. Spheroidal inclusions of anorthosite in magnetite diorite. Luipershoek 149 JS.

inclusions of anorthosite (Fig. 17) outcrops a small distance below Seam 21 on Luipershoek 149 JS. In appearance it is analogous to the "Boulder-anorthosite" below the Merensky Reef (Cousins, 1964, p. 228) and the "Tennis-ball Marker" of the Main Zone in the Kruis River area (Von Gruenewaldt, 1966, p. 50) in which the inclusions are spheres of pyroxenite. No satisfactory explanation for the origin of these rocks can be offered at this stage.

4. The Magnetitite Seams of the Upper Zone

The magnetitite seams of the Upper Zone were described in detail by Molyneux (1964, p. 57-77) in his investigation of the rock types at Magnet Heights. Not all the seams are exposed in the Roossenekal area, but those which are present are strikingly similar to those at Magnet Heights. The nature of most of the magnetitite seams developed in the Roossenekal area are diagrammatically illustrated in Fig. 18.

a) Magnetitite Seams of Subzone A

The magnetitite seams of this subzone differ slightly from those described by Molyneux (1964, p. 57-58). Lower Seam 1 usually consists of 5cm of solid magnetitite at the base, followed by about 75cm of feldspathic magnetitite. The upper contact is usually gradational into the overlying magnetite gabbro. This seam is exceptionally thick on the farm Zwartkop 142 JS where it consists of massive and plagioclase-rich magnetitite alternating with magnetite gabbro over a thickness of 2, 5 to 3 metres.

Lower Seam 2 is very similar to Lower Seam 1, and is about 80cm thick and composed of feldspathic magnetitite with lenticular patches of solid magnetitite near its base. Lower Seam 3 was only observed on Zwartkop 142 JS where it consists of about 1m of feldspathic magnetitite.

An additional thin magnetitite seam was found on Zwartkop in the magnetitite gabbros about half-way between Lower Seam 3 and the Main Magnetitite Seam. This seam consists of 4cm of solid magnetitite at the base and 11cm of feldspathic magnetitite at the top.

b) Magnetitite Seams of Subzone B

i) The Main Magnetitite Seam is the most prominent of all the seams of the Upper Zone, and owing to its thickness and its solid nature, it outcrops practically everywhere in the Bushveld Complex where this zone is developed. It forms prominent pavements east of the main road from Middelburg to Steelpoort and is currently being mined north of Roossenekal by Highveld Steel and

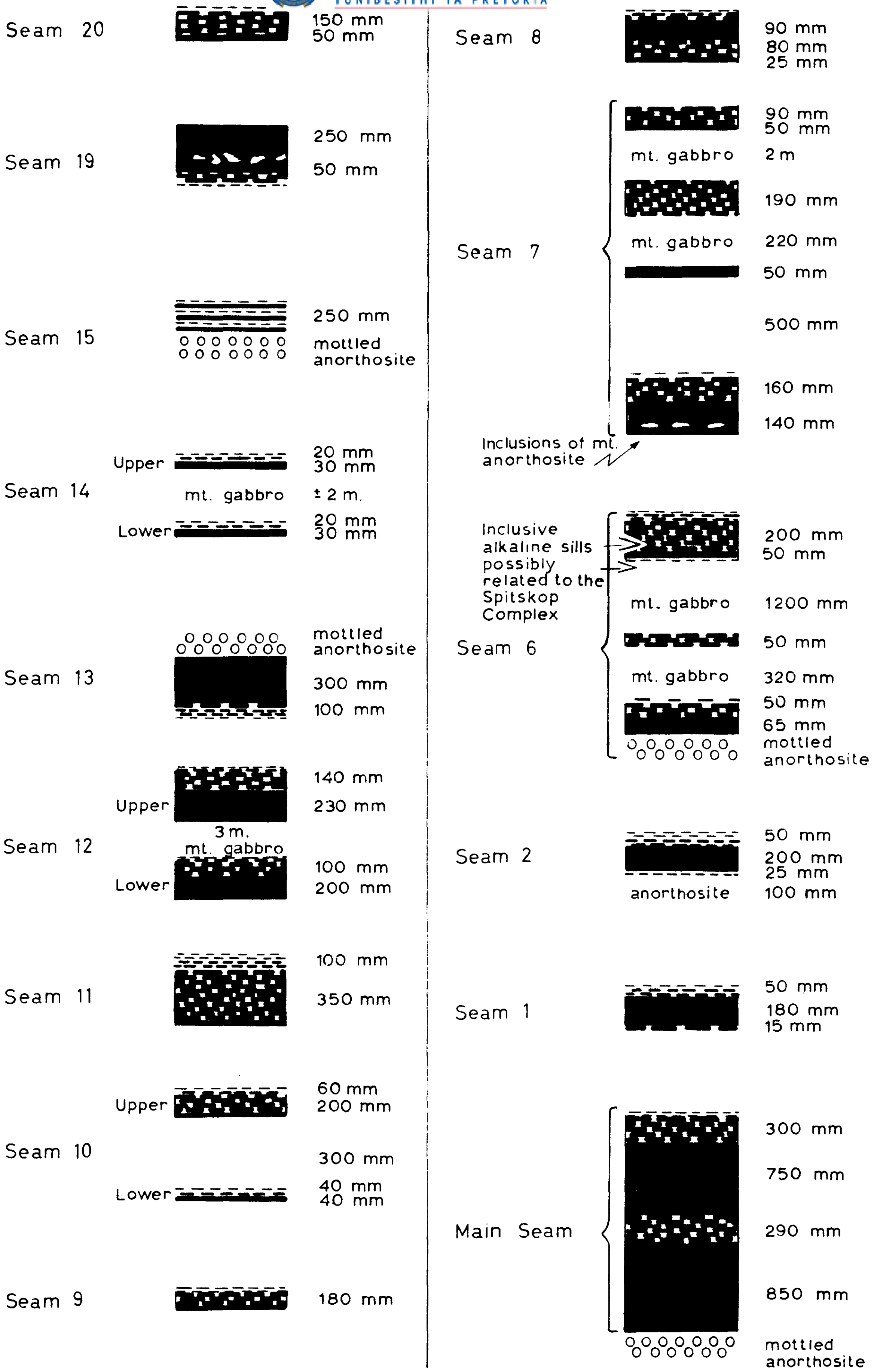

FIG. 18. SCHEMATIC REPRESENTATION OF SOME OF THE MAGNETITITE SEAMS OF SUBZONES B, C AND D OF THE UPPER ZONE. SOLID - PURE MAGNETITITE, DOTTED - FELDSPATHIC MAGNETITITE. STRIPED - GRADATION INTO MAGNETITE GABBRO.

Vanadium Corporation Limited (Fig. 19). Up-dip from these pavements, large areas are covered by a thick layer of magnetitite rubble, owing to dislocation of the seam caused by the weathering of the underlying anorthosite (Folder I).

ii) Only the first two of the five magnetitite seams which are present within 30m above the Main Seam at Magnet Heights (Molyneux, 1964, p. 65-67) were found in this area. This may in part be due to poor outcrops as especially Seams 3 and 5 are friable and feldspathic and only mappable in areas of good exposure (ibid., p. 67).

iii) Seams 6 and 7 are exposed in the Mapochs River at the boundary between Mapochsgronde 500 JS and Zwartkop 142 JS. Both consist of several seams over thicknesses of 2 and 3, 5m respectively (Fig. 18). In the remainder of the area they form small, rubble strewn scarps which run parallel to each other for several kilometres along strike.

c) Magnetitite Seams of Subzone C

i) The lower three seams, Nos 8, 9 and 10, of this subzone succeed one another at short intervals and consist mostly of feldspathic magnetitite. They usually tend to weather to rubble composed of small fragments and outcrops are to be seen only in river sections, except in the case of Seam 8 which forms a few pavements overlying the fine-grained olivine-bearing norite. Seam 10 consists of two thin seams, approximately 30cm apart. (Figs. 18 and 20).

ii) Although feldspathic, Seam 11 could be followed along strike for many kilometres, and is usually found at the base of a fairly resistant olivine gabbro. It is the thickest of the seams of Subzone C and forms pavements on Onverwacht 148 JS and Luipershoek 149 JS.

iii) Seam 12 consists of two seams, very similar in nature and about 3m apart. (Fig. 18).

iv) Seam 13 is unusual in so far as it has a sharp upper contact with the overlying mottled anorthosite and a gradational lower contact with the underlying magnetite gabbro. This seam, together with the overlying mottled anorthosite is an excellent marker and its nature and appearance is similar to that at Magnet Heights (ibid., p. 75).

v) Seam 14 consists of two thin seams about 2m apart and outcrops only sporadically. On Luipershoek 149 JS the upper one is locally much thicker and consists of 50cm of feldspathic magnetitite.

Fig. 19. One of the quarries on the Main Magnetitite Seam at the Mapochs Mine, Roossenekal.

Fig.20. Outcrop of Magnetitite Seam 10 on Luipershoek 149 JS. Note the thin lower seam about 30 cm below the more prominent upper seam.

d) Magnetitite Seams of Subzone D

i) The lowest seam of this subzone, No. 15, is usually not well developed, but a perfect exposure is on Onverwacht 148 JS where it is seen together with underlying mottled anorthosite and the overlying magnetite anorthosite and magnetite gabbro on a steep cliff on the south side of the Steelpoort River. The seam is very thin, and consists of a few thin magnetitite bands, alternating with magnetite anorthosite.

The presence of this seam is also indicated by rubble on the southern portion of Onverwacht 148 JS and also on Steynsdrift 145 JS. In the case of the latter occurrence, the magnetitite fragments are fairly large, about 10cm in diameter, which indicates a local thickening of the seam.

ii) The only indication of a magnetitite seam which could correspond to Seam 16 of the Magnet Heights area is the presence of a small amount of magnetitite rubble associated with a thin layer of magnetite gabbro near the common beacon of the farms Onverwacht 148 JS, Duikerskrans 173 JS and Mapochsgronde 500 JS.

iii) Seam 17 is close on 60cm thick and is well developed on the farm Onverwacht 148 JS. Its presence is usually indicated by large blocks of magnetitite, but nowhere could exposures be found to indicate contact-relationships with the over- and underlying rocks. This seam is considerably thinner at the boundary between Duikerskrans 173 JS and Mapochsgronde 500 JS where it consists of a few thin stringers of magnetitite in magnetite anorthosite.

iv) Seams 18 and 19 occur close to each other in a river section on Luipershoek 149 JS, only a small distance above Seam 17. Seam 18 is a thin feldspathic magnetitite, whereas Seam 19 is about 30cm thick and has a gradational lower contact and a sharp upper contact (Figs. 21 and 22). These seams peter out gradually in a southerly direction and in the valley of the Steelpoort River on Duikerskrans 173 JS only one of these was observed as a thin concentration of magnetite in the gabbroic rocks.

v) Seam 20, seldom seen in outcrop, is about 20cm thick. The lower 5cm of the seam are fairly solid and the upper 15cm feldspathic. It rests with a sharp lower contact on magnetite anorthosite.

vi) The giant of all the magnetitite seams is undoubtedly Seam 21. It is almost 10m thick, but owing to a large number of lenses of anorthosite, it is friable and seldom forms prominent outcrops (Fig. 23). Small cumulus crystals

Fig. 21. Banded magnetite gabbro below Seam 19 (at hammer). The banding is caused by varying amounts of magnetite Onverwacht 148 JS.

Fig 22. Magnetitite Seam 19, characterized by a sharp upper contact, gradational lower contact and irregularly shaped inclusions of anorthositic material at its base. Onverwacht 148 JS.

of olivine are distributed evenly throughout the magnetitite seam. The presence of the seam can clearly be noticed on aerial photographs as a low ridge which runs parallel to the foot of the Sekhukhune Plateau. It could be followed for about 20km along strike, from Paardekloof 176 JS in the south, where a few outcrops are present in the dongas below Tauteshoogte, up to the boundary of Steynsdrift 145 JS in the north where it disappears under a thick covering of talus at the foot of the plateau. Six kilometres farther north, it reappears at a topographical level much lower than to the south, approximately in line with Seam 15 on Steynsdrift 145 JS. Hammerbeck (1970, Fig. 1, p. 300) considers this to be due to faulting. In the west of the area, it outcrops in a few places on Doornpoort 171 JS and it was also intersected in a bore-hole (DDH2, Folder I) drilled by the Anglo American Corporation on this farm.

5. Pronounced lateral variation of facies in the Layered Sequence

The sequence of rock types in Subzone D of the Upper Zone between Bothasberg and Tauteshoogte differs considerably from that described above. This lateral "facies change" takes place over a distance of about 10km, but owing to poor exposures south-east of Tauteshoogte, it could not be studied in detail. Outcrops in the upper reaches of the Blood River are, however, slightly better and it is therefore possible to attempt a correlation between the two sequences.

When the rocks of Subzone D are followed southwards from Onverwacht 148 JS, a noticeable increase in the amount of olivine diorite between Seams 17 and 21 can be observed. The former seam gradually becomes thinner and disappears on Paardekloof 176 JS, whereas olivine-free rocks below Seam 21 make way for olivine-bearing rocks. Olivine diorite was also intersected above and below this magnetitite seam in bore-hole DDH2 on Doornpoort 171 JS, which indicates that the change in sequence also takes place in a westerly direction.

Farther to the south, in the valley of the Blood River, the lowest horizon exposed along the road from Stoffberg to Groblersdal consists of apatite-free olivine gabbro which contains plagioclase of composition An_{51}. It is overlain by a prominent magnetitite seam which could be followed intermittently in the Blood River and its tributaries from Rhenosterhoek 180 JS in the east to Grootkop 185 JS in the west (Folder I and Fig. 32). On the farm Rhenosterhoek 180 JS it consists of one massive seam, about 1-1,5m thick, characterized by a

Fig. 23. Numerous lenticular inclusions of anorthosite in Magnetitite Seam 21. Onverwacht 148 JS.

Fig. 24. The magnetitite seam on Kafferskraal 181 JS.

15cm feldspathic parting in the middle, but on the south-eastern portion of Kafferskraal 181 JS, it locally splits into three seams of variable thicknesses (Fig. 24). In the northern tributaries of the Blood River, on the farm Kafferskraal 181 JS, it consists of two seams. The lower one is 60 cm thick and is separated by 1m of weathered magnetite gabbro from the upper seam which is about 45cm thick. On Grootkop 185 JS only one seam, 1m thick, was observed. A mottled anorthosite, the plagioclase of which has a composition of An_{52} overlies this seam on the south-eastern portion of Kafferskraal 181 JS. The mottles in the lower metre of this anorthosite are smaller than those in the upper portion of the anorthosite, thus, in appearance, closely resembling those which overlie Seam 13 to the north.

A thin magnetitite seam, a few centimetres thick with a sharp lower and gradational upper contact, outcrops in the Blood River a short distance to the west of the above-mentioned occurrence. The over- and underlying rocks of this seam are very weathered and it could not be determined whether they are olivine-bearing or not. Overlying the mottled anorthosite is olivine-free magnetite diorite (plagioclase An_{48}) in which a magnetitite seam, 10cm thick, is present on Blaauwbank 179 JS.

The overlying olivine diorite (Folder I, Fig. 32) could be followed in several stream beds from Blaauwbank 179 JS in the east to Grootkop 185 JS in the west. Along these river sections and on the slopes of Grootkop, fairly continuous outcrops are present right up against the roof and no additional magnetitite seam was observed. This olivine diorite contains plagioclase with a composition of An_{42} or lower which corresponds to that above Seam 21 farther north. Apatite is present in appreciable quantities in these rocks in contrast with the olivine gabbros lower down in the sequence.

The composition of the plagioclase of the rocks over- and underlying the prominent magnetitite seam in the Blood River valley, corresponds to that of Subzone C in the north. This is also borne out by the absence of cumulus apatite in the olivine gabbro. The overlying olivine-free rocks fall in the diorite field of composition on the grounds that the plagioclase is andesine and may therefore be correlated with the olivine diorite at the base of Subzone D farther north.

The sequence of rocks exposed in the Blood River valley is similar to that described by Groeneveld (1970, Fig. 3, p. 70) from south of Stoffberg. A considerable number of faults seem to be present between Bothasberg and

Tauteshoogte and this, together with relatively poor exposures, (Fig. 32), makes it impossible at this stage to calculate thicknesses accurately. For the construction of this sequence (Fig. 25) the diagrammatic section by Groeneveld (1970, Fig. 3) was therefore used. The sequence of rocks in the Stoffberg area (ibid., Figs. 1 and 3) and also that in the Blood River valley are referred to in the ensuing discussion as the southern section, whereas the sequence of the Tauteshoogte-Roossenekal area will be referred to as the northern section (Fig. 25). To illustrate lateral cryptic variation of some of the cumulus phases, compositions of these are added in both sections on Figure 25.

Groeneveld (1970, Fig. 3) correlates the prominent magnetitite seam in the Blood River valley and also to the east of Bothasberg with Magnetitite Seam 21 east of Tauteshoogte (ibid., p. 44) but notes the distinct differences between the two. The magnetitite seams between this seam and the Main Seam in the Stoffberg area are correlated with those of Subzone C farther north. On the basis of this correlation, the whole sequence between the Main Seam and Seam 21 is reduced by about 50 per cent, i.e. from 1870m to about 900m, whereas the olivine-diorites above Seam 21 in the northern section have a fourfold increase in thickness in the south. These tremendous variations in thicknesses between the various parts of the Upper Zone take place over a distance of only 10km whereas the total thickness of the Upper Zone decreases by only about 15 per cent over the same distance.

On the grounds of this rather small difference in total thickness, the author attempted a correlation based on certain marker horizons in both sequences and also on the appearance of certain cumulus phases (Fig. 25).

The magnetitite seams of Groeneveld's Subzone C occur about 200m above the Main Seam in the Stoffberg area, at a height which corresponds closely to Magnetitite Seams 6 and 7 in the northern section. Olivine appears in both sequences between 500-600m above the Main Seam, and the prominent magnetitite seam in the Blood River valley corresponds to a position of Seam 13 to the north. As already mentioned above, the mottled anorthosite which overlies this magnetitite seam in the south is very similar in appearance to that above Seam 13 to the north. In both sections, cumulus apatite appears about 250m above these seams.

If the composition of cumulus phases in the two sections, above and below horizons which can be correlated with certainty, as for instance the Main

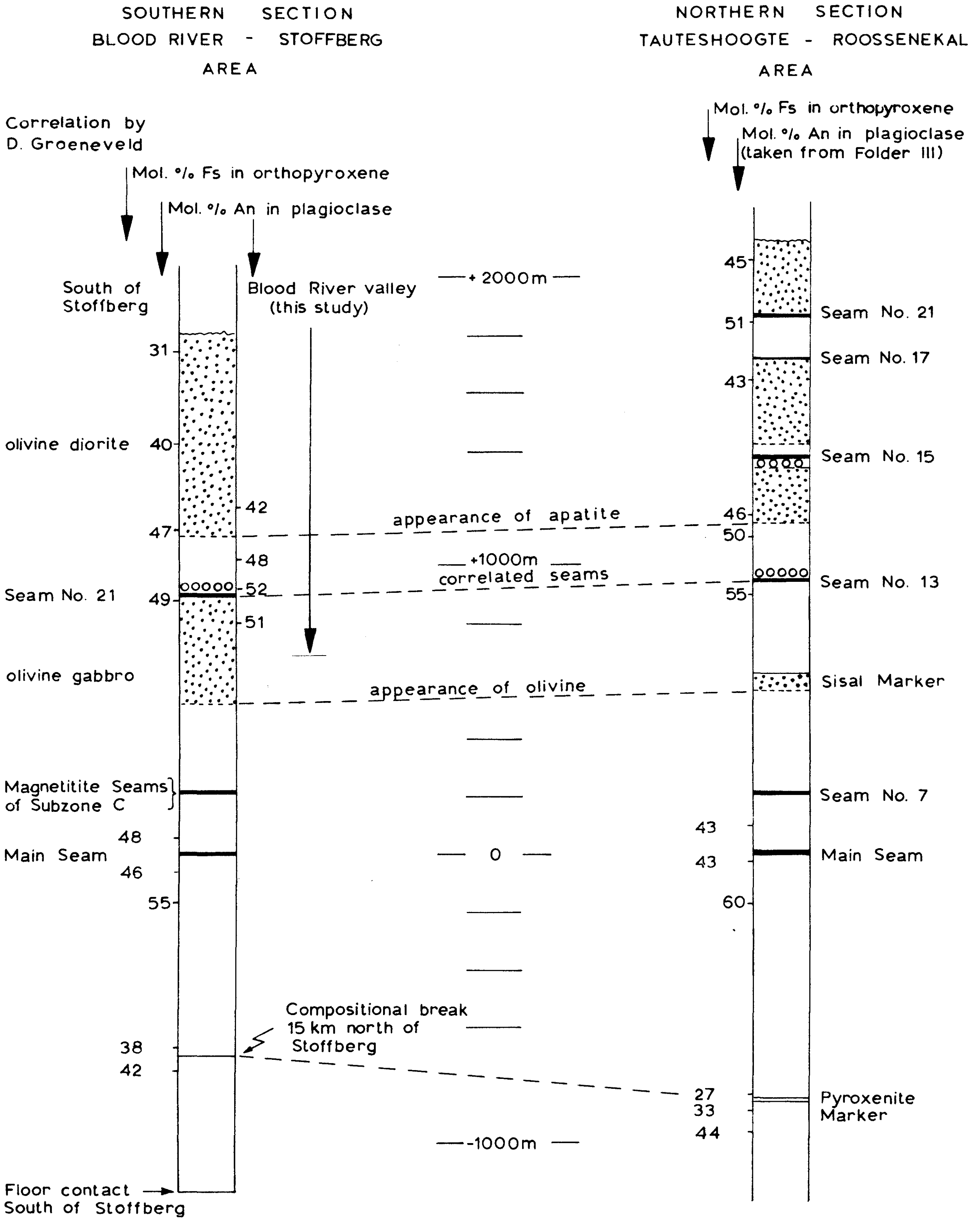

FIG. 25. DIAGRAMMATIC REPRESENTATION OF THE FACIES CHANGE IN THE BUSHVELD COMPLEX. LEFT-HAND COLUMN AND COMPOSITION OF CUMULUS PHASES FROM AREA SOUTH OF STOFFBERG AFTER GROENEVELD (1970, FIG. 1, 2 AND 3)

Magnetitite Seam and the compositional break at the Pyroxenite Marker are compared, an increase in the less refractory components of these phases from north to south is noted.

The thickness of the complete succession of rocks of the Layered Sequence south of Stoffberg is given by Groeneveld as being about 3000m (ibid., Figs. 2 and 3) which is considerably thinner than the Layered Sequence farther to the north. This is probably due to lateral extension of the magma chamber during crystallization which may have been caused by an influx of large quantities of fresh, undifferentiated magma. Lateral extension caused the magma to be emplaced in relatively cool environments and consequently conductive heat loss was more effective in the south than in the north where an extensive metamorphic aureole was already established in the over- and underlying rocks. It is therefore envisaged that a lateral temperature gradient existed in the magma, resulting in differences in composition of cumulus phases which settled simultaneously in the two areas.

Lateral cryptic variation of cumulus phases has been described by Hughes (1970, p. 323) from the Great Dyke. He found that in the lower rhythmically layered sequence of the Hartley Complex, the orthopyroxene in correlated layers changes in composition from the centre to the margin of the complex. In the marginal areas the orthopyroxene contains on an average, between 4-6 per cent less of the En molecule than in the central portion some 120km away. This is considered by him to be due to a more rapid decrease in temperature in a thinner body of basic magma that gave rise to a condensed sequence in the marginal areas of the complex compared to the central area.

Another explanation for the observed lateral cryptic variation in the Bushveld Complex is the influx of fresh, undifferentiated magma in the central portion of the chamber, thus pushing the existing differentiated magma outwards into the marginal areas. This would result in a change in composition of the magma from north to south, a possibility already mentioned in the section dealing with the rock types at the top of Subzone B of the Main Zone. The appearance of cumulus apatite at the same height in the intrusion in both sequences militates against such differences in composition. If the magma in the south were more differentiated than that in the north, cumulus apatite would be expected to appear at a lower position in the southern sequence. As this is not the case, the phosphorus concentration in the magma is considered to be the decisive factor in the proposed correlation. Fractional crystallization caused a gradual enrichment of the phosphorus content in the remaining magma which reached saturation at the top of Subzone C. Cumulus apatite is therefore present in the overlying rocks in both sections, but owing to differences in temperature during crystallization of correlated horizons in the two sequences, apatite is associated with lower-temperature phases in the south and with higher-temperature phases in the north.

This difference in temperature and consequent crystallization of less refractory phases in the south also had a pronounced effect on the succession of rock types in the two sequences. Crystallization of lower-temperature phases extracted more iron from the magma in the south than in the north with the result that the crystallizing magma in the north was enriched in iron. Small periodic increases in the oxygen pressure (Osborn, 1962, p. 221-225) gave rise to the lower magnetitite seams of Subzone C in the north, but did not cause the formation of magnetitite seams in the cooler, less iron-rich magma in the south. Crystallization of the ferromagnesian silicates, although Fe-rich, probably also led to some increase in the Fe-content of the magma in the south, so that the upper magnetitite seams of Subzone C are developed in both areas. The absence of magnetitite seams of Subzone D in the south may possibly also be due to extraction of sufficient iron from the magma during crystallization of the ferromagnesian silicates.

6. Mafic pegmatoids in the Layered Sequence

a) Magnetitite pipes

A striking feature of the area is the presence of numerous magnetitite pipes of which more than 100 were encountered in the field. Most of these are shown on the map (Folder I) and many occurrences indicated by one pipe actually consist of a cluster of a few small pipes (Fig. 26). The largest one is situated 100m east of Mapochsgronde 500 JS on the farm Klipbankspruit 76 JT (Fig. 27) and measures about 30m in diameter. The majority of pipes are however considerably smaller and the presence of some is indicated only by a few large boulders of magnetitite in the field. They are mostly circular in outline, but one elongated dyke-like pipe, 7m wide and 35m long is situated about 0,5km west of Galgkop on Mapochsgronde 500 JS.

The magnetitite pipes are encountered from the middle of Subzone B of the Main Zone up to Subzone D of the Upper Sone. The lowest occurrence consists

Fig. 26. A cluster of several small magnetitite pipes in the Upper Zone on Onverwacht 148 JS. Rocks in foreground are magnetite gabbro of Subzone C. Prominent ridge in middle distance is olivine-diorite at the base of Subzone D. Sekhukhune Plateau in background.

Fig. 27. A prominent magnetitite pipe on Klipbankspruit 76 JT. In the distance on the left are sediments of the Pretoria Series and on the right gabbros of the Main Zone.

of a cluster of small pipes, not far south of the beacon CH-IN 11 on the farm Uysedoorns 47 JT, whereas the highest plug is situated on the horizon of Magnetitite Seam 21 on the farm Steynsdrift 145 JS.

According to Willemse (1969b, p. 192) diallagite pegmatoid is sometimes found associated with these magnetitite pipes, but owing to the extensive magnetitite rubble which surrounds these pipes, no such rock type was observed in this area.

The distribution of the magnetitite pipes, most of which occur in two well-defined zones in the sequence, is of interest. The lower concentration of pipes is situated in Subzone C of the Main Zone, east of Roossenekal, whereas the upper concentration of pipes is at a horizon above and below Magnetitite Seam 8 in the Upper Zone. This distribution of the pipes would seem to favour the contention of Willemse (1964, p. 118) that their magma could have originated by a process such as filter-pressing or lateral secretion leading to a concentration of iron-rich fluids. Such a process would depend on the amount and composition of intercumulus liquid present in the crystal cumulate, and the forces by which these liquids were concentrated to escape to higher levels in the form of pipes. On a relatively small scale such a process could have given rise to single pipes, or, on a more regional scale, a concentration of pipes at certain horizons, as described above, could have originated.

The distribution in the sequence of the majority of magnetitite pipes in this area contradicts Coertze's (1962, p. 256) hypothesis that their emplacement was controlled by fault-zones, as no such faulting, with which the pipes could be associated, was observed.

b) Vermiculite-bearing pegmatoids

Two vermiculite-bearing pegmatoids are located in this area. One is situated close to the Erts Railway Station on the horizon of the feldspathic pyroxenite of the Upper Zone, whereas the other one occurs 3km south of Roossenekal, in the middle of Subzone B of the Main Zone (Folder I). According to the residents of the area, three additional pipes are known, all of which fall outside the area mapped. Of these, two are apparently situated north of Laersdrif and one north of the Mapochs Dam.

The first mentioned occurrence was investigated in some detail by Willemse (1953, p. 3-9). He considers it to be pipe-like in form and to transgress the layering of the country-rocks. Associated coarse-grained pyroxene crystals suggest, according to him, pegmatitic affinities of the rocks and a possible genetic relationship to diallagite pegmatoids which occur widely in the Bushveld Complex. Investigation of the physical properties of the vermiculite (ibid., p. 5-6) revealed it to be of a quality inferior to that from Phalaborwa, owing to an exfoliation factor which is only about half of that of the latter occurrence.

Gossans carrying chalcopyrite and malachite were also described by him (ibid., p. 7) from this locality. Analyses of the ore showed that it contains, apart from Cu, small quantities of Au and Ag, but negligible amounts of Pt and Ni.

Prospecting operations which started a few months ago, revealed additional interesting information about the pipe. For the greater part it seems to consist of intensely brecciated country-rock (Fig. 28). Unfortunately the big chunks of gabbroic rock are strongly weathered and it was not possible to determine the composition of cumulus phases in order to decide whether they were derived from lower horizons. Their angular nature would, however, indicate that they were not derived from any great depth, as is the case with the perfectly rounded inclusions in a similar pipe on Tweefontein 360 KT, close to the famous chromite occurrence at the Dwars River bridge (Ferguson and McCarthy, 1970, p. 75).

The large boulders of gabbroic rocks are embedded in diallagite pegmatoid which is mostly altered to brown amphibole. Occasional green malachite staining of this amphibole indicates that the pegmatoidal liquids also contained some copper and sulphur. On surface this gives rise to the Cu-bearing gossan described by Willemse. Crystals of magnetite and vermiculite are present in this amphibole-rock, but the bulk of the vermiculite occurs as large pockets, a few metres in diameter in the zone of brecciation (Fig. 29).

On the northern side of the present prospecting pit, an extremely magnetite-rich, vermiculite-bearing pegmatoid cuts across the zone of brecciation (Fig. 30). This pegmatoid contains, apart from books of vermiculite approximately 30cm in diameter, also smaller plates of this mineral in the magnetite. The magnetite of this pipe is extremely coarse-grained and forms crystals of up to 3cm in diameter, which indicates that it is not part of a magnetitite seam as previously believed by Willemse (1953, p. 4) but part of the pegmatoid.

The observed relationships point towards a forceful injection of the peg-

Fig. 28. Brecciated country-rock of the vermiculite-bearing pegmatoid west of Roossenekal. The matrix is amphibolized vermiculite-bearing diallagite pegmatoid.

Fig. 29. A large pocket of very coarse-grained vermiculite (bottom). Vermiculite-bearing pegmatoid west of Roossenekal.

matoid. It is envisaged that aggregation of volatile-rich intercumulus liquids took place at a lower horizon. The pressure of these liquids must have been higher than the load pressure and they probably intruded the overlying rocks in a pipe-like vent, simultaneously brecciating the country-rocks. The pipe itself is now filled with vermiculite and diallagite-bearing magnetitite whereas large pockets of vermiculite also crystallized in the surrounding zone of brecciation.

Only portions of this pipe have so far been opened up by exploration, and the actual shape is therefore not yet known, as it does not outcrop on surface. The width has been traversed by a wide trench, about 25m long. Excavation parallel to its major axis has not exceeded 30m at the time of writing, but the pipe seems to be elongated in a N-S direction.

The presence of the vermiculite pipe south of Roossenekal is indicated by small dumps of this mineral. No further information about this pipe could be obtained as prospecting operations ceased a long time ago and the pits have since fallen in.

The association of magnetitite with vermiculite and diallagite pegmatoid in these pipes clearly indicates that a genetic relationship exists between the various pipe-like bodies frequently encountered in the Bushveld Complex, as was envisaged by Willemse (1970a, p. 11).

c) Anorthositic pegmatoid

Coarse-grained anorthositic rocks are occasionally encountered in Subzones C and D of the Upper Zone. They usually outcrop as fairly large boulders over areas a few metres in diameter and have no preferred orientation with regard to the layering of the complex, or any preferred concentration with respect to position in this part of the Layered Sequence. In the field they are easily recognised by their light colour and large, anhedral crystals of plagioclase which may attain a length of 1cm or more.

Two specimens, G318 and G232 from close to the base of Subzone C on Onverwacht 148 JS and from the vicinity of Magnetitite Seam 20 on Duikerskrans 173 JS respectively, were investigated. In both occurrences the rocks consist of between 80-90 per cent of plagioclase, the core of which has a composition of about An_{62} whereas the mantle has an anorthite content of 52 per cent. The intercumulus minerals are, in order of decreasing abundance, green pleochroic hornblende, which in places contains small patches of clinopyroxene, quartz, magnetite and apatite.

Fig. 30. Magnetite-vermiculite-diallage pegmatoid (dark) cutting across brecciated country-rock (left). Shiny material at hammer and centre right is vermiculite. Vermiculite-bearing pegmatoid west of Roossenekal.

Fig. 31. Anorthositic pegmatoid (white) on Duikerskrans 173 JS. Note the coarse-grained nature of the pegmatoid and its sharp contact with the magnetite diorite (dark).

Of interest is the fact that the composition of the plagioclase in the pegmatoid is a few mol. per cent higher in anorthite than that of the surrounding country-rocks, and that they are often bent and saussuritized. The occurrence on Duikerskrans 173 JS has an irregular but sharp contact with the surrounding magnetite diorite (Fig. 31). Boshoff (1942, p. 53-55) also noted the presence of these rocks and found some of the plagioclase crystals to have a composition as high as An_{70-80}.

If these anorthositic rocks are pegmatoids of similar origin to the various other types in the Layered Sequence (Willemse, 1964, p. 118 and 1969a, p. 11) i.e. that they originated as a result of a concentration of volatile-rich intercumulus liquids and the emplacement of these into higher horizons, then the plagioclase is expected to be enriched in the albite molecule. However, as pointed out by Bowen and Tuttle (Wager and Brown, 1968, p. 387) the crystallization of a melt with moderate amounts of dissolved water, would, under sufficient load pressure, result in an increase in water and pH_2O in the remaining liquid and this in turn would have the effect of lowering the liquidus-solidus temperatures of the anorthite-albite system (Yoder et al., in Wager and Brown, 1968, p. 387). If, therefore, volatile-rich intercumulus liquid is expelled from the interstices of a pile of cumulus crystals, owing to an increase in the load pressure, and this liquid moves under pressure to higher levels in the intrusion, the plagioclase which crystallizes from it may have a higher anorthite content than that in the surrounding rocks. The bent plagioclase crystals and the associated hornblende indicate that the former were subjected to pressure and that the liquid from which they crystallized was enriched in water.

d) Diallagite pegmatoids

Two diallagite pegmatoids are located near the northern boundary of the farm Pietersburg 44 JT (Folder I) but were not investigated.