THE PETROLOGY OF THE IGNEOUS AND THE METAMORPHIC ROCKS IN THE VREDEFORT DOME AND THE ADJOINING PARTS OF THE POTCHEFSTROOM SYNCLINE

by

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ABSTRACT

The Igneous Rocks

Interpretation of gravity anomalies, the petrology of the igneous rock-suites, and the metamorphism of the rocks of the Witwatersrand System and some of the associated igneous rocks in and around the Vredefort Dome, indicate that this structure with its core of Archaean granite, is eccentrically underlain by a large mafic pluton (the central pluton).

Two igneous rock-suites synchronous with the igneous activity in the Bushveld Complex include the most important igneous rocks in the Vredefort Dome and the adjoining Potchefstroom Syncline. The oldest is a tholeiitic suite which forms sills, mainly in the sedimentary collar of the Dome. These sills are composed of dolerite, hyperite and norite. Variation in mineralogical composition of these sills shows a gravitational concentration of ferromagnesian minerals towards the stratigraphic base. This is regarded as proof that these sills were emplaced before the strata attained a vertical attitude during their overturning. The average mineralogical compositions of some of these sills were determined and they were found to contain between 45 and 80 per cent of pyroxene, whereas a chilled dolerite of one of these sills contains only 52 per cent of pyroxene. This variation in the average composition of the different sills is interpreted as the result of separation of magma at different stages and levels from a larger differentiating pluton, consequently these sills are considered to represent satellites of the central pluton.

The youngest is an alkaline suite and is represented by the Roodekraal and Rietfontein Complexes, the Lindequesdrift Intrusion, and the peralkaline rocks of the Vredefort Dome. The mafic portion of the Rietfontein Complex is layered and is probably funnel-shaped. It is composed of two rock series, namely a wehrlite-olivine gabbro series and a troctolite-picrogabbro

series. These series probably originated from two pulses of magma with small differences in composition. Crystallization in both series commenced with the primary precipitation of two essential minerals, i.e. pyroxene and olivine, and plagioclase and olivine, and terminated with the precipitation of the three essential minerals: olivine, pyroxene, and plagioclase.

The major rock-types of the Roodekraal Complex and the Lindequesdrift Intrusions are dioritic in composition. The spessartite at Lindequesdrift crystallized from a dioritic magma which probably contained a higher concentration of volatile constituents than the dioritic magma of the Roodekraal Complex.

The peralkaline rock-type of the Rietfontein Complex is mainly a hypersolvus granite, whereas the two plutons along the Vaal River are composed of subsolvus alkali granite and quartz syenite. A peralkaline syenitic magma which probably orginated in the mantle by selective melting, was the primary magma from which the alkali granite developed by assimilation of quartz-rich sedimentary rocks.

Dykes of mariupolite which are probably rooted in the alkali granite plutons were emplaced in the roof and the hood-zone of the plutons along the Vaal River. There is a complete compositional range between the alkali syenite and the mariupolite, with a composition which falls in the nepheline field of the system SiO_2-Ks-Ne. The available evidence indicates that the mariupolite orginated by desilication of a peralkaline syenitic magma.

The dykes of bronzite granophyre are the youngest intrusions which have the same age as the Bushveld Complex in the Vredefort Dome. The granophyre is considered to be a hybrid rock which originated through assimilation of mainly pelitic and granitic material by a dioritic magma.

All the igneous intrusions which have the same age as the Bushveld Complex are probably related to the central pluton which represents the focus of igneous activity in the Vredefort Dome. This pluton is probably a complex one which is composed mainly of mafic rocks.

The Metamorphic Rocks

The earliest metamorphism in the Vredefort Dome attained the grade of the amphibolite and the granulite facies, and can be related to the Archaean granite. Subsequently the rocks of the Witwatersrand, Dominion Reef, and Ventersdorp Systems were regionally metamorphosed to low-grade products (greenschist facies). During and after the main episode of dome formation the rocks of the Dominion Reef and Witwatersrand Systems, and the intrusive mafic rocks of probable Ventersdorp age in the Vredefort Dome, were thermally metamorphosed by the central pluton and the alkali granite.

The chemical composition of the parent-rocks had a profound influence on the mineral assemblages which developed during the metamorphism, especially in the lower grades, but in the higher grades physical conditions played an important rôle owing to an increase of the mutual substitution of Mg^{++} and Fe^{++}. The order of crystallization of the metamorphic minerals in the aluminous hornfelses is as follows:

chlorite, biotite and cordierite, almandine, staurolite, kyanite, sillimanite, and in the ferruginous hornfelses: chlorite, almandine, cummingtonite.

Three different zones of metamorphism of the mafic igneous rocks can be recognized: an outer zone composed of the assemblage chlorite, albite-oligoclase, epidote and calcite, followed by a zone of actinolite and plagioclase (An_{65}) which is partly altered to clinozoisite, and an inner high-grade zone composed of the assemblage hornblende and plagioclase (An_{45}). A zone of polymetamorphism can also be recognized. These zones are concentrically disposed around the central pluton. Discordant with these zones are metamorphic zones which are related to the alkali granite.

The distribution of metamorphic zones and the evidence of polymetamorphism is interpreted as the result of the intrusion of tholeiitic magma in the initial stage, and the later emplacement of magmas of the alkaline suite, both in the central pluton, and also as separate plutons. The PT curve depicting conditions for the metamorphism caused by the alkali granite along the Vaal River, follows the boundary curve for andalusite and kyanite in the system Al_2SiO_5. The contact-metamorphism in the Vredefort Dome took place under higher pressures than those under which the albite-epidote hornfels and hornblende hornfels facies developed. The metamorphic facies or subfacies in the Vredefort Dome may be termed the chloritoid hornfels and the almandine-staurolite-hornfels facies or subfacies.

The Pseudotachylyte

The pseudotachylyte penetrates all the rocks which are older than the Pilanesberg Complex in the Vredefort Dome with the exception of the bronzite granophyre. Veins and sheets of pseudotachylyte can be distinguised. They are irregular in form and contain numerous inclusions of the adjacent country-rocks. Foreign inclusions which must have moved a considerable distance from their place of origin are often found in the large veins of pseudotachylyte. Most of the inclusions in the pseudotachylyte are well rounded. Recrystallized pseudotachylyte is the rule rather than the exception. An intrusive and a non-intrusive type can be distinguished in some veins. Petrographically three varieties of pseudotachylyte can be distinguished, namely, a mylonitic and a metamorphic variety and a true pseudotachylyte which shows evidence of crystallization from a melt.

The different theories on the origin of pseudotachylyte are reviewed, and it is concluded that the pseudotachylyte of the Vredefort Dome represents a tuffisite which originated through gas action related to the central pluton and its satellitic intrusions.

Geological History of the Vredefort Dome

The main events which took place during the development of the Vredefort Dome and which were synchronous with the magmatic activity in the Bushveld Igneous Complex, can be summarized as follows:

a. the emplacement of rocks of the tholeiitic suite and the metamorphism caused by the tholeiitic part of the central pluton before overturning of the Witwatersrand and Ventersdorp Systems,

b. the final overturning and faulting of the intrusions of the tholeiitic suite, the epidiorites, the Witwatersrand and Ventersdorp Systems, probably caused by the intrusion of magma with alkaline affinities in the central pluton,

c. emplacement of the plutons of the alkali suite along major strike-faults and a second period of contact-metamorphism caused by these plutons and that part of the central pluton which consists of rocks of the alkaline suite,

d. development of the pseudotachylyte, and

e. emplacement of the dykes of bronzite granophyre.

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I. INTRODUCTION

The Vredefort Dome, with its core of Archaean granite and thick collar of sedimentary rocks and lava, is one of the several dome structures which are found in, and on the rim of the Witwatersrand basin. It is unique in being the only one in which the greater part of the collar is overturned. The diameter of the core along the north-east axis is approximately 27 miles (43 km), and along the north-west axis about 35 miles (56 km) if Maree's (1944, Fig. 1) interpretation of the gravity anomalies is accepted.

Because of the unusual structure of the Vredefort Dome, a number of publications has appeared in which different theories on the origin of the dome have been expounded. The dome structure was recognized towards the end of the nineteenth century by Molengraaff and by Draper (Hall and Molengraaff,1925, p.2). Prior to Hall and Molengraaff's memoir (1925) and Nel's (1927) detailed mapping of the dome, the difference of opinion on the origin of the dome was, mainly due to a lack of detailed knowledge, centered around the intrusive or non-intrusive nature of the Archaean granite in relation to the Witwatersrand System. After Hall and Molengraaff (1925, p.21) and Nel (1927, p.56) had established the non-intrusive relation of the granite core, the origin of the dome was the main theme of most subsequent publications.

Hall and Molengraaff (1925) and Nel (1927) focussed attention on the diversity of rock-types which are present in the Vredefort Dome. The first extensive petrological study of the rocks in the dome since 1927 was made by Willemse (1937) on the Archaean granite and the highly metamorphosed rocks of the Swaziland System, and by Brink (1956) on the hybrid rocks on Tweefontein 385.

The primary purpose of this investigation is to present a more detailed study of the post-Witwatersrand igneous and metamorphic phenomena from a petrological point of view. Obviously, getting involved in other problems concerning the Vredefort Dome is unavoidable. It appears that igneous activity, metamorphism, diastrophism and probably sedimentation, are all related phenomena which have a bearing on the origin of the dome. From a study of the literature on the Vredefort Dome and frequent visits to the dome, it became evident that in the light of modern developments in petrology, a more detailed investigation might help to solve some of the problems to which reference will be made in the sequel.

To achieve this, the necessity of more detailed mapping was realized; consequently the major part of the area occupied by metamorphosed rocks of the Witwatersrand System was remapped on a scale of 1:10,000 with the aid of aerial photographs. During the mapping the different types of hornfels and igneous rock were differentiated as far as it was permissible for such a scale. This large-scale mapping (Plate I, sheets 1, 2, 3, 4 and 5; and Plate II) proved the existence of several large strike-faults, hitherto unknown in the Vredefort Dome. Furthermore, it was possible to distinguish between at least three different ages of mafic intrusions which were considered by Hall and Molengraaff (1925, p.52) and by Nel (1927, p.67) to have been derived from a common magma. Microscopic study of the metamorphic rocks has made possible the recognition of different mappable metamorphic zones.

An attempt to make a complete inventory of the literature on the Vredefort Dome would end in quite an extensive list. For a fairly complete summary of the literature up to 1925, reference should be made to Hall and Molengraaff (1925, p.1-9). Reference to literature subsequent to 1925 will be made later in the text.

The conventional methods were used in the petrographic study of the rocks. The volumetric composition of rocks was estimated by point-counting according to the method devised by Chayes (1956). To facilitate the estimation of the relative proportions of potassium-feldspar and plagioclase, potassium-feldspar was stained with sodium cobaltinitrite. In order to differentiate between calcite and dolomite in the marbles, calcite was stained with a solution of alizarin S and hydrochloric acid.

The refractive indices of minerals were determined by the immersion method to an accuracy of ± 0.002. Optic axial angles and extinction angles of minerals were measured on the universal stage to an accuracy of ± 1 - 2 degrees.

Because the areas mapped represent only portions of existing geological sheet-maps, the old numbers of the farms in the Transvaal are retained on the accompanying maps to facilitate reference to these sheet-maps.

II. SUBDIVISION OF THE IGNEOUS ROCKS INTO SUITES

The post-Witwatersrand intrusive rocks in the Vredefort Dome can be subdivided into different groups according to their relative ages and relations to different events in the history of the Dome and the surrounding synclinorium. These groups are also characterized by different chemical affinities and mineralogical peculiarities. To differentiate between these groups, the terms rock-suite and rock-series will be used. Because both terms are not strictly defined in petrology, they will be used as follows: The term suite will be used in a broad sense for rocks which show certain common chemical and mineralogical features. Rock-series are subdivisions of rock-suites and represent rocks which have very close chemical and mineralogical similarities. In both divisions, no genetic relationships are necessarily implied.

The oldest post-Witwatersrand intrusions are represented by sills and dykes of epidiorite which can be correlated with the Ventersdorp volcanism.The largest group of igneous rocks have the same age as the Bushveld Complex and comprises an older suite with tholeiitic affinities, and a younger suite with alkaline affinities. The third group includes the dykes of foyaite porphyry, diorite and dolerite of the Pilanesberg dyke-swarm. The youngest intrusions are represented by dolerite sills of Karroo age, which probably also include the large Annas Rust sill.

Yoder and Tilley (1962, p.354) define tholeiitic basalt as orthopyroxene-normative, and alkali basalt as nepheline-normative basaltic rocks. Yoder and Tilley (1962, p.354) and Poldervaart (1964, p.229) summarize the differences as follows: The olivine of some tholeiitic rocks shows evidence of a reaction relation with orthopyroxene and pigeonite. The predominant pyroxene of tholeiite is a calcium-poor augite and, when free silica is present, it is an interstitial silica mineral or silica-rich glass. In alkali basalt, olivine crystallizes parallel with pyroxene, which is predominantly a calcium-rich augite or titanaugite, and orthopyroxene is scarce or absent. Exsolution lamellae which are common in the pyroxenes of tholeiitic rocks are absent. A mesostasis, when present, is composed of feldspathoid, zeolite or alkali feldspar.

Yoder and Tilley (1962, p.349) suggest that the phases in the system diopside-forsterite-nepheline-quartz contain the principal components of all the major phases of basalt, but they also realize that the ignoring of iron is one of the major deficiencies in such a presentation. Using this system as a basis, Poldervaart (1964, p.231) worked out a procedure to distinguish tholeiite from alkali basalt. After the calculation of the C.I.P.W. norm all Na_2O is recalculated to nepheline, all (Mg, Fe)O, after allotments for ilmenite, magnetite and diopside have been made, is recalculated as olivine. Quartz includes the normative quartz plus ½ SiO_2 for normative hypersthene and 2/3 SiO_2 for normative albite. After conversion of the molecular values to weight percentages they are recalculated to 100. If the following equation gives a positive value, the basalt is an alkali basalt but for tholeiite this value is negative: 0.53 nepheline $- 0.47$ quartz $= 0.0$. Basaltic rocks without normative hypersthene are automatically classed as alkali basalts, therefore distinction with the aid of this equation is only necessary for alkali basalts with small amounts of normative hypersthene and tholeiites with normative olivine.

Application of Poldervaart's procedure to the mafic rocks of Rietfontein and the lamprophyric rocks of the Lindequesdrift area, gives positive values which indicate that these rocks can be considered as alkali basaltic. The pyroxene of the mafic rocks of the Rietfontein Complex seldom shows exsolution phenomena and the wollastonite content ranges between 38 and 42 per cent. If all the pyroxene in the norms of the analyzed rocks of the Rietfontein Complex is calculated as clinopyroxene the wollastonite content ranges between 39 and 46 per cent. Furthermore, the anorthite content of the plagioclase of these rocks ranges between 20 and 45 per cent and the normative values for the plagioclase of the analysed rocks between 16 and 37 per cent.

The doleritic rocks of the sills not only contain normative hypersthene but also modal hypersthene ; some contain small amounts of olivine and others contain up to about 10 per cent of micropegmatite, and are therefore typical tholeiitic rocks.

III. THE THOLEIITIC SUITE

A. Distribution and Age

Rocks of this suite include sills of dolerite, hyperite, norite and pyroxenite, which are intruded in the Lower Division of the Witwatersrand System, and also in the Archaean granite in a zone approximately 3 km wide below the contact with the Dominion Reef System. In the central part of the Archaean granite, rocks of this suite are unknown, with the exception of a few small intrusions on Schulpspruit 540 and adjoining farms. It is interesting to note that, apart from the dykes in the Upper Division of the Witwatersrand System, the above is also the area in which the sills of epidiorite were emplaced.

The outcrops of dolerite between Vredefort and Annas Rust 4 and on Winddam 454 and Erfdeel 684 are probably parts of the undulating Annas Rust sill. The different rock-types of the tholeiitic suite are not limited to any particular stratigraphic horizon. Melanorite was emplaced in the upper part of the Jeppestown Series and in the Archaean granite; dolerite is intrusive into the Archaean granite,the Hospital Hill Series, the Government Reef Series, and the Jeppestown Series.

The intrusions of this group exhibit the following features which have a bearing on their age relation relative to the episode of dome formation:

(1) They are all cut by pseudotachylyte which is older than the Pilanesberg dykes.

(2) Faults displace these intrusions and the rocks of the Witwatersrand System alike.

(3) The intrusions display the features of inverted sills (Fig.1):

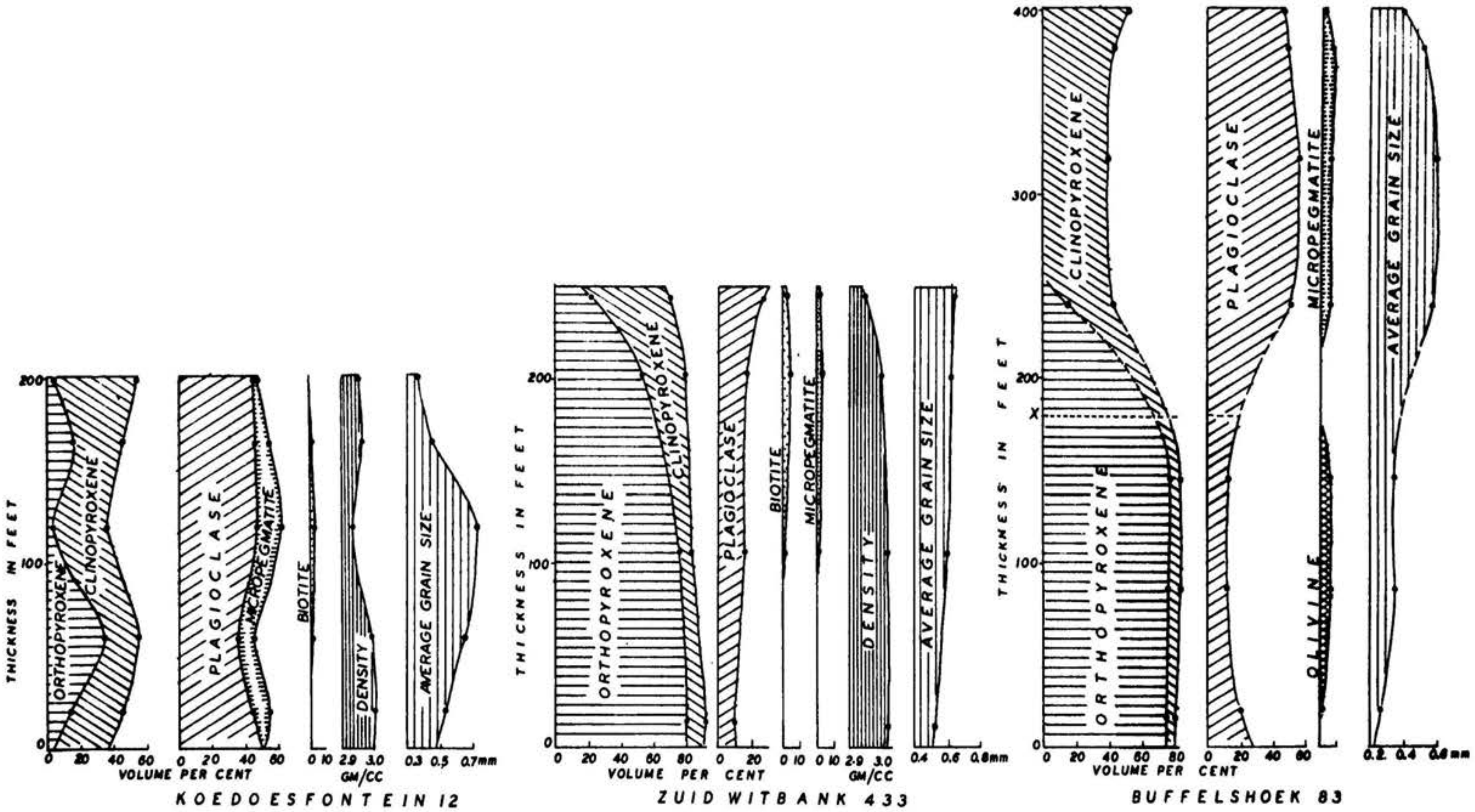

Fig. 1. Variation in the mineral composition and the physical properties of the rocks of three sills of the tholeiitic suite in the Vredefort Dome.

(i) The rocks have their maximum grain-size nearer to the stratigraphic top than the stratigraphic bottom of the sills.

(ii) There is a general increase in the colour-index of the rocks from the stratigraphic top towards the stratigraphic bottom of the sills.

(iii) There is also an increase in the density of the rocks towards the stratigraphic bottom of the sills.

(iv) Where micropegmatite and biotite are present in these rocks, the maximum concentration is reached nearer to the stratigraphic top than the stratigraphic bottom of the sills.

(v) Where olivine is present in some of these sills it also shows a tendency to be concentrated in the lower (stratigraphically) parts of the sills.

It is clear from the above evidence that these sills were emplaced when the rocks of the Witwatersrand System were still horizontal or had a low to moderate dip, as would be expected in a normal dome with outward dips, i.e. they were emplaced before the overtilting of the strata took place, and also before the stage of extensive faulting in the Vredefort Dome.

The rocks of this suite are also considered to have the same age as the Bushveld Complex for the following reasons:

(1) There is a close similarity in mineralogical composition between the rocks of this suite and some of the Bushveld rocks e.g. pyroxenite, norite, hyperite and dolerite (gabbro) i.e. the Bushveld rocks below the Upper Zone.

(2) Similar rocks are found in the Pretoria Series in the Potchefstroom Synclinorium where the intrusions are also displaced

by faults which are probably related to the faulting in the Vredefort Dome.

(3) The intrusions of the tholeiitic suite are younger than the epidiorite intrusions, which can be correlated with the Ventersdorp volcanism, and older than the alkaline rocks which, according to age determinations carried out by L.O. Nicolaysen (personal communication), are similar to those of the Bushveld Complex.

B. Nomenclature

The tholeiitic rocks in the Vredefort Dome range from slightly oversaturated to slightly undersaturated types and have colour-indices between about 40 and 92. If pyroxenite is defined as a rock which contains more than 90 per cent of pyroxene (Hatch, Wells and Wells, 1961, p.280 and 307), pyroxenite is a very subordinate rock type in this group. The bulk of the rocks classified by Nel (1927, p.61) as pyroxenite, must then be termed melanorite which grades into pyroxenite. Examples of this rock type are found in the sills in the Archaean granite on Zuid Witbank 433 and Moray 505, a sill in the main Jeppestown quartzite (J.Q.3) on Buffelskloof 83 and Koedoesfontein 12, and one on Doornhoek 1000. Mesotype norite is found on Koedoeslaagte 59 below the upper Government Reef quartzite (G.R.Q.9), in the main Jeppestown quartzite (J.Q.3) west of the Vaal River in the Orange Free State (Plate I).

Hyperite, if defined as a rock with a composition intermediate between norite and gabbro (Johannsen, 1937, p.238), constitutes a considerable portion of the tholeiitic rocks. Because there is a complete gradation between norite and gabbro in the strict sense (Holmes, 1928, p.166, and 103), some arbitrary boundaries must be drawn for the intermediate types. Holmes (1928, p.167) suggests that when a norite contains augite, it may be termed hyperite or hypersthene gabbro when augite is the dominant pyroxene. After the analogy of hypersthene gabbro, augite norite is preferable to hyperite. This is also the scheme adopted by Hatch, Wells and Wells (1961, p.307). Because of the difficulty in distinguishing between augite norite and bronzite dolerite in the field, the term hyperite will be used to include both types as defined above. This is apparently also the sense in which the term is used by Hall and Molengraaff (1925, p.43) and by Nel (1927, p.61).

A rock-type with such an intermediate composition and a pronounced poikilitic texture (Plate VIA) is shown as poikilitic hyperite (P.H.) on the map (Plate I), because the texture of this rock-type is easily recognizable in hand-specimen. Some petrographers consider the ophitic texture as essential in the definition of dolerite whereas to others texture is subordinate, provided that the rock has the appropriate composition and a hypabyssal mode of occurrence (Hatch, Wells and Wells, 1961, p.321). If the first definition is adopted, ~~a~~ some of the rocks hitherto described as dolerite will, strictly speaking, not qualify as dolerite. Most of the doleritic rocks in the Vredefort Dome are not ophitic. If the second alternative is adopted, this rock-type can be described as a poikilitic bronzite dolerite or an augite norite. The thick sill above the sixth Government Reef quartzite (G.R.Q.6) contains typical examples of these rock-types.

Dolerite is intrusive mainly in the Government Reef Series and in the Jeppestown Series. The largest intrusion of dolerite in the Vredefort Dome, which has the same age as the Bushveld Complex, resembles a cedar-tree and is intrusive into the Jeppestown Series on Rebok Kop 290 (Plate I, sheet 1)

The terms pyroxenite and norite are generally used for medium to coarse-grained rocks (plutonic) but, owing to the lack of appropriate terms for the hypabyssal equivalents of these rocks, the terms norite and pyroxenite are here extended to include the finer-grained varieties of similar composition. The suggestion of Hatch, Wells and Wells (1961, p.322) to use the prefix micro- to distinguish the fine-grained rocks from their medium to coarse-grained equivalents appears to be useful in this case, but in order to be consistent, dolerite should then be replaced by microgabbro, a term which seems to be appropriate for non-ophitic dolerites, if ophitic texture is considered to be an essential factor in the definition of dolerite.

C. Mineralogy

1. Pyroxene

The orthopyroxene crystals in the norite and the melanorite have an average length of about 0.5 mm, the phenocrysts in the poikilitic hyperite about 1.5 mm, and in the upper part of a thin sill above the eight Government Reef quartzite (G.R.Q.8) on Koedoesfontein 12, the orthopyroxene attains a length of 7.5 mm. The orthopyroxene crystals in the rocks of the tholeiitic suite are usually subhedral prismatic.

The composition of the orthopyroxene of the norites is Fs_{11} ($2V_z$=85°). A zonal structure in the phenocrysts of orthopyroxene in the poikilitic hyperite is a common phenomenon. Under the microscope the zoning is perceptible between crossed nicols owing to an increase in birefringence towards the margins of crystals. The value of $2V_x$ decreases from 84° in the core to 70° on the margin of the crystals (Fs_{16-25}). The orthopyroxene in the norite and the poikilitic hyperite is homogeneous without exsolution phenomena.

Phenocrysts of orthopyroxene, up to 2 mm in diameter, are present in the dolerite above the melanorite in the main Jeppestown quartzite (J.Q.3) on Buffelshoek 83 and in the dolerite above the poikilitic hyperite in the Government Reef Series on Rietpoort 66 on the Potchefstroom-Parys road. These phenocrysts enclose feldspar laths partly and completely but the associated augite is free from enclosed feldspar. The phenocrysts show a graphic intergrowth of clino- and orthopyroxene, and in some crystals the graphic intergrowth grades into lamellar intergrowth of clinopyroxene parallel to (100) of the orthopyroxene. The cores of phenocrysts usually have no intergrowth structures but show an uneven or wavy extinction. Walker and Poldervaart (1949, p.636) ascribe similar phenomena in orthopyroxene in some Karroo dolerites to exsolution, and the uneven extinction also to exsolution, but on a submicroscopic scale. The intergrowth consists in a considerable part of clinopyroxene and probably represents an orthopyroxene which originally contained a high percentage of $CaSiO_3$, a phenomenon which is to be expected when the rate of crystallization was high (Walker and Poldervaart 1949, p.637). Measurements of $2V_x$ of the orthopyroxene on the universal stage gave an average value of 84° (Fs_{14}) but owing to the uneven extinction, this value cannot be considered to be very reliable. This composition however, falls well outside the field for orthopyroxene which originated by the inversion of pigeonite.

In general the crystals of augite are anhedral, but in the poikilitic hyperite subhedral crystals are common. Apart from lamellar twinning, simple twinning on (100) is frequent. In some dolerites the augite often shows a zonal structure. In some rocks augite is altered to tremolite or actinolite. The melanorite on Zuid Witbank 433 (Plate 1, sheet 2) and similar rocks on Moray 505 (Plate 1, sheet 1), contain accessory clinopyroxene which is partly or nearly completely altered to tremolite. This pyroxene has the optical properties of augite ($2V_z$=50) but has a peculiar chocolate-brown colour and is non-pleochroic. Usually only remnants of this pyroxene are left in the aggregates of tremolite. In the tremolite aggregates, where the pyroxene has disappeared or only very small remnants are left, the amphibole has inherited this brown colour in the central part of the aggregate or adjacent to the pyroxene remnant. The optical properties of the tremolite are not affected by this brown colouration. In the same rocks the quartz of the micropegmatite has a similar but much paler colour. The accessory augite in the melanorite on Buffelshoek 83 (Plate 1, sheet 3) does not show this brown colouration or alteration to tremolite. It is noteworthy that the brown pyroxene is found in the aureole of high-grade metamorphism and the clear pyroxene on Buffelshoek outside this aureole. This staining appears to be related to the contact-metamorphism. Small amounts of pigeonite are also present in the dolerite above the melanorite on Buffelshoek 83.

2. Feldspar

The feldspar in the rocks of the tholeiitic suite is labradorite (An_{60-65}). Normal zoning of the plagioclase is a common feature and is sometimes strongly developed (An_{85-40}). The feldspar is usually lath-shaped to prismatic. In the poikilitic hyperite tabular crystals up to 1 cm in diameter enclose abundant small crystals of pyroxene. Thin, lath-shaped crystals of plagioclase in the norite frequently show a fan-like arrangement, especially in the finer-grained varieties.

3. Accessory Minerals

Up to about 10 per cent of micropegmatite occurs interstitially between the pyroxene and the feldspar of most rock-types of the tholeiitic suite.

In the poikilitic hyperite and some of the melanorites, small amounts of olivine (Fa_{17}, $2V_x = 88°$), up to about 6 per cent, takes the place of micropegmatite. The crystals have an average diameter of 0.1 to 0.2 mm. A reddish-brown variety of biotite is an accessory mineral in several of the rocks of this suite and varies sympathetically with the amount of micropegmatite. It is usually associated with magnetite.

4. Sulphides

Sulphides are present in a small intrusion of dolerite on Groot Eiland 35 (plate IV), as disseminated patches up to about 1 cm in diameter. These patches are composed of pyrrhotite with subordinate pyrite, pentlandite and chalcopyrite. Between the margins of the sulphide patches and the silicate lies a zone of magnetite which contains exsolved lamellae, elongated and irregular blebs of ilmenite. Pyrite forms small grains which are enclosed by the other sulphides, and apparently represents the first mineral in the sulphide paragenesis. Chalcopyrite is interstitial to the other sulphides. Pentlandite is present on the rims of large pyrrhotite crystals and probably originated by exsolution from pyrrhotite. The paragenetic sequence is as follows: magnetite, pyrite, pentlandite, chalcopyrite.

The sulphide minerals are associated with late magnetite and appear to have been concentrated in the residual liquid. The concentration of sulphide was probably too low to form an immiscible liquid fraction during an earlier stage in the consolidation of the dolerite.

D. Petrography

1. General

One of the most interesting rock-types of this suite is the poikilitic hyperite. This rock contains subhedral phenocrysts of pyroxene up to 2 mm in length, set in a fine-grained ground-mass of pyroxene (up to 0.25 mm in length) with which small amounts of olivine are sometimes associated. Both phenocrysts and ground-mass pyroxene and olivine (up to 0.2 mm in diameter) are enclosed in large crystals of plagioclase up to 1 cm in diameter (Plate VIA). Where these rocks are slightly oversaturated small patches of micropegmatite are found between the large plagioclase crystals. Apart from twinning on (010) as composition plane, lamellae twinned according to the Pericline law are also prominently developed in the plagioclase crystals. The following types of poikilitic hyperite can be distinguished:

Pyroxene phenocrysts	Pyroxene in ground-mass	Accessory minerals
bronzite	augite	olivine
bronzite	augite and bronzite	olivine
bronzite and augite	bronzite	micropegmatite
augite and bronzite	bronzite and augite	- - - - -
augite	bronzite	- - - - -

The rocks of this group (poikilitic hyperites) have high colour-indices which range from 50 to 85 (Appendix A, Table 1). Where augite becomes a subordinate constituent, phenocrysts of pyroxene are absent and the feldspar crystals are much reduced in grain-size but the pyroxene crystals are still poikilitically enclosed in feldspar. In rocks with accessory augite, phenocrysts of both pyroxene and feldspar are absent, and the rocks (norite) have a hypidiomorphic texture.

The norite rock-types range from mesotype norite to melanorite and feldspathic pyroxenite. In some of the melanorites the feldspar forms long slender laths which have a subparallel or fan-like arrangement. This type of rock usually contains phenocrysts of bronzite. The melanorite, and the feldspathic pyroxenite into which it grades, are both hypidiomorphic granular rocks with interstitial feldspar and accessory, small phenocrysts of augite enclosing small crystals of bronzite and olivine, when olivine is present. The enclosed olivine crystals have the same size as the olivine in the ground-mass, but the bronzite crystals are much smaller than those of the ground-mass.

The dolerites are mesotype rocks having colour-indices which range from 35 to 60. The texture is hypidiomorphic to subophitic and the rocks range in composition from ordinary dolerite to bronzite dolerite, even in the same intrusion. Pegmatitic schlieren are medium-grained, gabbroic, and usually contain micropegmatite, a constituent which is present in nearly all ordinary dolerites in the Vredefort Dome.

Specimens were collected in the Heidelberg area for comparison with the igneous rocks in the Vredefort Dome. The most abundant type in this area is a dolerite with accessory micropegmatite and is termed a quartz dolerite by Rogers (1922, p.57). Poikilitic augite norite and melanorite which are less prominently developed in the Heidelberg area are indistinguishable from similar rocks in the Vredefort Dome. Similar rocks which are intrusive into the Transvaal System are also known in the Potchefstroom Synclinorium.

To show the variation in the individual intrusions, a few selected examples can be discussed (Appendix A, Table 1). In this discussion, where reference is made to lower or upper contacts of sills, it will be used in the stratigraphic sense because these intrusions are considered to be inverted sills.

2. The Melanorite Sill on Zuid Witbank 433

This sill is intrusive into the Archaean granite (Plate 1, sheet 2) and is about 250 feet thick. The main rock-type is a melanorite which grades into a feldspathic pyroxenite with less than 10 per cent of plagioclase. Volumetrically bronzite increases towards the lower contact whereas plagioclase increases upwards. Micropegmatite and biotite are present only in the upper half of the sill. There is also an increase in the average grain-size towards the upper contact and a downward increase in the density of the rocks (Fig. 1; Appendix A, Table 1).

Augite is an accessory constituent and has the chocolate-brown colour described above. The augite is partly altered to tremolite and in the upper part of the sill it is completely replaced by tremolite. The amount of tremolite increases upwards. Because the bronzite is practically unaltered it can be inferred that in the original rock, augite increased upwards. The plagioclase (An_{65}) and the bronzite (Fs_{15}) show little variation in composition.

3. The Sill on Buffelshoek 83

This sill is intrusive into the main Jeppestown quartzite (J.Q.3) (Plate 1, sheet 4) It is about 400 feet thick and is composed of melanorite in the lower part and dolerite in the upper part (Fig. 1; Appendix A, Table 1). The melanorite is practically identical to the melanorite on Zuid Witbank. The augite in this rock is fresh and does not show any signs of alteration. The rock contains up to 5 per cent of olivine. Owing to poor outcrops the contact between the upper dolerite and lower melanorite could not be studied in the field. The lower part of the upper unit, or alternatively the upper part of the lower unit, contains about 15 per cent of orthopyroxene phenocrysts which enclose small crystals of feldspar. This orthopyroxene shows exsolution of the graphic-intergrowth type. The rock also contains accessory pigeonite ($2V_Z$= 5º10°) which is present together with the augite in the ground-mass. The rocks of the upper unit contain small coarser-grained schlieren in the fine-grained dolerite.

4. The Sill on Koedoesfontein 12

This sill which is intrusive into the upper, thick Government Reef quartzite (G.R.Q.8) (plate 1, sheet 3), about half a mile east of the boundary between Koedoesfontein 12 and Koedoeslaagte 59 is about 200 feet thick. Volumetrically, bronzite shows two concentration peaks (Fig. 1; Appendix A, Table 1); the highest in the lower third and another in the upper third. The lowest concentration is some distance above the middle of the sill, which is also the level of maximum concentration of plagioclase, micropegmatite and biotite, and also of maximum grain-size. The clinopyroxene increases upwards and also downwards from the position of maximum concentration of the bronzite.

The poikilitic hyperite above the sixth Government Reef quartzite (G.R.Q.6) shows a similar concentration of pyroxene toward the lower contact (85 per cent) and also a high concentration near the upper contact (77 per cent) with the lowest concentration (72 per cent) some distance above the middle of the sill.

E. Petrogenesis of the Tholeiitic Suite

Hess (1960, p.188) states that in dolerite sills crystallization from the roof downwards is generally slower than from the floor upwards, and that the final residue of magma crystallizes about three quarters of the way up from the floor. The composition and the sequence of phases separating from the roof downwards, duplicate in a condensed form the sequence from the floor upwards (Hess 1960, Fig. 39). According to him the reason for this phenomenon is that the increase in pressure downwards slightly favours crystallization, and convective circulation in the magma tends to~~o~~ keep the hottest portion below the roof.

At the upper, chilled contact of the sill on Koedoesfontein 12 the rock contains phenocrysts of bronzite in a finer-grained, more or less equigranular ground-mass of augite and labradorite which indicates that bronzite was the first mineral to crystallize. At an early stage bronzite crystallized over a smaller thickness of the sill in the upper part than in the lower part, whereas no crystallization took place in the central part of the sill, because the temperature gradient was steeper in the upper than in the lower part. If the rate of crystallization were higher in the lower part of the sill than in the upper part, it would be expected that at a given stage more bronzite would have crystallized in the lower part than in the upper part. Gravitational sinking of bronzite would then have led to the development of two zones in the sill in which it shows a high concentration of bronzite with the highest in the lower zone. Residual magma would have tended to move from the lower part toward the central part of the sill and also from the zone of the upper concentration upwards, to cause an enrichment in constituents for potential clinopyroxene in the upper part and the central part of the sill. This residual magma would eventually have crystallized as augite and labradorite.

Augite and labradorite would also crystallize from the floor upwards and from the roof downwards, with the last fraction crystallizing in the upper third of the sill. Volatile constituents would also reach their highest concentration at a late stage in this zone, consequently the largest grain-size, as well as the maximum amount of micropegmatite and biotite would be found in this portion of the sill (Fig. 1).

In the melanorite of Zuid Witbank 433 there is an increase in the amount of bronzite towards the floor of the sill. Augite and plagioclase are interstitial to the bronzite and increase upwards, but the expected highest concentration is at the top of the sill and not two-thirds or three-quarters of the way up in the sill. Unfortunately the chilled contact-rocks are not exposed. Gravitati~~ve~~onal sinking of the orthopyroxene and the concomitant rise of residual fluid (potential augite and labradorite) is evident from the volumetric variation of constituents over the whole thickness of the sill (Fig. 1).

In the melanorite forming the sill on Buffelshoek 83 the highest concentration of feldspar is near the bottom and also towards the upper part of the sill. If this sill represents a single intrusion, gravitational sinking of bronzite must have been an important process in producing this large variation in the composition of the rocks. The variation in the mineral composition of the lower part has a distribution pattern similar to that of the melanorite sill on Zuid Witbank. If gravitational sinking of bronzite had been operative in the Zuid Witbank sill, it must also have been operative to a larger extent in the Buffelshoek sill which is nearly twice as thick.

The differentiation in the orthopyroxene-rich hypabyssal rocks is more striking than in the clinopyroxene-rich rocks (i.e. ordinary dolerites). In plutonic complexes, e.g. the Bushveld Igneous Complex, the greatest diversity of rock-types is also found in the Critical Zone where orthopyroxene is the main dark mineral, compared with the Main Zone where clinopyroxene is the principal dark mineral. According to Hess (1960, p.143) this is also the case in the Stillwater Complex, and he considers this phenomenon to be the result of a difference in grain-size between orthopyroxene and plagioclase, because the settling velocity of orthopyroxene was about 25 times as high as that of the lighter and smaller plagioclase crystals.

From Fig. 1 the average volumetric compositions of the three sills described above were calculated from the areas between the variation curves and the ordinate (Table 1). Barth (1962, p.115) defines the boundary plane between the phase volumes in which felsic and mafic minerals are precipitated from a basaltic magma by the equation $ab' + 2di' + 2.3\ hy' = 123$. If the sill on Buffelshoek is taken as an example, and the volumetric composition is recalculated to a composition by weight, taking the specific gravity of augite and bronzite as 3.3 and that of labradorite An_{65} as 2.7 and neglecting olivine and micropegmatite, the percentages of the minerals by weight for the average rock are: orthopyroxene = 44.5, clinopyroxene = 24.5, and plagioclase = 31.0. For his calculations Barth used normative constituents, but if modal values

Table 1

Average volumetric mineralogical composition of some intrusions of the tholeiitic suite.

Sill	Plagioclase	Clinopyroxene	Orthopyroxene	Olivine	Micropegmatite
Zuid Witbank	19	15	66	---	---
Buffelshoek	34	22	40	2	2
Koedoesfontein	45	33	14	---	8
Bergplaats 420 chilled dolerite	46	52	---	---	2

are used the following is obtained:

$$ab' + 2di' + 2.3\ hy' = 123$$

$$10.8 + 49.0 + 102.3 = 162.1$$

This result indicates that the composition of the undifferentiated magma falls in the pyroxene field. After the crystallization of about 37 per cent of the bronzite the residual liquid (63 per cent) would be composed of 24.5 parts of clinopyroxene, 31 parts of plagioclase and 7.5 parts of bronzite. Recalculation to 100 gives clinopyroxene = 39.4 per cent, plagioclase = 48.5 per cent, and bronzite = 12.1 per cent.

$$ab' + 2di' + 2.3\ hy' = 123$$

$$17.0 + 78.8 + 27.6 = 123.4$$

At the stage, where 37 per cent of the bronzite had crystallized, plagioclase would begin to crystallize together with pyroxene. Recalculation of the above data to volumetric ratios, indicates that 33 per cent of the original magma was consolidated when plagioclase began to crystallize and that the crystal mush was about 175 - 180 feet thick (position marked X on Fig. 1). Up to this horizon in the sill the average composition of the rocks is orthopyroxene = 73 per cent, olivine = 2 per cent, and 25 per cent of interstitial plagioclase and augite.

Hess (1960, p.109) calculated the interstitial plagioclase and clinopyroxene for the norite of the Stillwater Complex and concluded that the crystal mush contained 26 - 29 per cent of interstitial liquid. The interstitial liquid in the bronzite mush on Buffelshoek was probably greater than 25 per cent because further growth of bronzite probably took place after the accumulation.

The gravitational sinking of bronzite was probably facilitated by a lower viscosity of the magma during its crystallization and during the stage in which clinopyroxene and plagioclase crystallized the viscosity was probably considerably higher. If this inference is correct, it also implies that the high magnesium content of the magma was probably conducive to a low viscosity. During the stage in which plagioclase and augite crystallized a large amount of magnesium had already been extracted from the magma. According to Hess (1960, p.141) the settling velocity of pyroxene is about seven times as great as that of plagioclase crystals with the same radius, but the settling velocity varies inversely proportional to the viscosity e.g. a tenfold increase in viscosity of the liquid would cause a tenfold decrease in the settling velocity of crystals. This is probably the reason for the small increase in clinopyroxene above the melanorite zone and probably also an explanation for the small variation in the composition of the dolerite sills.

The reason for the less conspicuous differentiation in the Zuid Witbank sill is that the boundary surface separating the plagioclase field from the pyroxene field in the system Di-SiO_2-An-Ne was never pierced or was pierced only in the end-stage of crystallization, i.e. the original magma had such a composition that the potential augite and plagioclase was just sufficient (34 per cent) to form an interstitial fluid after the crystallization of bronzite.

Comparison of the average composition of the different sills in the Vredefort Dome (Fig. 2 and Table 1) poses other problems: How do basaltic magmas with such a variation in composition originate in the same comagmatic province? Are they derived from a common magma source, and what is the composition of the parent-magma? The trend in the modal variation of the rocks of this suite is the following: With increase in the feldspar, clinopyroxene also increases and orthopyroxene decreases up to a stage in which the rock consists of practically only clinopyroxene and plagioclase and has a composition near or on the boundary surface defined by $ab' + 2di' + 2.3hy' = 123$.

Two alternatives can be offered to explain the origin of the different magmas which produced the sills:

(1) Basaltic magma with a composition near to the phase boundary between pyroxene and plagioclase was emplaced in the central part of the dome, and differentiation products of this magma separated at intervals and invaded the rocks of the Witwatersrand System and the Archaean granite.

(2) The different magmas originated in depth (the mantle) and represent fractions of selective melting of primitive mantle material e.g. garnet peridotite, at different temperatures.

It is generally accepted that basaltic magma is a primary magma (Turner and Verhoogen, 1960, p.432). Yoder and Tilley (1962, p.518) show that basaltic magma can be produced by complete melting of rocks such as eclogite, or amphibolite. Because eclogite melts in a "eutectic-like" fashion, they suggest that eclogite itself must be a product of partial melting of more primitive material such as garnet peridotite.

According to Barth (1962, p.183) basalts of different petrographic provinces show close chemical similarities. This is to be expected if basalt represents a low-temperature fraction of more mafic material and its composition will be close to the field boundary for the two major components, feldspar and pyroxene. The chilled dolerite (Table 1) comes very close to such a composition, but the average composition of the other sills shows a marked deviation from this composition, which militates against the second alternative suggested above.

There is convincing evidence (which will be discussed later, see p. 99) that the core of the dome is underlain by a central mafic pluton (Plate III). It is possible that the tholeiitic intrusions have been derived from this central pluton. The parent-magma from which they were derived probably had a doleritic to bronzite-doleritic composition. In such an intrusion the bronzite would crystallize early and settle under the influence of gravity. Magma with different proportions of bronzite, or without bronzite, may have separated at different intervals and at different levels from the magma of the central pluton and may have led to the emplacement of the different sills.

The Zuid Witbank intrusion would then represent a magma which was composed of bronzite with at least 34 per cent of interstitial fluid (probably more) and the Buffelshoek intrusion one with approximately 60 per cent of interstitial liquid. The dolerite intrusions then, would have been nearly completely liquid.

F. The Annas Rust Sill

The dolerite of the Annas Rust sheet will not be described here as it forms the subject of an M.Sc. thesis by B.F. Liebenberg and lies for the greater part outside the area with which this investigation is concerned. There are, however, remnants of this intrusion on the eastern portion of Rietpoort 66, where it cuts across the strata of the Government Reef Series (Plate I, Sheet 4). Here it is an olivine dolerite similar to that of the Annas Rust area. It is not cut by pseudotachylyte. Because veins of pseudotachylyte are abundant in the pre-Karroo rocks of the Vredefort Dome this dolerite is considered to be either of Karroo age or possibly post-Waterberg, because the Wonderfontein dyke (post-Waterberg) is also not affected by pseudotachylyte.

IV. THE ALKALINE SUITE

A. Age and Field Relations

The alkaline suite comprises a large variety of rock-types which range from ultramafic through intermediate to peralkaline types. The following intrusions are included in this suite (Plate III):

(1) the Rietfontein Complex which consists of a differentiated intrusion of olivine sodagabbro, troctolite, wehrlite and picrite into which a pluton of alkali granite is intrusive;

(2) the plutons of alkali granite and the associated dykes of mariupolite along the Vaal River in the Vredefort Dome;

(3) the Lindequesdrift intrusion which is composed of lamprophyric and syenitic rocks;

(4) the Roodekraal Complex which is composed of andesite, diorite and a few dykes of albitite;

(5) the dykes of wehrlite and lamprophyre on Koedoesfontein 12 and a dyke of lamprophyre on Kopjeskraal 89;

(6) the dykes of alkali granite aplite in the north-eastern sector of the Vredefort Dome;

(7) the dykes of bronzite granophyre in the central part of the Vredefort Dome.

The age and also the relation of this suite of rocks relative to the episode of dome formation are borne out by the following relationships:

(1) The Rietfontein Complex is intrusive into the Ventersdorp and Transvaal Systems and is cut by the Wonderfontein dyke which is considered to have the same age as Pilanesberg (Schreiner and Van Niekerk, 1958, p.197).

(2) On Roodekraal 37, the diorite is intrusive into the andesite which flowed out on an eroded surface of the Pretoria Series. The

andesite overlaps the highly tilted Pretoria Series from the Magaliesberg quartzite down to the middle of the Ongeluk lava. Furthermore, one of the lowermost lava flows contains pebbles of quartzite, apparently derived from the Magaliesberg quartzite, at its base. The Complex also cuts across the sill of diabase in the central part of the Potchefstroom Synclinorium.

(3) L.O. Nicolaysen (personal communication) obtained age values for the alkali granite, the mariupolite, and the bronzite granophyre in the Vredefort Dome which correspond to values for the Bushveld Complex.

(4) The Roodekraal and Rietfontein Complexes, and the plutons of alkali granite along the Vaal River were emplaced along large strike-faults. On Schurwedraai 382 the walls of the fault-plane were forced apart by the magma and this resulted in the dome-like structure of the pluton of alkali granite. The plutons of alkali granite are themselves not affected by the faults which are so extensively developed throughout the area.

(5) The alkali granite along the Vaal River and also the Rietfontein Complex (alkali granite and mafic rocks) cut across rocks of the tholeiitic suite.

Apart from a similar relative age of the intrusions of the alkaline suite, a few common features which point to a possible genetic relation between the different intrusions can be noted:

(1) In the mafic members of the suite the feldspar is a soda-rich variety with an anorthite content below 40 per cent, whereas that of the tholeiitic suite is labradorite. In the alkali granite and the mariupolite, albite is the predominant feldspar.

(2) Orthopyroxene is common in the tholeiitic rocks but is virtually

absent from rocks of the alkaline suite.

(3) Similar lamprophyric rocks (spessartite) are found in the Rietfontein Complex, the Lindequesdrift intrusion and the small dykes on Koedoesfontein 12 and Koppieskraal 89.

(4) A wehrlite similar to that of the Rietfontein Complex forms two dykes on Koedoesfontein 12 in the Vredefort Dome.

(5) Copper mineralization is associated with the Roodekraal Complex and also with an alkali granite aplite on Vechthoek 159 in the Vredefort Dome.

The evidence enumerated above points not only to a possible genetic relation between the different intrusions of the alkaline suite but also to the fact that they were emplaced at a late stage in the history of the Dome and the Synclinorium. Furthermore, because these intrusions have the same age as the Bushveld Complex, but are younger than the tholeiitic suite, it is reasonable to consider the alkaline suite to be contemporaneous with the late stages of magmatic activity in the Bushveld Complex.

B. The Mafic Rocks of the Rietfontein Complex and Related Rocks in the Vredefort Dome

1. Structure and Distribution

This complex which occupies an area of about 7 square miles (18 square kilometres) on two adjacent farms, Rietfontein 163 and Rietfontein 54, is intrusive into the upper lavas of the Ventersdorp System and the sedimentary rocks of the Black Reef and the Dolomite Series. The southern half of the complex consists of mafic and ultramafic rocks and the northern half of alkali granite (Plate II). The dip of the country-rock ranges from 25° to 70° SE, towards the Vredefort Dome. The Wonderfontein dyke cuts across the complex and strikes due north. There are small outcrops of dolerite on the south-western, the north-eastern and the north-western boundaries of the complex. These outcrops represent remnants of a sill into which the complex is intrusive.

Owing to the low relief of the area, the greater part of the complex is covered with soil, with the result that exposures are poor and structural relations could not be determined with much certainty. The mafic portion of the complex is divided into two separate bodies by a strip of country-rock in which the Black Reef Series and the Dolomite Series are highly disturbed.

The contact of the mafic pluton is exposed over a very short distance in a small stream-bed along the southern edge of the complex. Here the mafic rocks dip approximately 55° N.

Both the granite intrusion and the mafic intrusion are elongated parallel to the strike of the country-rock formations. A directed structure (foliation) due to the subparallel arrangement of tabular crystals of feldspar is clearly visible on weathered surfaces of the mafic rocks. The strike of the foliation is more or less parallel to the major axis of the mafic pluton and the dip varies from 75° to 80° N, except for the area near the northern contact in the vicinity of the Wonderfontein dyke where the dips of the troctolite and the olivine gabbro are reversed.

The discordant character of both the granite and the mafic portions of the complex is corroborated by the field evidence (Plate II), but with the available data it is impossible to establish the form of the intrusions with certainty. However, the mafic portion appears to represent two elongated funnel-shaped intrusions which are connected at depth.

Not far from the Wonderfontein dyke in the south-eastern part of the mafic pluton is a small vein of gabbro pegmatite which is about one foot (30 cm) thick.

2. Nomenclature

The colour-index of the rocks of the mafic portion of the Rietfontein complex ranges between 47 and 100, with the majority above 60. The texture of these rocks is medium-grained, hypidiomorphic to allotriomorphic,

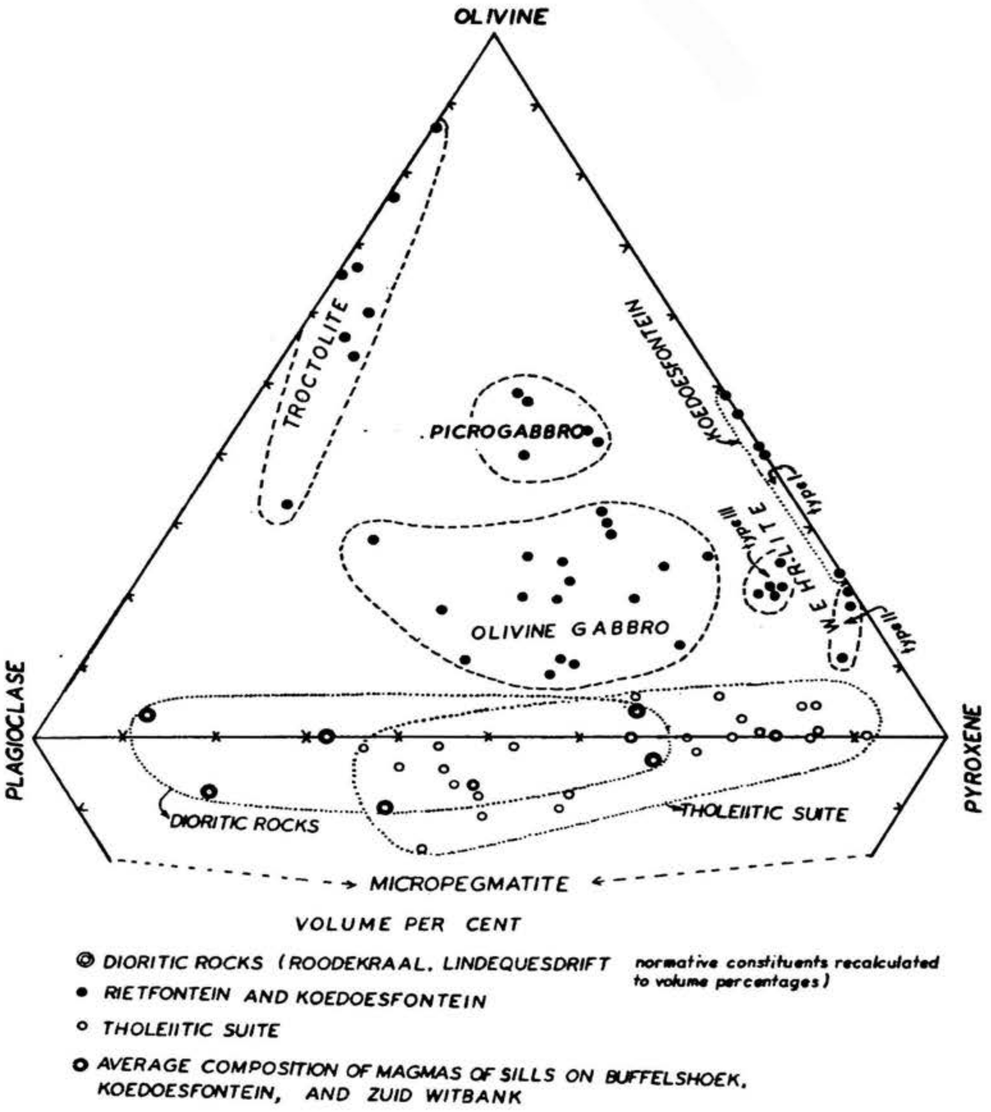

Fig. 2. Variation in the mineralogical composition of the mafic rocks of the Vredefort Dome.

and they are composed essentially of augite, olivine and plagioclase (An_{20-45}). Volumetrically, olivine ranges from 10 to 70 per cent, pyroxene from 0 to 83 per cent, and plagioclase from 0 to 47 per cent. In terms of these components (neglecting accessory constituents) four rock-types can be distinguised (Table 2 and Fig.2).

Table 2

Variation in the mineralogical composition of the mafic rocks of the Rietfontein Complex (volumetric percentage).

Pyroxene	Olivine	Plagioclase	Rock type
35-70	10-35	10-50	Olivine gabbro
25-45	35-50	15-30	Picrogabbro
0-10	50-90	10-40	Troctolite
50-85	10-50	0-10	Wehrlite

The nomenclature of the rocks within the compositional range shown in Table 2, is to a certain extent ambiguous. In its original sense the term gabbro (Holmes, 1928, p.103) is used for a phanerocrystalline rock composed of clinopyroxene and plagioclase (anorthite content more than 50 per cent), and the term diorite (Holmes, 1928, p.81, Johannsen, 1937, p.147) is used for a rock composed of hornblende and plagioclase (anorthite content less than 50 per cent). To distinguish gabbro from diorite Johannsen (1937, p.148) uses only the composition of the feldspar (dividing line An_{50}) with further subdivisions according to the ferromagnesian minerals. Shand (1950, p.391) uses the colour-index, diorite being leucocratic and gabbro mesotype to melanocratic, with further subdivisions according to the composition of the feldspar (dividing line An_{50}).

Subsequently he (1952, p.62) argues for the distinction between the two rock-types to be based on the nature of the ferromagnesian minerals rather than on the composition of the feldspar, mainly because the change from pyroxene to amphibole marks the crossing of an important physico-chemical boundary. In the original definitions no provision was made for rocks composed of amphibole + plagioclase ($An_{>50}$) and clinopyroxene + plagioclase ($An_{<50}$). For the purpose of this study the following scheme will be adopted :

	amphibole + plagioclase	clinopyroxene + plagioclase
An<50	diorite	sodāgabbro
An>50	calcic diorite	gabbro

The olivine sodāgabbro which contains more than 35 per cent of olivine would be termed picrite in the terminology used by Scholtz (1936, p.99). In its original sense picrite was used by Tschermak (Johannsen, 1937, p.433) for an extrusive peridotite. Tyrrell (1938, p.116), Harker (1954, p.80) and Howell (1962, p.220) describe a picrite as an olivine teschenite, i.e. a rock with decidedly alkaline affinities. Because of these differences in the usage of the term picrite, it is proposed to use picro- only as a prefix,e.g. picronorite, picrogabbro, picrosodāgabbro. For the sake of convenience, olivine gabbro and picrogabbro will be used instead of olivine sodāgabbro and picrosodāgabbro.

Only loose blocks of an uncommon rock-type,which is composed of phenocrysts of brown hornblende in a fine- to medium-grained ground-mass of plagioclase (An_5) and augite,was found in the Rietfontein Complex. This rock-type makes up the bulk of the Lindequesdrift Intrusion. These rocks have been described by Jansen (Nel and Jansen, 1957, p.45) as hornblendite and akerite. He used the term akerite probably because the C.I.P.W. symbols for these rocks indicate "akerose" in this system of classification. The mineral composition of these rocks is different from that of akerite from the type-area in Sweden (Barth, 1945, p.48) where it can be described as an augite syenite or a syenodiorite with rectangular crystals of feldspar whose bounding faces are (001) and (010). Barth (1945, p.48) states that the term akerite should only be applied to augite syenites or syenodiorites showing this characteristic texture. The composition of the rocks of Rietfontein and Lindequesdrift is dioritic rather than syenitic or syenodioritic. Bailey's term, appinite (Holmes, 1928, p.34), "a group term for melanocratic varieties of syenite, monzonite and diorite which are rich in hornblende; like the vogesites and spessartites of which appinite is regarded as the plutonic equivalent ....", appears to be an appropriate term but in such a case the term appinite must be qualified,e.g. dioritic appinite or spessartitic appinite.

Howell (1962, p.163) defines a lamprophyre as a dark-coloured dyke-rock in which ferromagnesian minerals are present both as phenocrysts and in the ground-mass,and the light minerals are restricted to the ground-mass. The only reason for not designating the rocks from Lindequesdrift and Rietfontein as lamprophyres is the fact that they do not form dykes. Similar rocks however, form dykes on Koedoesfontein 12 and Koppieskraal 89, and can thus be classified as lamprophyre (and more spesifically spessartite).

The phenocrysts in the rocks from Lindequesdrift and Rietfontein are up to 1 cm in length and the ground-mass ranges from fine-grained in Jansen's (Nel and Jansen, 1957, p.45) hornblendite to medium-grained in his akerite. Both represent facies of the same body. These rocks, including Jansen's hornblendite which has a colour-index below 80, will be termed spessartite.

3. Mineralogy and Petrography

Three types of wehrlite can be distinguished (Fig. 2):

(a) a type with interstitial olivine,

(b) an allotriomorphic type with less than 5 per cent of feldspar, and

(c) a hypidiomorphic type with 5 to 10 per cent of feldspar.

a. Wehrlite of the First Type. - The first type is represented by two separate bodies on Koedoesfontein 12 on the northern slopes of the hill of Main-Bird quartzite south of the Potchefstroom-Parys road (Plate I, Sheet 4). Owing to the abundance of quartzite debris, exposures are poor. The intrusions appear to be short dykes. The wehrlite of the southern dyke contains between 40 and 50 per cent of olivine (β=1.695, Fa_{23}), whereas that of the northern body contains about 25 per cent of olivine with the same composition (Appendix A, Table 2). The interstitial character of the olivine is particularly striking in the wehrlite of the southern dyke (Plate VI B). The rock is medium-grained with most crystals subhedral and has a texture very similar to that which Washington has termed "clathrate" (Johannsen, 1939, p.205). The olivine crystals are arranged in such a way that in thin section the texture has the appearance of a net or a section through a sponge, in which the "holes" are occupied by pyroxene crystals. The "threads" between the "pyroxene holes" are composed of small olivine crystals, and where a number of these "threads" come together the "knots" consists of aggregates of larger olivine crystals (Plate VI B). Olivine crystals are not enclosed in pyroxene crystals or vice versa.

The augite (β=1.690, $2V_z$=45°, Wo_{38} En_{44} Fs_{18}) crystals are sub- to anhedral and frequently show diallage and salite partings as well as schiller structure due to numerous small, orientated, opaque to semi-opaque, brown inclusions, probably hematite. The inclusions are rod- and plate-like in form (0.0005 to 0.001 mm thick). These inclusions are arranged in a regular pattern, mainly parallel to (100), (010), and (001) and are usually crowded along the parting planes. Under the low magnification some augite crystals have a greyish colour; this is due to the close spacing of the inclusions which are evenly distributed over the crystal or patchy in some crystals. The origin of these inclusions is not clear, but they may represent exsolution of ferric oxide from the pyroxene.

Twinning on (100) is seldom developed. The pyroxene shows a small amount of alteration to brown hornblende which is usually distributed in small irregular patches over some crystals. The hornblende probably developed by reaction of the late residual fluid with pyroxene to accomodate the alkalis and aluminium.

The olivine crystals are anhedral and are partly altered to a pale yellow serpentine and magnetite dust along cracks which form veinlets in the olivine crystals. Some of these veinlets even cut pyroxene crystals. This alteration is probably the result of weathering. The crystals of olivine are highly irregular in outline. The form of the crystals is frequently determined by the space between the pyroxene crystals, e.g. a crystal of olivine sometimes surrounds a part of a pyroxene crystal.

At first sight, the textural relations described above indicate that the olivine followed the pyroxene in the paragenetic sequence. Such an interpretation is probably in harmony with a diopsidic pyroxene and a very iron-rich olivine, but the olivine (Fa_{23}) is not an iron-rich variety. It is significant in this texture that the average pyroxene crystal has several times the size of the average olivine crystal and that small crystals of pyroxene are in places enclosed in the olivine "ground-mass" but not in the olivine crystals. Furthermore the olivine crystals are always crowded together and the pyroxene shows a similar tendency, i.e. olivine and pyroxene are "separated".

According to Wager (1959, p.77) and Hawkes (1967, p.477) olivine nucleates with greater ease than the more complex silicates,e.g. pyroxene and feldspar. With undercooling the temperature at which olivine nucleates rapidly would probably be the temperature at which pyroxene nucleates slowly (the two minerals are considered to have crystallized cotectically), consequently the pyroxene crystals would grow to a larger size than the olivine crystals. If the olivine, and also to a certain extent the pyroxene,form clusters, as for example in a glomeroporthyritic texture, the development of the texture of the wehrlite can be visualized. During the final stage of crystallization of the ~~rock~~ magma the temperature of the fluid would probably be above the temperature of rapid nucleation of olivine because heat is evolved during crystallization. Furthermore, the amount of volatile constituents would have increased and would also depress the temperature of crystallization. Under these conditions both minerals would nucelate slowly and only a few new crystals would develop, i.e. the few small crystals of pyroxene and some of the olivine crystals. During this stage the final crystallization would be mainly by addition to the already existing crystals.

Primary magnetite is a minor accessory constituent of which crystals are enclosed in the pyroxene and olivine. More generally magnetite forms irregular patches interstitially between pyroxene and olivine. In the wehrlite of the southern dyke,primary magnetite makes up only a fraction of one per cent,but the wehrlite which forms the northern dyke contains up to 2 per cent of magnetite.

b. Wehrlite of the Second Type. - The second type of wehrlite (Plate VII A) probably grades into the olivine gabbro but owing to poor exposures this could not be established with certainty. It represents the contact-rock on the southern contacts of the two bodies of mafic rock

(Plate II). This wehrlite is medium-grained allotriomorphic and contains about 20 per cent of olivine. Augite (β =1.694, $2V_z$= 46°, $Wo_{39}En_{41}Fs_{20}$) forms anhedral interlocking grains. Lamellar twinning parallel to (001) is present in some crystals and produces a herringbone structure in crystals with orthopinacoidal twinning. The pyroxene shows alteration to brown hornblende and also to actinolite or even to magnetite and tremolite. The alteration to brown hornblende probably represents a late magmatic stage whereas tremolite and actinolite resulted from deuteric alteration. Accessory orthopyroxene (Fs_{19}) forms large crystals enclosing small anhedral augite and/or olivine crystals. The olivine (β =1.707, $2V_x$=85°, Fa_{25}) forms small anhedral to subhedral crystals of approximately half the diameter of pyroxene whereas the olivine crystals enclosed in the pyroxene are about half the size of the olivine crystals lying between the pyroxene. Olivine crystals are sometimes clustered together. Olivine is usually fresh but may show a small amount of alteration to serpentine and magnetite dust.

Interstitial feldspar (An_{20}) makes up less than 5 per cent of the bulk composition of the rock. Magnetite is a primary accessory mineral which is usually interstitial, with a margin of reddish-brown biotite frequently around it.

If this rock represents a crystal accumulate (as it probably does), the pyroxene must have grown considerably after accumulation whereas the olivine did so to a lesser extent.

c. Wehrlite of the Third Type. - The third type of wehrlite (Plate VII B) grades into the olivine gabbro. The texture of this rock is medium-grained, hypidiomorphic granular.The plagioclase (An_{20}) ranges from 5 to 10 per cent. It is interstitial and consists in some specimens of large crystals which enclose the dark minerals poikilitically. Feldspar crystals which appear to be a primary precipitate are seldom present.

The pyroxene (β=1.696, $2V_z$=47°, $Wo_{39}En_{39}Fs_{22}$) crystals are generally subhedral and frequently euhedral. Twinning on (100) is quite common. Lamellar twinning is seldom seen, but when it is present it consists of a few lamellae parallel to (001). The pyroxene is completely fresh, apart from a few specks of brown hornblende in some crystals.

The olivine crystals (β=1.695, Fa_{23}) are generally subhedral but may also be euhedral. The average diameter of the crystals is a little less than that of the pyroxene but about twice that of the olivine in the first type of wehrlite. It is remarkably fresh and seldom shows any signs of alteration. Occasionally the olivine crystals form clusters.

Magnetite is a prominent accessory mineral ranging from 2 to 8 per cent. It occurs as small inclusions in the olivine and pyroxene but where the concentration is high it is mainly interstitial. On contacts between feldspar and magnetite a brown hornblende or a reddish-brown biotite is sometimes developed.

d. The Olivine Gabbro. - The compositional range of the olivine gabbro is the following: olivine 10-30 per cent, augite 35-70 per cent and plagioclase 10-50 per cent (Appendix A, Table 2). The colour-index of the bulk of the gabbro is higher than 60. The olivine gabbro is a medium-grained hypidiomorphic granular rock. It has a subparallel orientation of the plagioclase crystals which is especially evident in the mesotype gabbro. The feldspar crystals (An_{36-37}) are tabular parallel to (010) and are up to 0.75 cm in length. This parallel orientation of the feldspar can be termed foliation (Billings, 1954, p.286) or igneous lamination (Wager and Deer,1939, p.271, and p. 37). Frequently a few large crystals of plagioclase form a cluster with subparallel orientation of the crystals. With an increase in the colour-index of the rocks the tabular form and the orientation of the feldspar becomes less evident.

Feldspar crystals which can be described as primary precipitate crystals are frequently bent and in rare cases a faint oscillatory zoning is evident in polarized light.

The pyroxene (β=1.649, $2V_z$=52, $Wo_{42}En_{39}Fs_{19}$) of the olivine gabbro is subhedral and twinning on (100) does not occur as frequently as in the third type of wehrlite. Lamellar twinning parallel to (001) is present in some crystals. In some specimens the pyroxene encloses small laths of plagioclase and/or small grains of olivine. Bronzite is a rare constituent.

The olivine crystals (β=1.694, Fa_{23}) are usually anhedral to subhedral. In some rocks small anhedral crystals of olivine are clustered together, and these are then closely associated with interstitial magnetite. The large olivine crystals have a greater tendency to show crystal faces.

The accessory minerals are magnetite, apatite, and brown hornblende. The magnetite is either enclosed in olivine and pyroxene or, where it makes up more than 2 per cent of the rock, it is interstitial.

e. The Picrogabbro and the Troctolite. - The picrogabbro is represented by two main types which differ texturally. The first type is associated with the troctolite in the vicinity of the Wonderfontein dyke and the second type is associated with the olivine gabbro in the eastern outcrop of the mafic rocks (Plate II). Igneous lamination is strongly developed in the first type owing to the subparallel orientation of primary precipitate feldspar, but in the second type it is not so clearly developed because the greater part of the feldspar is either interstitial or forms large poikilitic crystals.

The olivine in the subtype with the poikilitic feldspar is subhedral to euhedral and the pyroxene is anhedral to subhedral.The pyroxene frequently encloses small rounded grains of olivine. In this subtype the olivine represents the primary precipitate and the pyroxene appears to have grown considerably after accumulation. In the subtype which grades texturally into the olivine gabbro, the olivine shows a slighter tendency towards idiomorphism and the feldspar does not consist of large poikilitic crystals. A few clusters of primary precipitate feldspar are present in the rock. The larger feldspar crystals include the dark minerals only partly or in their margins.

The first type of picrogabbro is texturally similar to the troctolite and actually represents a troctolite with about 30 to 40 per cent of pyroxene. It will be considered together with the troctolite. The difference between the pyroxene of the two rock-types is that in the troctolite the pyroxene forms large poikilitic crystals which enclose olivine and small feldspar laths, whereas that of the picrogabbro (β=1.695, $2V_z$=52, $Wo_{42}En_{38}Fs_{20}$) consists of small crystals with approximately the same diameter as the olivine. In the troctolite the igneous lamination is prominently developed owing to the parallel orientation of primary precipitate feldspar crystals (An_{37}). The spaces between the feldspar crystals are filled with small crystals of olivine (β=1.694, Fa_{23}). In rare cases the troctolite also contains a few large crystals of olivine. The small olivine crystals form interlocking aggregates (Plate VIII A) which are elongated parallel to the feldspar crystals. The olivine is partly enclosed along the margins of the feldspar crystals which must have undergone further growth after the precipitation of the olivine.

Magnetite is interstitial and is closely associated with olivine. In a type of troctolite containing between 15 and 20 per cent of magnetite, the feldspar consists of large crystals which enclose numerous small crystals of olivine. Brown hornblende is an accessory constituent which frequently forms a rim around magnetite, usually on contacts between magnetite and feldspar.

f. Pegmatites. - Pegmatites in the mafic portion of the complex are rare. Only one short vein about 30 cms wide is present in the south-eastern part of the complex. It is a very coarse-grained rock consisting of plagioclase (An_6) and hornblende with accessory quartz which is sometimes intergrown with feldspar (myrmekite). Sphene is a minor accessory mineral. The hornblende is a green variety and some crystals of feldspar show the "checker" variety of twinning (Johannsen 1937, p.135).

g. Reaction with the Country-rock. - On the contacts between the mafic portion of the Rietfontein Complex and the country-rock (dolomitic limestone and andesite) a certain amount of contamination has taken place. On the western and southern contacts of the southern body, a wehrlite on the contact with the andesite contains approximately 5 per cent of green spinel (pleonaste). On the northern side of the eastern exposure of the mafic rocks a loose block composed mainly of clinopyroxene with accessory plagioclase and calcite was picked up. The pyroxene is partly replaced by a green and a brown hornblende. Plagioclase and calcite are interstitial. Minor accessory minerals include sphene, chlorite and zoisite.

h. The Kaffirskraal Intrusion. - For comparison with the mafic rocks of the alkaline suite, specimens were also collected from the ultramafic intrusion on Kaffirskraal 301, south-west of Heidelberg. This intrusion shows alkaline rather than tholeiitic affinities, if the criteria discussed above are applied. The principal rock-type of this pluton is an augitite with a considerable amount of magnetite. In the central part of the pluton a body of ilmenite magnetitite is exposed.

The augitite is composed of augite which frequently shows simple (100) or lamellar twinning. A late reaction product of the augite is accessory brown hornblende which is found mainly on the rims of pyroxene crystals. Apart from a few small crystals which are included in the augite, the bulk of the magnetite is interstitial.

The chill-phase of the pluton is a fine-grained dolerite which is composed of scattered phenocrysts of olivine in a ground-mass of lath-shaped plagioclase (An_{45}) and augite. The phenocrysts of olivine partly enclose the plagioclase laths, thus producing a texture similar to the subophitic texture of dolerite. Accessory minerals are magnetite and brown biotite which frequently forms rims around the magnetite.

The norm calculated from a chemical analysis of the augitite (Nel and Jansen, 1957, p.44) does not give a reliable representation of the pyroxene of the rock because a considerable part of the magnetite of the rock appears to be oxidized. However, the norm of the chilled dolerite (Nel and Jansen, 1957, p.44) indicates no normative hypersthene. The augitite and the associated magnetitite probably originated from a magma which had the bulk composition of the chilled olivine dolerite. If the normative values for pyroxene, plagioclase and olivine of this dolerite are plotted on the phase diagram for the system Fo-Di-An the composition of the rock falls in the pyroxene field which indicates that pyroxene would have been the first major constituent to crystallize from this magma. Gravitational settling of augite would lead to the development of the augitite in the lower part of the intrusion. At a later stage when plagioclase and olivine crystallized together with augite, gabbroic rocks would develop in the upper part of the pluton. The pluton has been eroded to such a depth that only the cumulative rocks and the chill-phase are exposed at the present level.

Nel and Jansen (1957, p.43) consider the small outcrops of norite and hyperite in the pluton to represent possible xenoliths. Additional evidence for such an interpretation is the fact that the orthopyroxene of these rocks shows exsolution parallel to (100). The orthopyroxene of similar rocks from sills in the Heidelberg area is homogeneous and does not show exsolution. This exsolution is considered to be the result of prolonged heating of the inclusion by the magma of the Kaffirskraal Intrusion.

The above data indicate that the Kaffirskraal Intrusion is younger than the rocks of the tholeiitic suite, and that the age of this intrusion is probably similar to that of the mafic portion of the Rietfontein Complex.

4. Petrogenesis of the Mafic Rocks

The crystallization and petrogenesis of the mafic rocks will be discussed in the light of experimental work (Yoder and Tilley, 1962) on the phase relations in basaltic magmas and also in terms of crystal nucleation (Wager, 1959, and Hawkes, 1967).

a. Phase Relations. -

Because no contacts between the different rock-types are exposed it is difficult to establish whether the mafic portion of the complex represents a simple or a multiple intrusion. The mafic rocks of the Rietfontein Complex comprise two series, a troctolite-picrogabbro series and an olivine gabbro-wehrlite series. The two series give rise to two separate sets of al, fm, c, alk, and mg curves (Fig. 3) whereas in the $MgO-FeO+\frac{1}{2}Fe_2O_3-\frac{1}{2}K_2O+\frac{1}{2}Na_2O$ diagram (Fig. 8 p.102) the variation curve splits in two. The possibility of several intrusions or pulses of magma must therefore be considered in the explanation of the variation in the rocks of the mafic portion of the complex.

Yoder and Tilley (1962, p.395) represent the "simple iron-free system for critically undersaturated basalt" by the four components Di-Fo-Ab-An. In this system the three major phase volumes Di, Fo and plagioclase have three common planes Di-Fo, Di-plagioclase, and Fo-plagioclase in which two phases are in equilibrium with each other and with liquid. Along

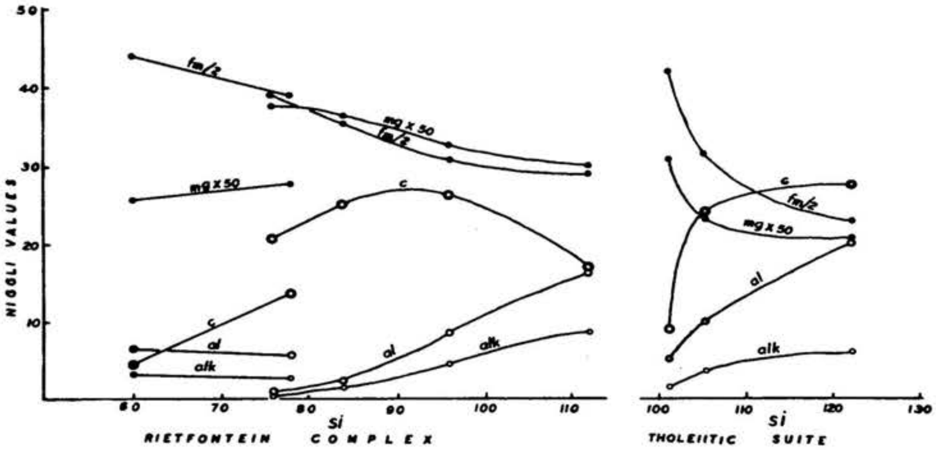

Fig. 3. Variation in the Niggli values of the mafic rocks of the Rietfontein Complex and rocks of the tholeiitic suite. The set of curves in the left part of the diagram represents the troctolite-picrogabbro series and the set in the middle part the olivine gabbro-wehrlite series.

the three-phase curve all three phases and the liquid are in equilibrium. The temperatures at the two piercing points at the ends of the four-phase curve differ by only 135°C and the relative porportions of the phases at the piercing points are Di=49,Fo=7.5, An=43.5 and Di=8.0, Fo=1.5, Ab=90.5. The piercing point for any intermediate composition of plagioclase falls between these two piercing points. According to Yoder and Tilley (1962, p.396) the initial bulk composition of basalts should lie very close to the four-phase curve which suggests that basalts are products of fractional melting or fractional crystallization. A section through the tetrehedron at Fo-Di-An_{35} is illustrated in Fig. 4 with C as the piercing point for these components. In this case all the mafic rocks of the Rietfontein Complex and the wehrlite of Koedoesfontein fall in the forsterite field quite a distance away from the piercing point C and the three-phase curve CE. This indicates that the complex, as it is exposed at present, represents only cumulate rocks and that rocks which should have a composition close to the piercing point C have been removed by erosion, or that for the composition of the Rietfontein magma the piercing point C and the curve CE have shifted some distance into the olivine field, thus enlarging the fields of pyroxene and plagioclase. Whatever the situation may have been, it is clear from petrographic evidence that pyroxene was one of the first minerals to crystallize.

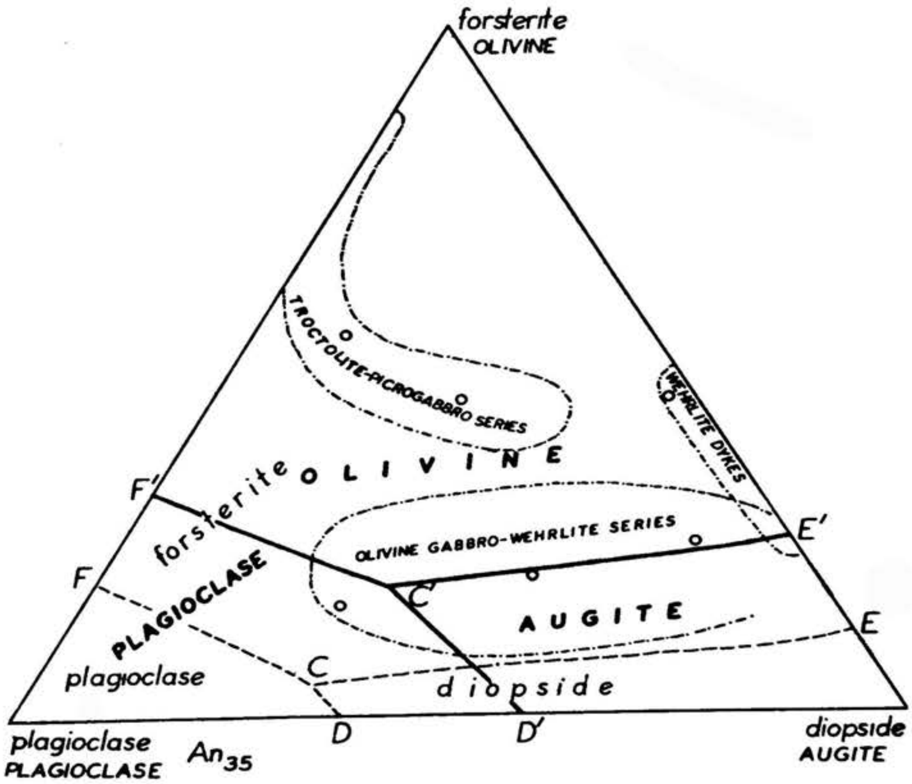

Fig. 4. A section through the Di-Fo-Ab-An tetrahedron (Yoder and Tilley, 1962, Fig. 10) at the Di-Fo-An_{35} position, on to which suggested curves (bold) for the system olivine-augite-An_{35}, the normative composition of analyzed rocks and the fields of modal (weight) variation of the mafic rocks of the Rietfontein Complex are plotted.

In the olivine gabbro on Rietfontein, plagioclase, olivine, and augite appear to have crystallized more or less simultaneously, consequently the piercing point for the iron-free system will probably have to be shifted towards the forsterite-apex in order to accomodate the system An_{35}-Fo_{25}-augite, i.e. to a position within the field of the gabbros, to say C' (Fig. 4). If CE. is shifted to C'E' this curve will represent more or less the average compositional trend of the wehrlite-gabbro series. Curve FC must then be shifted towards F'C'.

In the second type of wehrlite the olivine and augite appear to have crystallized more or less simultaneously. This rock-type represents a crystal accumulate in which the pyroxene shows further growth after accumulation (hence the anhedral crystals) and the small amounts of feldspar crystallized interstitially. The original composition of the magma probably lay close to the cotectic curve C'E' where approximately 20 per cent of olivine and 80 per cent of pyroxene would crystallize together. Crystallization would follow the curve E'C' towards C' where olivine, pyroxene and augite would crystallize together to produce the gabbro. Crystallization in such an order explains the development of the olivine gabbro-wehrlite series.

Mineral variation along a traverse more or less parallel to the minor axis of the mafic portion of the complex (Fig. 5) in the vicinity of the Wonderfontein dyke shows that there is an antipathetic relation between the relative proportions of pyroxene and plagioclase in the olivine gabbro-wehrlite series with olivine more or less constant. This variation is not linear. The reasons for this variation are probably the further addition of magma, movement in the magma (as a result of flowing, igneous lamination would develop), and the relative rates of sinking of the different minerals.

The third type of wehrlite probably resulted from such a fresh influx

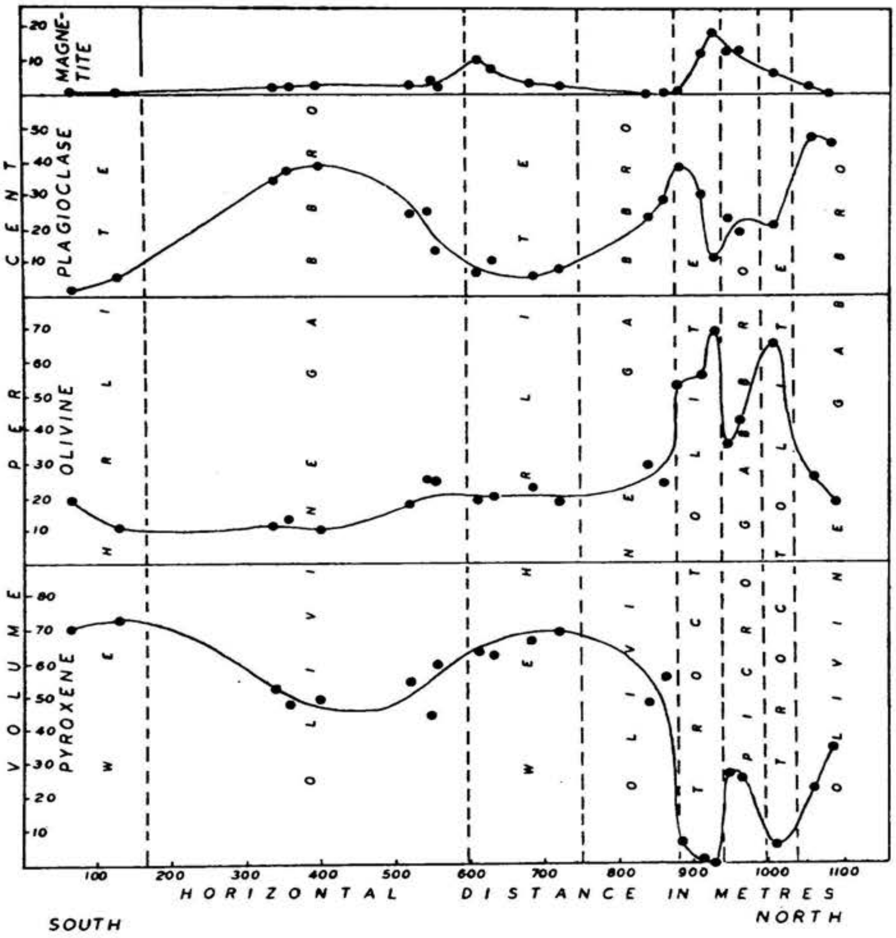

Fig. 5. Mineral variation along a route parallel to the minor axis of the mafic portion of the Rietfontein Complex in the vicinity of the Wonderfontein dyke.

of magma after the greater part of the first pulse had crystallized. If the original composition was such as proposed above (composition near or on E'C' some distance away from piercing point E', Fig. 4), a new addition would inhibit the crystallization of feldspar. Crystallization would proceed in a manner similar to that of the first pulse until the piercing point C' was reached, after which gabbro would crystallize again. Such a second pulse would also explain the occurrence of gabbro below the wehrlite on the southern contact of the complex on Rietfontein 54 (Plate II).

If the gabbro resulted largely from the simultaneous crystallization of plagioclase, pyroxene and olivine, i.e. crystallization at the piercing point C', subsequent crystallization of plagioclase and olivine (without pyroxene) could only have taken place if the composition of the liquid were to move to the cotectic line E'C' and the temperature were to increase, or otherwise pyroxene must have been effectively subtracted from the three co-precipitating phases olivine, plagioclase and pyroxene. In the case of the last alternative a pyroxene-rich rock should have formed in contact with the troctolite.

If the troctolite is considered to have developed from a separate intrusion or heave of magma, the composition of which would fall near to or on the curve F'C', crystallization of olivine and plagioclase would proceed until C' was reached and then pyroxene would take part in the crystallization process and lead to the development of a picrogabbro.

If the above explanation is correct, it can be concluded that the crystallization of a magma of which the composition falls more or less on the cotectic curve E'C' would produce olivine gabbro, and one with a composition more or less on the cotectic curve F'C' would produce picrogabbro. In the case of the rocks of the Rietfontein Complex, the olivine gabbro is actually a wehrlite to which plagioclase has been added and the picrogabbro a troctolite to which pyroxene has been added. A liquid which followed the curve F'C' would already be rich in suspended crystals of olivine and plagioclase when the piercing point C' was reached, whereafter pyroxene would become an additional phase, whereas a liquid which followed the curve E'C' would in turn contain suspended crystals of olivine and pyroxene when plagioclase joined in the process of crystallization at C'. A possible reason why the troctolite-picrogabbro series falls in the olivine field is that these rocks are cumulate rocks which originated as a result of the mechanical concentration of their constituent minerals under the influence of gravity and movement of the magma. Because of the great difference in the sinking velocity of olivine and plagioclase there would be a greater tendency for these two minerals to become separated and thus produce more olivine-rich rocks than would be the case with the olivine and pyroxene which produced the wehrlite.

The wehrlite intrusions on Koedoesfontein are probably related to the mafic portion of the Rietfontein Complex. If these dykes resulted from the intrusion and crystallization of a magma with wehrlitic composition, this magma would have had an extraordinary composition. The variation in composition (the olivine content ranges between 20 and 50 per cent) of the rocks and their medium grain-size for such small intrusions, militate against such a possibility. It is possible that the wehrlite bodies are remnants of a larger differentiated intrusion of which the upper part has been removed by erosion. If this were so the original magma would have had a composition similar to the one which produced the olivine gabbro-wehrlite series on Rietfontein. It is possible that the wehrlite represents an intrusion of a crystal accumulate which developed from an olivine basaltic magma at deeper levels, but then the interstitial liquid must by some process or other have lost its potential feldspar-forming constituents. Diffusion of constituents between the interstitial liquid and the overlying magma, as postulated by Hess (1960, p.111) for the Stillwater Complex, could be responsible for the removal of potential feldspar-forming constituents. Because crystallization is involved in this process, the crystal mush would be more or less solid and probably incapable of intrusion at the stage when approximately all the potential feldspar-forming constituents were removed.

Acceptance of two basaltic magmas with such differences in composition that the one type lies on the cotectic curve F'C' and the other on the cotectic curve E'C' (Fig. 4) raises the problem of their origin. It is conceivable that basaltic magmas which differ in composition to such an extent can originate in depth, e.g. in the mantle, by selective or complete melting of materials with different composition and physical properties, and probably also under different conditions of pressure. The compositional differences between the two magmas need not be greater than the differences between tholeiite and alkali basalt.

b. Nucleation. - Hawkes (1967, p.473) states that what he terms units in the Freetown Complex of Sierra Leone comprise the following series : dunite → troctolite → olivine gabbro → anorthosite. This corresponds to one of the series of the Rietfontein Complex, but another unit can also be visualized which would correspond to the other series of the Rietfontein Complex : dunite → wehrlite → olivine gabbro → anorthosite. Differentiation of one olivine basaltic magma into two series after the stage in which olivine gabbro develops, requires an interruption in the crystallization of either pyroxene or feldspar or both, depending on the rock-type which develops in the next stage. In the Rietfontein Complex where monomineralic members are lacking, the transition from the wehrlite- olivine gabbro series to the troctolite-picrogabbro series requires an interuption in the crystallization of pyroxene.

According to Wager (1959, p.78) and Hawkes (1967, p.473) undercooling of the magma and differences in the power of nucleation of the constituent minerals could cause such an interuption. Hawkes (1967, p.482) states that the order of abundant nucleation is olivine, pyroxene and plagioclase, which is in accordance with Wager's (1959, p.77) statement that minerals with a simple structure crystallize readily whereas more complex silicates do not. According to Eitel (1965, p.14 & Fig. A.4) the rate of crystallization decreases with increasing viscosity whereas the rate of nucleation increases to a maximum.

In the rocks of the Rietfontein Complex the olivine and the pyroxene of the picrogabbro are of approximately the same grain-size, which is several times smaller than that of the feldspar, consequently pyroxene and olivine crystals are more numerous than the feldspar crystals per unit volume of rock. If the size and the number of crystals per unit volume are functions of the ease of nucleation, the pyroxene and olivine must have nucleated more rapidly than the plagioclase in the picrogabbro. A similar condition holds for the olivine and the feldspar of the troctolite (Plate VIII A).

In the Rietfontein Complex three units can be recognized: the second which is more or less a repetition of the first, and the third unit which would have originated subsequent to the crystallization of the olivine gabbro of the second unit (Fig. 5). Cessation of crystallization could be the result of a rise in temperature due to crystallization of the gabbro and also due to an increase in volatile constituents in the magma. Both factors would tend to lower the temperature of crystallization at this stage.

The third cycle was then initiated with undercooling of the magma, crystallization of olivine at the temperature of rapid nucleation, and slow nucleation of the feldspar under the same conditions. During this stage troctolite was formed. At a later stage when pyroxene started to crystallize the picrogabbro was formed.

Such a mechanism, as visualized by Hawkes (1967, p.474), would be efficient provided that the temperature range of rapid nucleation, which is termed the middle labile region by Wager and Brown (1968, p.120), of one mineral does not overlap that of other minerals, i.e. while the one mineral nucleates freely, the other minerals do not nucleate or nucleate only insignificantly.

Yoder and Tilley (1962, p.383) have found in their experiments with the major types of basalt that all the principal silicate phases appear within a temperature range of less than 80°C. Hess (1941, p.583) concludes that after about 60 per cent of a basaltic magma has crystallized the drop in temperature will be only 40°C. Where two or more minerals crystallize under cotectic conditions the temperature range of crystallization will be determined by the amount of fractionation. With little fractionation this range will be small. In a liquid from which pyroxene and plagioclase or olivine, pyroxene and plagioclase should crystallize together under conditions of equilibrium, the middle labile regions for the different minerals, if they should crystallize in a sequence, must be very narrow and the condition of rapid nucleation must be attained rapidly, and not gradually as is figured by Eitel (1965, Fig. A.4), to fit into the small temperature range in which all the major silicate phases crystallize.

The order of rapid nucleation appears to differ for different magmas. Wager (1959, p.77) for example suggests the following order for some rocks of the Bushveld: chromite, bronzite, plagioclase, and for the marginal gabbro of the Skaergaard intrusion Wager and Brown (1968, p.119) suggest the early nucleation of plagioclase and olivine and a subsequent nucleation for pyroxene. In the rocks of the Rietfontein Complex the order of rapid nucleation for the wehrlite-olivine gabbro series is pyroxene and olivine at an early stage and plagioclase at a later stage; for the troctolite-picrogabbro series the order is olivine and plagioclase at an early stage and pyroxene at a later stage. It thus appears that the concentration of the constituents of a particular mineral in the magma must also be an important factor in determining the temperature at which nucleation will have a maximum value. For one particular composition of a magma one mineral reaches the condition of rapid nucleation (or supersaturation) earlier than in another magma with a lower concentration of the constituents of the same mineral, i.e. different degrees of undercooling are necessary to reach the supersaturated condition for a particular mineral in different magmas.

The southern band of troctolite and the picrogabbro can be regarded as one unit and the other band of troctolite and the northern band of olivine gabbro as another unit (Fig. 5). An alternative interpretation is that the two bodies of troctolite are interconnected lower down and also the two bands of olivine gabbro on both sides of the two bands of troctolite (Fig. 5). This could only be ascertained if structural details of the complex were available. However, the dip of the igneous lamination of the olivine gabbro on either side of the two bands of troctolite conforms with that of a syncline, whereas the troctolite and picrogabbro have a discordant relation to the southern limb of the syncline. This interpretation is more in line with the idea of two separate magmas.

C. The Dioritic Series

The Roodekraal Complex and the Lindequesdrift Intrusion are the main representatives of the dioritic series. It is not intended to give a full account of the Roodekraal Complex because it falls outside the scope of this study. The Roodekraal Complex appears to be a laccolithic or ethmolithic body and is composed of coarse-grained sodagabbro and diorite as well as various smaller bodies of fine-grained dioritic rocks which are all intrusive into a cover of andesitic lava. The rocks of this complex have undergone extensive hydrothermal alteration, e.g. albitization of the feldspar, alteration of the pyroxene to actinolitic hornblende, epidotization and finally the deposition of chalcopyrite and bornite in all the rock-types, especially the andesite. The latest stage of magmatic intrusion is represented by small dykes of nearly pure oligoclase rocks which are also albitized (Bisschoff, 1950, p.26).

The Lindequesdrift Intrusion (Jansen, 1957, p.45) is a poorly exposed pluton which is elongated parallel to the strike of the Dolomite country-rock and is composed of lamprophyric rocks. Dykes of similar lamprophyric rocks which are apparently related to this intrusion were emplaced in the pre-Karroo rocks in the Vereeniging-Heidelberg area (Jansen, 1957, p.45; Rogers, 1922, p.63).

1. The Lamprophyric Rocks

The rocks of this group have a dioritic composition (spessartite) and are characterized by their phenocrysts of hornblende in a ground-mass of plagioclase (albite to oligoclase) and augite.

On Koppieskraal 89, about half a mile east of the Vaal River and about 100 yards south of the small epidiorite sill on the road to Parys, (Plate I, sheet 3) there is a dyke of spessartite which is intrusive into the Archaean granite. This dyke strikes more or less parallel to the epidiorite and can easily be mistaken for epidorite because the porphyritic texture is not very pronounced and the hornblende is a green variety. The plagioclase (An_{30}) of the spessartite has a small grain-size but in some specimens it forms large poikilitic plates which enclose hornblende and augite, whereas the small crystals of recrystallized feldspar of the epidiorites have a composition of An_{45} and remnants of the original feldspar have a composition of An_{65}. Accessory minerals include quartz, subhedral to euhedral titanite, and apatite.

On Koedoesfontein 12, near the northern end of the southern dyke of wehrlite (Plate I, Sheet 4) there is a small dyke of spessartite which is rather variable in composition and ranges from leucocratic to melanocratic. These two extreme colour-types appear to form small schlieren in the average mesotype lamprophyre. This average spessartite is a fine-grained rock which is composed of phenocrysts (about 2 mm in diameter) of brown hornblende in a ground-mass of plagioclase and augite. The brown hornblende ($2V_x = 70°-75°$) encloses small crystals of plagioclase but no augite. Frequently the brown hornblende grades into a green hornblende towards the margins of the crystals. Anhedral augite which is partly altered to green hornblende is the major dark constituent of the ground-mass. The small subhedral crystals of plagioclase (An_{25}) are frequently strongly zoned. The accessory minerals are quartz, apatite and magnetite.

At the south-western end of the northern body of wehrlite there is another body of spessartite which is probably a dyke. This spessartite is darker than the one described above and is composed of phenocrysts of augite in a ground-mass of plagioclase, brown hornblende and augite. The pyroxene has a prominent diallage parting, a feature which is also characteristic of the pyroxene of the associated wehrlite. The pyroxene tends to form clusters of 10 or more crystals. Magnetite is a prominent accessory mineral and constitutes up to approximately 10 per cent of the rock. Minor accessory minerals include quartz and apatite. There is probably a close genetic relationship between the lamprophyre and the wehrlite on Koedoesfontein.

On Rietfontein 163 specimens of the lamprophyric rock were obtained only from loose blocks because no outcrops could be found. This spessartite is composed of subhedral to euhedral phenocrysts of brown hornblende,up to about 1 cm in leng~~h~~th,in a medium- to fine-grained ground-mass of plagioclase (An_5) and augite. In weathered specimens hornblende crystals showing the following faces could be picked out : (110), (010), (100), (011), (031), $(1\bar{2}1)$ and $(\bar{1}01)$. Some hornblende crystals have a slightly greenish tint on the margins. The pleochroism is, X=straw-yellow, Y = yellowish brown and Z = dark brown, and $2V_x$ = 70°-75°. A basal parting is frequently developed. The augite is subhedral to anhedral and is partly altered to green hornblende which sometimes forms pseudomorphs after the pyroxene. The feldspar consists of anhedral crystals of the same size as the augite and also large poikilitic plates which enclose augite and hornblende.

Apart from having a slightly higher colour-index, the lamprophyric rocks of the Lindequesdrift Intrusion are very similar to those of the Rietfontein Complex. The amphibole phenocrysts in the lamprophyre of Rietfontein and those in the Lindequesdrift Intrusion are optically indistinguishable. However the augite crystals in the rocks of the Lindequesdrift Intrusion range from subhedral to euhedral and constitute a greater proportion of the rock. The feldspar (An_{20}) is highly altered and usually forms large poikilitic crystals which enclose augite and hornblende. Euhedral prisms of apatite and anhedral to euhedral crystals of magnetite are the major accessory minerals. Quartz and sphene are minor accessory constituents. The apatite is enclosed in both feldspar and amphibole but not in the augite. The hornblende phenocrysts enclose irregular remnants of randomly orientated augite and in places also similar randomly orientated inclusions of feldspar. The augite is frequently partly altered to green hornblende.

The dark variety of lamprohyre (Jansen's hornblendite, Nel and Jansen, 1957, p.47) is composed of large (1 cm in length) euhedral to subhedral phenocrysts of brown hornblende in a fine-grained ground-mass of plagioclase and augite. The feldspar usually forms large poikilitic crystals which enclose euhedral to subhedral crystals of augite, magnetite and amphibole. The phenocrysts of hornblende enclose irregular remnants of augite and feldspar and crystals of magnetite and apatite. The difference between this type and the one described above is that this darker variety contains a higher proportion of phenocrysts and more augite.

2. Petrogenesis of the Lamprophyric Rocks

Normally the hornblende which is present as large phenocrysts would be taken as the first mineral to have crystallized from the magma, but then the subsequent crystallization of augite in the ground-mass is just the opposite of what would be expected if Bowen's Reaction Principle is applied to these minerals. Judging by the irregular inclusions of clinopyroxene in the phenocrysts of hornblende, the clinopyroxene has apparently crystallized before the hornblende. The clinopyroxene in the ground-mass is generally subhedral to euhedral; these inclusions can therefore be regarded as corroded remnants resulting from reaction between the magma and the pyroxene.

Yoder and Tilley (1962, p.452) found that the order of crystallization of pyroxene and amphibole in alkali basaltic magmas is reversed at PH_2O = 5.3 kilobars. If this reversal of the order of crystallization of pyroxene and amphibole took place in the spessartite, the irregular remnants of pyroxene in the hornblende are difficult to explain.

The lamprophyric rocks have crystallized from a dioritic magma with a high concentration of water and other volatile constituents. As the crystallization of augite, and in some rocks also feldspar, continued, water would be concentrated in the residual liquid. At the appropriate temperature and vapour pressure of the water the residual liquid would not only produce hornblende but would also react with the crystalline products. Because the magma would not be nearly completely solidified at this stage, and because the viscosity of the liquid would probably be low owing to the high concentration of volatile constituents, the development of large crystals of hornblende would be possible. The spessartite which contains the phenocrysts of augite is a fine-grained rock. It crystallized from a magma which probably cooled rapidly, so that apart from plagioclase, all the amphibole crystallized in the ground-mass and a limited amount of reaction with pyroxene could take place.

The lamprophyric rocks are probably also related to the dioritic rocks of the Roodekraal Complex, but here the magma was apparently ~~been~~ relatively poor in water. It is possible that the Roodekraal rocks crystallized under shallow conditions, and that the water was expelled during volcanic activity, whereas the rocks of Lindequesdrift developed under conditions in which the water was retained in the magma.

D. The Alkali Granite

1. Distribution and Field Relations

The alkali granite on Rietfontein 163 is intrusive into the mafic portion of this complex. Veins of alkali granite which frequently follow joints cut across the mafic plutonic rocks and the dolerite. This pluton of alkali granite is elongated parallel to the strike of the Dolomite Series and has apparently been emplaced along a strike-fault in the Dolomite Series (Plate II).

The alkali granite is a medium-grained rock with a pink colour. During the course of detailed mapping of the Rietfontein Complex no granitic pegmatites were observed. A few small aplite veins were encountered in the granite in a stream bed which crosses the north-eastern extremity of the granite pluton. On the south-eastern contact, about

200 yards east of the Wonderfontein dyke, a hybrid rock is exposed which is composed of granite with numerous small, dark inclusions of hornfels. Desilication of the granite has evidently taken place on the contact between the granite and the dolomite.

There are two plutons of alkali granite along the Vaal River where it cuts across the strike of the rocks of the Witwatersrand System (Plate I, Sheet 2). The northern pluton (Schurwedraai pluton) occupies an area of approximately 1.5 square miles and the southern pluton (Baviaan Kranz pluton) occupies an area of about one square mile. A few small outcrops of alkali granite are also found in the stream bed near the north-eastern boundary of Koedoesfontein 12, and another one near the wehrlite dykes in the same vicinity (Plate I, sheet 4).

All these plutons were emplaced along major strike-faults. The Schurwedraai pluton was forcefully injected along the plane of a strike-fault. The walls of the fault were forced apart to such an extent that a dome was formed along the flanks of which the Jeppestown Series, duplicated by faulting, dips outwards. On the eastern flank of this pluton, on Koedoeslaagte 59, remnants of the roof, which is composed of rocks of the Jeppestown Series, are still preserved.

The Baviaan Kranz pluton is intrusive into the Government Reef Series. Here extensive faulting has apparently also been responsible for the location of the pluton. Worthy of notice is the disappearance of the thick Government Reef quartzite (G.R.Q.3) on the southern flank of the pluton on Helena 780 and Eliza 972. This is in an area where a major strike-fault cuts this quartzite obliquely at a very small angle. In this area the quartzite which usually forms extensive outcrops has apparently been replaced by the granite. The possibility of chemical replacement (granitization) can be ruled out because the contacts between the alkali granite and the country-rock are sharp. Apart from a certain amount of assimilation of country-rock by the granite magma, no signs of granitization are observable in the quartzite.

The disappearance of the quartzite can therefore only be ascribed to faulting and the forceful injection of the granitic magma. Fault-blocks of country-rock, which were subsequently eroded, were probably displaced by the magma.

The location of the small intrusions on Koedoesfontein 12 has also apparently been controlled by faulting (Plate I, Sheet 4). They were emplaced in an area in which the strike of the Upper Division of the Witwatersrand System is perpendicular to that of the Lower Division of the Witwatersrand System. About 350 yards south-west of the northern outcrop of wehrlite on Koedoesfontein alkali granite was struck in a bore-hole for water. It thus appears that the area between the small outcrops of alkali granite and the road between Potchefstroom and Parys is probably underlain by another pluton of alkali granite.

Dykes of alkali granite aplite are found mainly in the eastern part of the Vredefort Dome. These rocks have been described by Nel (1927, p.72) as quartz keratophyre. Similar rocks have also been described by Rogers (1922, p.64) and by Jansen (Nel and Jansen, 1957, p.45) under the names of albitite, sölvsbergite, lestivarite, and bostonite (all alkali syenite aplites), and grorudite and quartz keratophyre (alkali granite aplites). These rocks show a close similarity to the dykes of oligoclase rock (now albitite) on Roodekraal 37. Two small dykes of albite syenite are intrusive into the Ventersdorp lava on Rooipoortjie 19, about half way between the Schurwedraai pluton and the Roodekraal Complex.

2. Mineralogy and Petrography

a. General. - The alkali granite is a sodic variety. The average value of K_2O/K_2O+Na_2O(molecular)for nine chemical analyses of this granite is 0.27. On the average it is composed of 80 per cent of feldspar, 10 per cent of quartz and 8 per cent of alkali amphibole and/or alkali pyroxene by volume. The volume of quartz in the alkali granite ranges from 2 to 22 per cent. The average value of normative quartz (equivalent norm) for nine chemical analyses is 20 per cent and ranges from 5 to 30 per cent. The reason for the difference between the average normative and average volumetric values for quartz must apparently be sought in the position on the plutons from which the eight analysed samples were taken. They were evidently taken near the contacts between these intrusive rocks and the surrounding sediments, along which quartzitic material had been assimilated and where exposures are better than in the central parts of the plutons. Furthermore the syenitic type has a more weathered appearance than the quartz-rich types. The new analysis (Appendix B, No. 16) represents the syenitic type which shows little or no evidence of assimilation of country-rock. The original magma must have been more alkali syenitic than granitic. The syenitic type has a patchy occurrence in the finer—grained alkali granite into which it grades. The best exposure of the alkali syenite is on Koedoeslaagte 59 where the outcrop south of the roof-contact is composed mainly of this type.

b. The Alkali Granite of the Rietfontein Complex. - The granite of this complex is a fine- to medium-grained, hypidiomorphic to allotriomorphic, leucocratic rock which is composed of alkali feldspar, quartz and sodic amphibole.

The feldspar of this alkali granite is an antiperthite. Apart from the frequent occurrence of Carlsbad twins, twinning of the host-crystals, according to the Albite law, is seldom developed. The potassium feldspar tends to weather more readily than the albite, with the result that the potassium feldspar has a slightly turbid appearance.

The exsolved potassium feldspar (orthoclase) shows a variety of forms of which the braided antiperthite is a common type. The exsolved potassium feldspar is usually elongated parallel to (001). Other types include patch- and film-antiperthite. There is a general tendency for the potassium feldspar to be more concentrated on the margins of the crystals, and in some specimens it forms a narrow mantle around a core of plagioclase which encloses a small amount of exsolved potassium feldspar. The exsolved potassium feldspar of the core and that of the mantle ~~gin~~ are optically continuous.

Albite (An_7) showing well developed narrow twinning lamellae is found in the granite and comprises not more than about 5 to 10 per cent of the rock. These phenocrysts ~~have~~ usually have about 2 to 3 times the length of the antiperthite crystals and attain a length of about 4 to 5 mm. They are usually practically free from exsolved potassium feldspar, are weakly zoned, and most of the crystals have narrow mantles of antiperthite. It seems that at a later stage the albite phenocrysts have undergone further growth of the material of which the antiperthite is composed, thus forming albite crystals with mantles of sanidine.

In a few examples small very fine-grained patches of orthoclase, albite and quartz are present interstitially to the larger crystals of quartz and antiperthite. In these areas the two feldspars are independent of each other.

The quartz forms anhedral crystals similar in size to the crystals of antiperthite. It is interstitial and seldom shows intergrowth with feldspar.

The dark mineral of the granite is a strongly pleochroic yellowish-brown to dark-green alkali amphibole. It is usually interstitial and encloses small subhedral crystals of feldspar. A basal parting is well developed and some crystals contain small remnants of diopsidic pyroxene. The extinction angle is about 25° and $2V_x$ = 45º50°. This amphibole is a magnesio-arfvedsonite.

Aegirine is not a constituent of the normal granite but is found together with amphibole only in the alkali syenite on the contact with the dolomite on Rietfontein 163. Both the amphibole and the pyroxene are interstitial. Some of the crystals of magnesio-arfvedsonite contain small patches of arfvedsonite. A mineral which is pleochroic from blood red to opaque is associated with the amphibole and the pyroxene. It is either chalcophanite or haematite.

The accessory minerals of the granite are magnetite, sphene, apatite and biotite.

This granite represents the hypersolvus type according to the scheme of subdivision of Tuttle and Bowen (1958, p.129).

c. The Alkali Granite of the Vredefort Dome. - The alkali granite of the plutons along the Vaal River is composed of albite, microcline, quartz, aegirine and arfvedsonite. The rocks are hypidiomorphic to allotriomorphic, medium to fine-grained alkali granite and alkali syenite. The syenitic types are usually coarser and more even grained than the granitic types, which are frequently porphyritic owing to scattered phenocrysts of albite up to 5 mm in length.

The feldspar of these rocks ranges from albite, which is free from exsolved microcline, through microcline antiperthite to microcline perthite, and microcline which is free from exsolved albite. In these rocks the amount of antiperthite exceeds the perthite by far. The perthite and the antiperthite are both of the patchy type.

The albite of the coarser-grained types and also the phenocrysts of the porphyritic types usually contain small amounts of exsolved microcline (5 to 10 per cent and less). These crystals are frequently weakly zoned. In some examples one or two narrow zones of exsolved microcline near the margins of the crystals probably represent original oscillatory zoning in the albite. An outstanding feature of the albite of the alkali granite and the syenite is the extremely narrow twinning lamellae (0.001 mm). Pericline twinning associated with Albite twinning causes a checker-board pattern in some crystals. In other examples microcline having a small amount of exsolved albite forms a narrow mantle around a core of antiperthite. This structure is reminiscent of the Rapakivi type of granite.

In the more potassic types, microcline appears as scattered phenocrysts. These crystals are interstitial and frequently include small randomly orientated crystals of albite. The crystals are rarely composed of a core of microcline perthite with a low percentage of exsolved albite and a mantle of albite. In the coarser-grained syenitic varieties microcline has an interstitial relation to albite which contains a very low percentage of exsolved microline (less than about 5 per cent).

In nearly all the rocks there are varying amounts of what appears to be a second crop of small anhedral crystals of microcline, albite, and quartz. The microcline is practically free from exsolved albite and the albite is free from microcline.

The quartz of these rocks is usually interstitial to the other minerals and ranges in diameter from a fraction of a millimetre to a few millimetres. Near the contacts with the quartzite the granite frequently contains "rounded grains" of quartz, up to about 5 mm in diameter. These grains are composed of a fine-grained mosaic of quartz and have apparently been derived from the quartzite.

The dark minerals of the alkali granite are interstitial arfvedsonite and aegirine which are intimately intergrown. The pleochroism of the amphibole is as follows: X = lavender blue, Y = blue green, Z = greenish grey, or X = blackish blue, Y = light green, Z = yellowish brown. A basal parting is usually well developed, and simple twinning on (100) is frequently present.

The aegirine is pleochroic from greenish yellow to deep bright green. Near contacts with argillaceous rocks the dark mineral is usually biotite which is pleochroic from yellowish brown to nearly opaque dark brown. Accessory minerals are magnetite, sphene and apatite.

d. Pegmatites. - Pegmatites are rare in the alkali granite. Only small veins are found in the plutons along the Vaal River. They are composed of microcline perthite, quartz, aegirine and accessory albite. A few of these veins are composed of microcline perthite, quartz and muscovite. In a vein (about 5 cm thick) on Koedoeslaagte 59, a small nest in the central part of the vein contains a rare brown mineral which shows alteration to limonite. It is closely associated with sphene. Qualitative analysis indicates that it is essentially an iron silicate with subordinate amounts of manganese. This mineral was submitted to Dr. W.R. Liebenberg and Dr. S.A. Hiemstra of the National Institute for Metallurgy for X-ray and further investigation. (Project C.35/65) They determined the following optical properties :

α = 1.795 (X = green)
β = ... (Y = olive green)
γ = 1.850 (Z = brownish yellow)
$2V_X$ = 64° ± 4°
Dispersion strong, $r > v$

The mineral has two good cleavages which make an angle of 86° with each other and have a zone axis parallel or nearly parallel to X. Spectrographic analysis revealed the following elements:

Major elements : Fe, Mn, Si.
Minor elements : Al, Ca, Mg, Na, Ti.
Trace elements : Ag, As, Be, Cd, Co, Cu, Mo, V.

An X-ray diffraction pattern was also obtained but Drs. Liebenberg and

Hiemstra could not find a pattern in the A.S.T.M. file or literature to match the pattern obtained. They concluded that this mineral "may be either a new mineral or an unknown species of pyroxene".

e. Reaction with the Country-rock. - On the contacts with the country-rock there is evidence of assimilation of sedimentary material by the alkali granite magma. Assimilation of quartzitic material has caused an increase in the quartz content of the granite. On the southern contact of the Baviaanskrantz pluton on Helena 780, the granite contains " rounded quartz grains" a few millimetres in diameter, which appear as small knobs on weathered surfaces. These knobs are composed of fine-grained aggregates of quartz. A similar phenomenon is found on Parsons Rust 465.

The assimilation of argillaceous material has destroyed the peralkaline character of the granite and is indicated by the presence of biotite as the only dark mineral near the contact with argillaceous beds of the Jeppestown Series on Koedoeslaagte 59. On Goedgedag 971 on the southern contact of the Baviaanskrantz pluton in the stream bed, Government Reef shales with a laminated structure are feldspathized. The laminae are about 5 mm wide and are in places intensely folded. This feldspathized material represents mostly xenoliths in the granite. This rock is composed of microcline, albite, quartz and accessory magnetite. The laminae are composed of feldspar and quartz (grain-size about 1.0 -1.5mm) and are separated from each other by a thin band (about 2 mm wide) which is composed of very fine quartz and feldspar (grain-size about 0.05 mm).

On Rietfontein 163 inclusions of sedimentary material in the granite are marked by a high concentration of greenish-brown or reddish-brown biotite with abundant pleochroic haloes around small inclusions of zircon. The assimilated argillaceous material has probably been derived from a thin band of shale in the dolomite. Owing to poor outcrops the contact between the granite and the dolomite is never exposed. However, near the southern contact of the granite and the dolomite in the vicinity of the sillimanite hornfels (Plate II), small lumps of a skarn rock can be picked up. It is composed mainly of pale-green diopside and grossularite and accessory calcite, albite, muscovite and zoisite. Where the xonoliths are clearly discernible their grain-size is smaller than that of the granite, but as they become more ghost-like, the grain-size increases to the same as the grain-size of the granite.

3. Crystallization and Petrogenesis of the Alkali Granite

The crystallization of the alkali granite can be considered in terms of the systems Or-Ab-H_2O and Or-Ab-SiO_2-H_2O (Tuttle and Bowen, 1958, p.37 and p.54). The anorthite content of the alkali granite is too low to have had any affect on the solid solution between potassium and sodium feldspar.

According to Tuttle and Bowen (1958, p.92), J.L. England synthesized riebeckite at 610°C, in an environment with a water content of less than 3.9 per cent. When the water content was greater than approximately 4 per cent, acmite was the major phase and also the only phase at temperatures above 610°C. If these results are applied to the alkali granite it is evident that the plutons along the Vaal River contained a higher percentage of water than the pluton on Rietfontein, because the dark minerals of the first-named plutons are both alkali amphibole and alkali pyroxene, whereas the dark mineral of the Rietfontein pluton is only alkali amphibole. However, where the Rietfontein pluton abuts against the Dolomite, the contact-rock (alkali syenite), contains only alkali pyroxene which indicates that water was absorbed from the country-rock by the magma, i.e. the magma was undersaturated with water.

During their experiments Tuttle and Bowen (1958, p.93) also found that unmixing and recrystallization of alkali feldspar are greatly facilitated by water vapour under high pressure, and they are of the opinion that a water vapour under high pressure controls exsolution to a large extent rather than the rate of cooling of the magma, with the result that most perthite granites contain amphibole. The granite of the Rietfontein pluton is a typical hypersolvus granite in which perthite is practically the only feldspar, whereas those forming the plutons along the Vaal River are subsolvus granites characterized by two feldspars, microcline and albite (cf. Tuttle and Bowen, 1958, p.129). If the experimental results of these two authors (1958, p.128) are further applied to the alkali granite, it becomes apparent that the Rietfontein pluton has crystallized at temperatures above 660°C and the plutons along the Vaal River, for the greater part at least, below 660°C. It is also possible that both types crystallized above 660°C, but that in the Vaal River plutons, where the concentration of water was higher, unmixing and recrystallization have led to the development of a two-feldspar rock.

In a discussion of the fractional crystallization of the alkali granite, the following phenomena must be taken into account :

(1) Nearly euhedral phenocrysts of albite are found in both the hypersolvus and subsolvus granites and some of these crystals show zonal exsolution of potassium feldspar.

(2) The syenitic types are nearly completely composed of this type of albite.

(3) The bulk of the hypersolvus granite is composed of antiperthite which frequently has a mantle of perthite which contains a small amount of exsolved albite. Both the albite and the potassium feldspar of the core are optically continuous with the same feldspars which form the mantle of the crystals.

(4) The bulk of the subsolvus granite consists of anhedral antiperthite

and subordinate anhedral perthite crystals, both containing varying amounts of exsolved microcline and albite respectively.

(5) The subsolvus granite frequently contains a second generation of albite, quartz, and potassium feldspar. This is seldom found in the hypersolvus granite.

From the above it is evident that the crystallization of the feldspars of the alkali granite commenced with nearly pure albite, followed by the bulk of the feldspar (antiperthite in the hypersolvus granite and antiperthite and perthite in the subsolvus granite) and in the closing stage albite and potassium feldspar. This order of crystallization closely corresponds to Tuttle and Bowen's (1958, p.97) description and explanation of the crystallization of the Rapakivi granite where P_{H2O} increased with progressive crystallization.

The normative weight ratio of orthoclase : albite in the alkali granite ranges between 13:87 and 50:50 with an average value of 27:73. The lowest orthoclase : albite ratio (13:87) is attained in the syenitic type. According to Tuttle and Bowen's (1958, p.40, Fig. 17) diagram the first feldspar to crystallize from a liquid with such an initial composition would have the approximate composition of Or_{2-3} Ab_{97-98} which is about the composition of the phenocrysts in the alkali granite and the albite of the syenitic types. The oscillatory zoning of the phenocrysts is probably the result of crystallization during the intrusion of the alkali granite. Tuttle and Bowen (1958, p.69) believe that not only changes in temperature but also in pressure can produce zoning. Changes in pressure could have taken place during the intrusion of the alkali granite as a result of a loss of volatile constituents or movements of the magma to higher levels.

An interesting sample of alkali granite from a bore-hole for water on Koedoesfontein 12 is composed of the following : 49 per cent of microcline perthite, 23 per cent of albite, 26 per cent of quartz and 2 per cent of biotite (Plate VIII B). The albite forms discrete anhedral to subhedral crystals which are enclosed or partly enclosed in perthite. Contacts between the albite and perthite crystals are usually corroded, i.e. partly replaced by perthite. The albite crystals are free from exsolved microcline. The perthite crystals are composed of microcline with about 30-40 per cent of exsolved albite.

Pure plagioclase without exsolved microcline can therefore be expected only in subsolvus rocks and perthite in hypersolvus rocks. This discrepancy can be explained only on the assumption that the albite crystallized under physical conditions which were different from those which prevailed during the crystallization of the rest of the rock, e.g. higher pressure conditions in which P_{H2O} was greater than about 4 kilobar, i.e. the conditions under which the solvus curve intersects the solidus.
At this stage the magma must have been highly sodic,in order to produce nearly pure albite. On emplacement this highly sodic magma assilimated potassium-rich sedimentary rocks which caused an enrichment in K_2O, Al_2O_3 and SiO_2, thus increasing the amount of potential potassium feldspar and quartz and destroying the peralkaline character of the magma. Assimilation would cause cooling of the magma and a change in composition towards the quartz-feldspar boundary in the lower temperature region. Albite would no longer be in equilibrium with the liquid under the new physical conditions and in the modified chemical environment. Being a mineral which forms at a higher temperature than the feldspar which would crystallize from the contaminated magma, the albite would react with the liquid. Potassium would enter into solid solution with the albite. Because solid diffusion is a slow process it could be expected that only the margins of crystals would be affected. These potassium-rich rims would serve as nuclei for the further growth of new feldspar

whereas the independent crystals of perthite would originate from new nuclei. After exsolution the final product would correspond to the rock described above.

The variation in composition of the alkali granite was to a large extent determined by the assimilation of country-rock rather than by fractional crystallization alone. Both processes were operative but it is difficult to ascertain the rôle of each quantitively. In Fig. 6 the values for normative quartz, albite and orthoclase of alkali granites which were analysed chemically are plotted and also modal weights of the same components of alkali granites which were analysed micrometrically.

Luth, Jahns and Tuttle (1964, fig. 4) extended the investigations of Tuttle and Bowen (1958) on the system Or-Ab-SiO_2-H_2O to P_{H2O} between 4 and 10 kilobar and showed that the feldspar minimum and also the Or-Ab-SiO_2 eutectic (Fig. 6 AB) shift towards the Ab-SiO_2 join and the boundary between quartz and feldspar towards the Or-Ab join. Furthermore they (p.674) found that between 3 and 4 kilobar the solvus curve for the feldspar intersects the solidus for feldspar. This intersection extends a distance towards the Ab-Or join but at 5 kilobar it extends down to the Ab-Or join to produce independent fields for Ab and Or. According to Tuttle and Bowen (1958, Fig. 17, p.40) the isobaric minimum for albite-orthoclase for P_{H_2O} between 0.5 and 4 kilobar ranges between Ab_{30} and Ab_{35}.

Carmichael and MacKenzie (1963, p.393) show that the addition of acmite and sodium silicate to the system Or-Ab-SiO_2-H_2O (P_{H_2O} = 1000 kg/cm^2) causes a shift of the feldspar minimum towards the Or-SiO_2 join (Fig. 6, curve D). With the exception of two modal analyses, all the chemical and modal analyses fall on the albite side of the isobaric minimum for Ab-Or at P_{H_2O} = 1000 k.g/cm^2. (Fig. 6 curve C). At 8.3 per

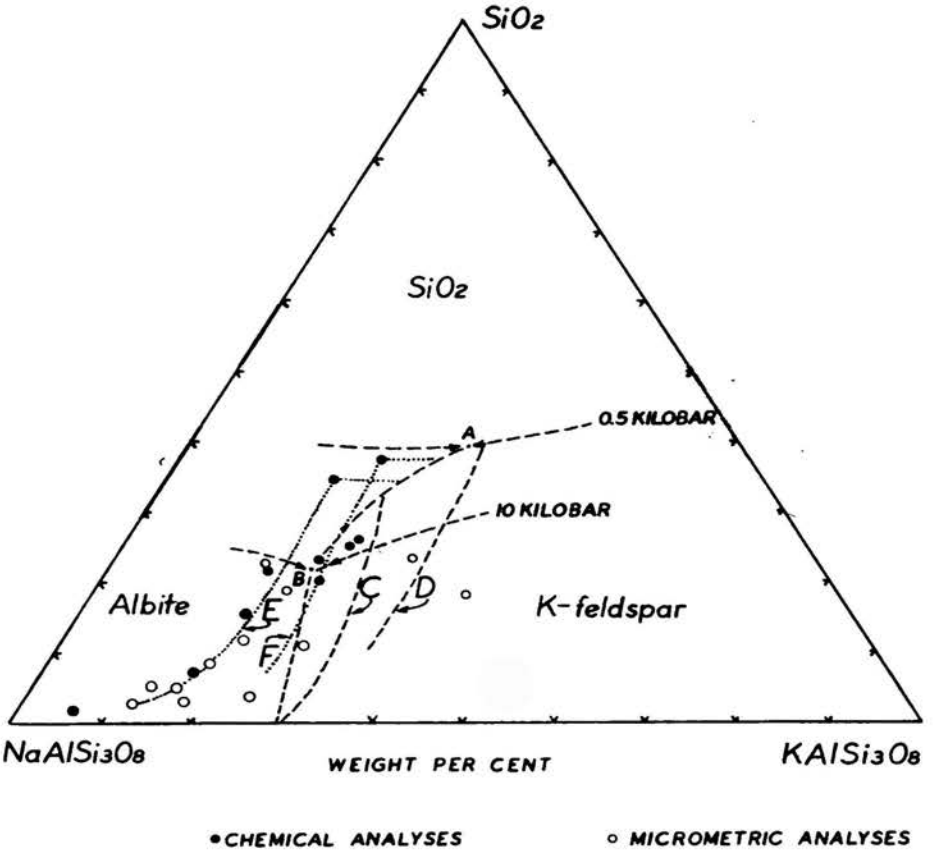

Figure 6. Crystallization curves for the subsolvus alkali granite (E), and the hypersolvus alkali granite (F). Curve AB represents the shift of the minimum (eutectic) on the feldspar-quartz boundary with increase in P_{H_2O} (Luth, Jahns and Tuttle, 1964, Fig. 4). Curve C represents the feldspar minimum (Tuttle and Bowen, 1958, Fig. 30). Curve D shows the shift of the feldspar minimum with the addition of 8.3 per cent of acmite + 8.3 per cent of Na_2SiO_3 (Carmichael and MacKenzie, 1963, Fig. 1).

cent acmite and 8.3 per cent sodium silicate (Fig. 6, curve D) only one of the rocks (containing 2.3 per cent of aegirine) falls on the orthoclase side of the minimum and at 4.5 per cent acmite and 4.5 per cent sodium silicate (curve half way between C and D) another one containing 4.3 per cent of arfvedsonite falls on the same side. The granite from the bore-hole described above also falls on the orthoclase side of the feldspar minimum. Because the liquid cannot cross the minimum from the albite side to the orthclase side, the composition of these rocks can only be explained in terms of the assimilation of potassium-bearing rocks.

It is therefore reasonable to accept that the uncontaminated magma had the composition of an albite-rich alkali syenite which was subsequently contaminated by the assimilation of foreign material.

Two small plugs of alkali syenite are intrusive into the Archaean granite on Witklip 138, about 12 miles south-west of Ventersdorp. The alkali syenite is composed mainly of albite and 10-15 per cent of aegirine and arfvedsonite which are intimately intergrown. This rock differs little from the quartz alkali syenite of the Schurwedraai pluton. These intrusions are probably related to the alkali granite in the Vredefort Dome (same petrographic province ?). Here the assimilation of country-rock (granite) would probably not have affected the peralkaline character of the magma, because in such a case the ratio of K+ Na : Al is already 1:1. In argillaceous sedimentary rocks where the ratio of K + Na : Al is less than 1:1, alkali which can combine with aluminium will be available in the magma and therefore not only the low-temperature fraction (alkali feldspar + quartz) will be extracted but also some extra aluminium. The analysed alkali syenite (Appendix B, No. 16) with its 3.2 per cent of acmite needs only the addition of about 0.6 per cent by weight of Al_2O_3 to destroy the peralkaline character.

The direction of mineralogical variation of the alkali granite is similar to that indicated by the fractionation curves determined by Tuttle and Bowen (1958, Fig. 30, p.65) for the experimental system $Or\text{-}Ab\text{-}SiO_2\text{-}H_2O$. Owing to the inhomogeneity of the magma, crystallization in the different parts of the plutons would begin at different points on the fractionation curves and the composition of the residual fluids would move towards the feldspar-quartz boundary-curve. The residual liquid of the syenitic type never attained a composition which falls on the quartz-feldspar boundary. In such a case the rock must be considered mainly from the viewpoint of the system Or-Ab-H_2O. However, in the more quartz-rich varieties the residual liquids reached the appropriate compositions for the quartz-feldspar boundary-curve. A rough estimate of the composition of the second crop of feldspar and quartz in the more quartz-rich subsolvus granites indicates that quartz is about one third of the bulk of the minerals forming the second crop.

The crystallization of the hypersolvus granite followed the curve F (Fig. 6). Recrystallization under subsolvus conditions did not progress very far. The orthoclase-rich mantles of some of the feldspar crystals are probably the result of an originally zoned, homogeneous feldspar and the movement of exsolved orthoclase towards the margins of crystals. An alternative interpretation is that the solidus intersected the solvus at a very late stage of crystallization in which further growth of potassium-rich feldspar on some crystals and albite-rich feldspar on others took place. This is improbable, because of the absence of antiperthite with a rim poorer in exsolved orthoclase than the core.

The subsolvus granite followed a course of crystallization represented by curve E (Fig. 6). The solidus for the alkali feldspar intersected the solvus quite early in the crystallization history of these rocks. As crystallization progressed P_{H_2O} increased and two feldspars with progressively smaller amounts of the other in solid solution crystallized. This explains the varying amounts of microcline in antiperthite and of albite in microcline. During the closing stages P_{H_2O} appears to have attained such a value that practically pure albite and microcline crystallized in the second generation of feldspar and quartz. This last stage however represents a small fraction of the total bulk of the rock and probably coincided with the pegmatitic stage of the granite.

The other alternative, namely that the alkali granite of the plutons along the Vaal River crystallized above 660°C under hypersolvus conditions, must be ruled out because of the presence of both antiperthite and perthite in these rocks. The presence of antiperthite and perthite cannot be explained in terms of a hypersolvus granite which has completely recrystallized under subsolvus conditions, because in the bulk of these rocks albite preponderates so much over microcline that antiperthite would be the only feldspar that could develop if the granite had crystallized under hypersolvus conditions. The crystallization under hypersolvus conditions and the development of a granite in which nearly all the feldspar is antiperthite, is well exemplified by the granite of the Rietfontein Complex.

A pressure of 4-5 kilobar for the crystallization of the alkali-granite plutons along the Vaal River corresponds to pressure conditions for the triple point of the Al_2SiO_5 polymorphs as determined by Newton (1966, p.171). Evidence that the pressure conditions during the crystallization of the alkali granite was more or less at triple point conditions is discussed later (p. 129). A lithostatic pressure of 4-5 kilobar would give a cover of the order of about 14-15 kilometre which is improbable. Some form of overpressure must have made a substantial addition to the lithostatic pressure. According to Rutland (1965, p.124) overpressures may reach values several times that of the shearing strength of the rocks and it is possible that such pressures can be reached in small pockets where a fluid overpressure is developed locally. The PT gradient of the metamorphism caused by the alkali granite (Fig. 15 p.196) is indicative of such a local overpressure.

4. Origin of the Peralkaline Granite

Bailey and Schairer (1966, p.151) maintain that the emplacement of peralkaline granite is a very characteristic part of granitic activity in the more stable continental areas. The association with subaluminous granite,according to them,is so constant that a different origin for each type seems improbable. Because there is at present no acceptable process for deriving a peralkaline granite from a subaluminous granite, they suggest the possibility that the primitive granite of non-orogenic areas is peralkaline and that the subaluminous types associated with peralkaline granite resulted from salic contamination. Luth, Jahns and Tuttle (1964, p.770) expressed the opinion that undersaturation with alumina may serve as a criterion for the recognition of granitic material derived from primary or primordial basaltic magma by differentiation.

The development of peralkaline rocks from alkali basalt is well established (see Turner and Verhoogen, 1960, p.165-202; Barth 1962, p.112-121). Trachyte, frequently peralkaline, and phonolite are normal differentiates of alkali basaltic magma. Carmichael and MacKenzie (1963, p.394) conclude that pantellerites are derived from trachyte. The uncontaminated magma of the alkali granite plutons actually had a trachytic composition. Luth, Jahns and Tuttle (1964, p.772) are also of the opinion that alumina-undersaturated extrusives represent a direct line of descent from more basic magmas with a low percentage of water.

It thus appears that peralkaline magmas are normal differentiates of alkali basaltic magmas. If then, a peralkaline liquid can develop from an alkali basaltic magma by fractional crystallization, it is also possible for such a liquid to develop from an undifferentiated alkali basalt by fractional melting. Furthermore, if alkali basalt is derived from primitive mantle-material by differential melting, a peralkaline liquid can also be derived from the same material by differential melting, but it will represent a low-temperature fraction.

Such an origin of peralkaline magma will explain the peralkaline intrusions which are not associated with large bodies of alkali basalt.

E. The Mariupolite

1. Nomenclature and Distribution

The nepheline syenites which are associated with the alkali granite in the Vredefort Dome have been termed canadite and litchfieldite by Hall and Molengraaff (1925, p.76). The term canadite ~~which~~ was introduced by Quensel for an albite-nepheline syenite with anorthite in the norm (Johannsen, 1938, p.186). The typical canadite, thus defined, is not a peralkaline rock. However the nepheline syenites of the Vredefort Dome are peralkaline rocks. Litchfieldite according to Barker (1965, p.3) is a biotite-bearing nepheline syenite. This type of rock is rare in the Vredefort Dome and is usually associated with pegmatitic varieties. The term mariupolite, as suggested by Tilley (1960, p.69), appears to be more appropriate. According to Johannsen (1938, p.211) Morozewicz used the term mariupolite for an albite-aegirine-nepheline syenite free from potassium feldspar, but in a later study he also included varieties which contain potassium feldspar.

The mariupolite dykes are intrusive mainly into the sedimentary roof- and hood-zone of the alkali granite on Koedoeslaagte 59, on the south-eastern side of the Schurwedraai pluton (Plate I, Sheet 2). Where the plutons are deeply eroded the mariupolite dykes are absent except for two small dykes in the central part of the Baviaan Krantz pluton. This mode of occurrence points to the possibility that the mariupolite dykes are rooted in the alkali granite. The host-rocks of the dykes include alkali granite, quartzite, slate and epidiorite. The larger dykes are intrusive into the country-rock of the alkali granite. The largest intrusion of mariupolite, in the valley south of the Schurwedraai pluton on Koedoeslaagte, has a lens-like outline and is about 500 feet wide.

An outstanding feature of the mariupolite dykes is that they are made up of two texturally different rock-types, namely a fine- to medium-grained portion and a coarse-grained, pegmatitic portion (Plate IX A). The pegmatitic portion consists of narrow bands, and in places of wavy or irregular elongated patches. The width of the pegmatitic bands range from less than a centimetre to about 30-40 cm. Microcline crystals attain a length of 15 cm, nepheline 7 cm, aegirine 2.5 cm and lepidomelane up to 10 cm. The pegmatitic bands are parallel to the strike of the dykes and their dips are conformable with that of the sedimentary formations where these dykes are intrusive into the Witwatersrand System, whereas the dykes in the alkali granite are more or less vertical. Because the orientation of the pegmatitic bands in the dykes are probably parallel to the walls of the dykes, the bedding planes of the sedimentary formations must have structurally controlled the emplacement of the mariupolitic magma.

Some of the dykes show a pronounced foliation which has resulted from the flow of partly crystallized magma, e.g. the southern dyke on Koedoeslaagte 59 which is intrusive into the shale below the second Jeppestown quartzite. The foliation is parallel to the walls of the dyke. In the largest dyke which is intrusive into the second Jeppestown quartzite (J.Q.2) on the southern contact of the alkali granite on Koedoeslaagte, parts of the fine-grained portions between the pegmatitic bands show a lamination perpendicular to the strike of the dyke.

Microcline crystals are sometimes orientated perpendicular to the walls of the pegmatitic bands, similar to vein fillings. In such cases the two contacts against the fine-grained mariupolite are sharp. From these contact surfaces the microcline crystals project inwards. The central part of such a band is sometimes filled with fine-grained mariupolite.

The composition of the pegmatitic bands varies considerably. Some of them are composed nearly entirely of microcline or nepheline; others are composed of microcline, nepheline and aegirine in varying proportions. In rare cases lepidomelane takes the place of aegirine.

2. Mineralogy and Petrography

The mariupolities are coarse-grained pegmatitic and medium to fine-grained hypidiomorphic rocks composed of albite, nepheline, aegirine, and microcline. Some specimens contain lepidomelane. Texturally they range from more or less equigranular to porphyritic types. A trachytic texture is in places well developed in the fine-grained varieties.

Albite is the most important feldspar of these rocks and has a tendency to be elongated parallel to the (010) face. The length of crystals ranges from a fraction of a millimetre to about 5 mm. In the fine-grained varieties albite is a more prominent constituent than microcline which is usually an accessory mineral. Apart from minor amounts of exsolved microcline in some crystals, the majority of the albite crystals are free from any exsolved potassium feldspar. Twinning of the albite is usually not as regular as in the albite of the alkali granite. Albite lamellae are frequently discontinuous, with sharp pointed ends. In some of the porphyritic varieties, phenocrysts of albite comprise about 50 per cent of the rock.

Microcline is more prominently developed in the pegmatitic varieties. It usually contains a low percentage of exsolved albite (10 - 15 per cent). Thin sections which were stained with sodium cobaltinitrite indicate that some crystals of microcline are practically free from albite. Microcline ranges from anhedral, interstitial grains to large subhedral crystals. Small subhedral laths of albite and needles of aegirine are usually enclosed in the microcline, even in the large crystals. The enclosed albite crystals are of more or less the same size as those of the ground-mass

The amount of nepheline ranges from less than one per cent in some of the fine-grained varieties to thin veins (2-3 cm wide) (Plate IX A) or patches (up to about 10 cm in diameter) which consist nearly completely of nepheline in the pegmatitic types. The composition of the nepheline (Appendix B, No. 33) conforms with that given by Morozewicz (Tilley 1960, p.69). In the fine-grained types nepheline usually forms anhedral phenocrysts. In the trachytic types nepheline is present as phenocrysts and also in the ground-mass, in which the elongation of the crystals is parallel to the direction of the flow lines, i.e. parallel to the orientation of the albite laths which also form phenocrysts and a component of the ground-mass. In the coarser-grained and pegmatitic varieties nepheline encloses small laths of albite and needles of aegirine. In the pegmatitic types nepheline is frequently interstitial and seldom encloses microcline. Lens-like streaks composed mainly of nepheline is present in the trachytic types.

Aegirine is the predominant dark mineral in the mariupolite, and usually forms small slender subhedral to euhedral prisms. The aegirine is of two types. The pleochroism of the one type is from brownish yellow to yellowish brown and it usually forms long slender prisms. This type corresponds to acmite. The other type corresponding to aegirine, usually forms short prisms and is strongly pleochroic from yellowish brown to dark brilliant green. Some crystals of acmite show patches or sometimes partial margins of aegirine on prismatic faces, or the aegirine may show patches of acmite. Twinning is of the simple type on (100). The alkali pyroxene is usually interstitial to albite.

Cancrinite is an accessory consituent which usually replaces nepheline. It is best developed in the litchfieldite which may contain up to about 5 per cent of cancrinite. Magnetite is a rare accessory mineral. In some of the fine-grained mariupolites the magnetite consists of idiomorphic octahedral crystals. Another accessory mineral is sphene which attains a length of about 5 mm in some of the pegmatites.

Lepidomelane is a characteristic mineral in the litchfieldite and in some pegmatitic areas in the dykes. It is strongly pleochroic from yellowish brown to nearly opaque dark brown.

3. Petrogenesis of the Mariupolite

Tilley (1957, p.332) subdivides the alkaline complexes into two categories, i.e. complexes which include nepheline syenite and in which the magmatic activity closes with quartz syenite or granite, and complexes which include granite and in which the magmatic activity ends with nepheline syenite. He cites the alkaline rocks of the Vredefort Dome as an example of the second group. In accordance with the opinion expressed by Hall and Molengraaff (1925, p.91), Tilley (1960, p.54) accepts a close genetic relationship between the alkali granite and the mariupolite. The following are features which point to such a close genetic relationship:

(1) The dykes of mariupolite are intrusive mainly in the roof- and the hood-zone of the alkali granite plutons.

(2) The mariupolite dykes are probably rooted in the alkali granite plutons.

(3) In both the alkali granite and the mariupolite there is a strong preponderance of sodium over potassium.

(4) Mineralogically the mariupolite represents a desilicated alkali granite.

(5) There is a complete mineralogical and chemical gradation between the granite and the mariupolite (Fig. 7). Chemically there is a decrease in SiO_2, $K_2O/K_2O + Na_2O$ and an increase in $Fe_2O_3/Fe_2O_3 + FeO$ and Al_2O_3 * ~~FeO~~ from the granite to the mariupolite.

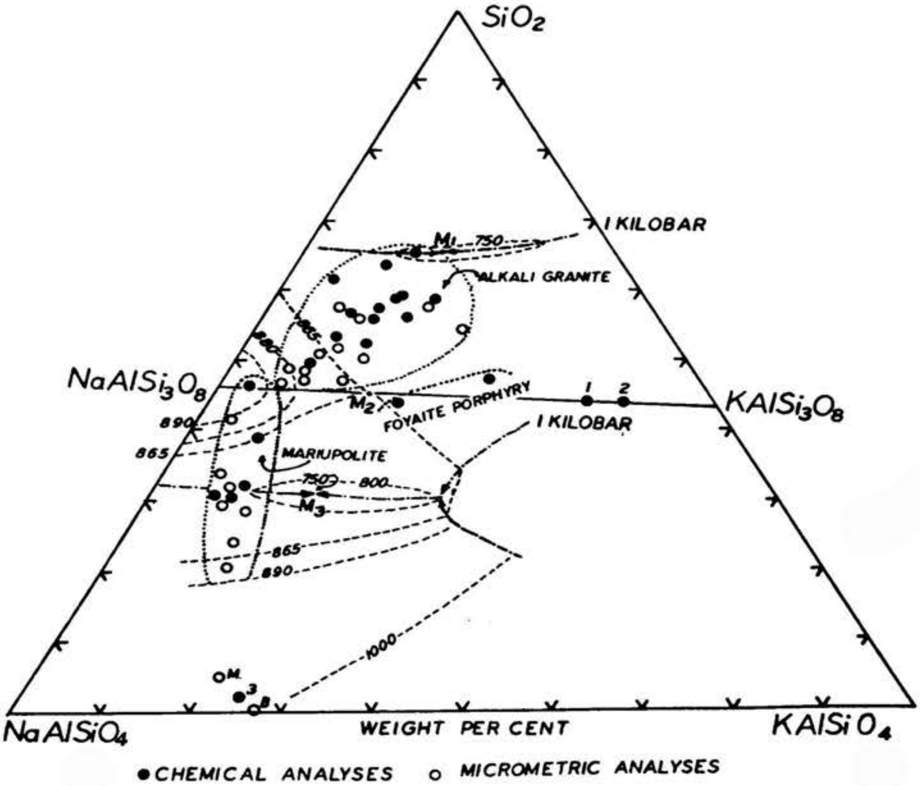

Fig. 7. Variation in the normative composition of the alkali granite and the mariupolite in terms of the system Ks-Ne-SiO_2 at P_{H_2O} = 1 kilobar. M_1 is the minimum on the quartz-feldspar boundary, M_2 the feldspar minimum, and M_3 the minimum on the feldspar-nepheline boundary. The boundary curves and temperature contours are taken from Fudali (1963, Fig.1). M and B represent the composition of nepheline according to the formulae of Morozewicz and Buerger, 3 the composition of nepheline and 1 and 2 the composition of microcline from the mariupolite of the Vredefort Dome.

If then a close genetic relationship between the alkali granite and the mariupolite is accepted, the main problem that arises is the passage of an oversaturated magma to an undersaturated magma. From the revised diagram for the system SiO_2-Ne-Ks (Schairer, 1950, Fig. 1) it is evident that a temperature maximum exists on the liquidus surface along the Ab-Or join. Fudali (1963, Fig. 1) and Hamilton and MacKenzie (1965, Fig.1) have shown that this condition still exists at $P_{H_2O} = 1000$ kg/cm^2. The disappearance of the thermal barrier at higher pressures is doubtful, therefore the change of an oversaturated liquid to an undersaturated liquid in the system SiO_2-Ne-Ks cannot be achieved by simple fractional crystallization. Only the extraction of SiO_2 from this system will cause liquids to cross this thermal barrier.

The direction of crystallization followed by liquids of mariupolitic composition is towards the field of nepheline convergence (Tilley, 1960,p.69), i.e. in a direction which cuts across the feldspar-nepheline boundary (Fig. 7) and the isotherms. If the direction of fractionation curves were followed i.e. from a point near albite towards M_3 and from a point near M towards M_3, at least two types of mariupolite magma would be necessary; one falling in the nepheline field and the other in the undersaturated part of the feldspar field. If it is possible for an alkali syenitic liquid to follow a course of crystallization towards the nepheline-feldspar boundary all the mariupolites should then fall in the undersaturated portion of the feldspar field. For the derivation of mariupolite from the alkali granite a process whereby silica is removed from the alkali granitic magma is a requisite.

The classic hypothesis of limestone syntexis of Daly and Shand cannot be applied to the peralkaline rocks of the Vredefort Dome. The alkali granite on Rietfontein,which is intrusive into the Dolomite Series, contains on the average more quartz than the alkali granite of the plutons along the Vaal River, which were emplaced in a quartz-rich environment. Furthermore, mariupolite is only associated with alkali granite which did not come into contact with limestone and is absent where the alkali granite is in contact with limestone.

Tilley (1957, p.332) is of the opinion that the presence of a compound which melts inconqruently such as acmite may provide an answer to this problem. If magnetite is precipitated in place of aegirine there will be an increase in the silica content of the liquid phase if iron oxide is not resorbed. Nolan (1966, p.150) found a reaction relation between acmite and magnetite in his experimental investigation of the system Ab-Ne-Ac-Di-H_2O, but failed to find positive evidence for such a relation in natural rocks. Resorption of magnetite may be important provided that the magnetite crystallizes before acmite. If Fe_2O_3 is taken up in the formation of aegirine, SiO_2 will be extracted from the liquid and may eventually cause an undersaturated liquid to develop. A prerequisite for this mechanism of desilication is that the magma must already be peralkaline, i.e. it should contain normative sodium silicate which will make the formation of aegirine possible.

Bailey and Schairer (1966, p.154) consider the crystallization of an iron-bearing albite in the system Na_2O-Al_2O_3-Fe_2O_3-SiO_2 as a possible means of development of an undersaturated liquid from an oversaturated liquid such as a quartz syenitic magma. During crystallization the iron-bearing analogue of albite ($NaFe^{+++}Si_3O_8$) will subtract more SiO_2 from the system than acmite ($Na\ Fe^{+++}Si_2O_6$), with the result that a liquid trending towards the undersaturated eutectic will develop. If this process had been operative in the alkali granite of the Vredefort Dome it may be expected that the liquid trend would only be towards the feldspar-nepheline boundary.

Another possible process by which silica may be removed from the magma is by volatile transfer. Several experiments by Tuttle and Bowen (1958, p.90) indicate that the vapour phase in equilibrium with hydrous granitic liquids is rich in silica. These experiments proved that if the vapour can escape from the liquid, considerable losses of silica take place. Some potassium feldspar is also lost through the vapour phase and this leads to an enrichment of albite in the liquid. MacKenzie (1957, p.500) found that a glass with composition $Ab_{69.2}$ $Qz_{30.8}$ held in an open capsule at 700°C and P_{H_2O} = 30,000 psi for 260 hours contained nepheline crystals near the open end of the capsule, nepheline and albite lower down and albite crystals with a small amount of glass at the bottom of the capsule. Since the silica content of the original glass was higher than that of albite, a considerable amount of silica must have been removed from the capsule in the vapour phase.

The simultaneous extraction of silica and orthoclase from a granitic or a quartz syenitic magma will cause the liquid to move from the oversaturated field across the Or-Ab join and the feldspar-nepheline boundary towards nepheline in the nepheline field. Plotted points which represent the quartz-alkali syenite and the mariupolite of the Vredefort Dome show such a trend (Fig. 7). The quartz syenite falls more less on the thermal barrier between oversaturated and undersaturated liquids.

If the process of extraction of silica and orthoclase from granitic liquids described above is applied to the alkaline rocks of the Vredefort Dome, the quartz syenite can be interpreted as having resulted from the removal of silica and orthoclase from the alkali granite magma. It therefore represents an intermediate step between granite and mariupolite. The quartz syenite has a higher Na/Na + K ratio than the alkali granite, and on Koedoeslaagte the highest concentration of mariupolite dykes is found in an area where the quartz syenite is most extensively developed. This relation points to a possible genetic relationship between the two rock types.

According to the interpretation given above for the history of crystallization of the alkali granite, the quartz syenite represents the original magma from which the alkali granite was evolved by assimilation. This interpretation is preferred for the following reasons :

(1) It will be shown under the discussion of the metamorphism of the region that a considerable area is underlain by alkali granite, i.e. the greater part of the alkali granite is still covered by its roof. If the quartz syenite had developed from the alkali granite by the removal of silica and orthoclase, quartz veins, and probably pegmatites, should be extensively developed in the roof. Apart from one large quartz vein on Commandonek 431, quartz veins are seldom found in the area and pegmatites are absent in the roof.

(2) The indubitable evidence of assimilation described above cannot be ignored. The alkali granites with the highest content of quartz are usually not peralkaline. So far no acceptable explanation has been found for a process by which the peraluminous granite can become peralkaline.

(3) Fractional crystallization of quartz alkali syenite has a normal trend towards the feldspar-quartz boundary.

(4) If the temperature contours for P_{H_2O} = 1 kilobar in the system SiO_2-Ks-Ne as determined by Fudali (1963, fig.1)are superimposed on figure 7, the alkali syenite and the mariupolite which lie nearest to nepheline, fall more or less in similar temperature regions, whereas an alkali granite near M_1 at P_{H_2O} = 1 kilobar falls in a temperature region about 100-150°C lower (Tuttle and Bowen, 1958, fig. 23).

If then during some late stage in the consolidation of the alkali syenitic magma the hood and the roof of the plutons were fractured (owing to shrinkage of the pluton), the residual fluid rich in vapour would move into areas of lower pressure and the vapour would escape into areas of still lower pressure. Such a transfer of vapour would remove silica, and to a lesser extent potassium and aluminium, from the liquid phase and lead to the development of an undersaturated liquid which would crystallize as the finer-grained portions of the mariupolite dykes. Removal of volatile components in the vapour phase would increase the viscosity of the fluid from which the mariupolite would crystallize. Viscous flow of magma is probably the reason for the strongly developed trachytic texture in some of the smaller dykes and portions of the larger dykes.

A pegmatitic phase is more extensively developed in the larger dykes than in the smaller ones in which it is practically absent. At a late stage of the crystallization of the mariupolite, the still liquid portion of the mariupolite magma would become sealed off owing to crystallization in the cooler environment of the upper part of the dykes. This would prevent further escape of volatile constituents. Progressive crystallization of the mariupolite magma would then cause the concentration of water in the residual liquid. Further shrinkage of the pluton of alkali granite would lead to the development of a younger set of fractures in the not completely consolidated mariupolite. The residual liquid of the mariupolite would then move towards these areas of lower pressure and crystallize as the pegmatitic phase. This pegmatitic material could not have been derived directly from the quartz alkali syenite because veins of this material are not found independently in the hood-zone or roof of the alkali granite. The highest degree of undersaturation is attained in the pegmatitic veins and schlieren in the mariupolite. Some of them are composed essentially of nepheline, others contain a high proportion of orthoclase and some are mica or aegirine rich. The residual fluids of the mariupolite had highly variable compositions which were probably dependent on the composition of the mariupolite fluid from which they were derived. It can be expected in a process as described above that the differential removal of silica and orthoclase and other constituents would cause a variation in the mariupolite magma, which would depend on the relative rate of removal and the time of sealing off of the lower part of the mariupolite magma in the lower parts of the dykes.

Tuttle and Bowen (1958, p.90) found that heating of a sample of Westerly granite at 4 kilobar and 700°C for 36 days caused the loss of about 50 per cent of the constituents of the rock in the vapour phase, and left behind monoclinic pyroxene and garnet with accessory feldspar and apatite. The quartz and the alkali feldspar had been almost completely abstracted from the initially completely liquid granite. In shorter runs on the experimental granite system the abstraction was much less. This may be the explanation for diaschistic dyke-rocks, e.g. lamprophyres, which are sometimes associated with and have probably been derived from magmas of leucocratic intrusions (c.f. Emmons, 1953, p.89). The small veins which contain a high percentage of aegirine probably also resulted from the removal of nearly all the leucocratic constituents. The experimental evidence thus indicates that variation in the amount of volatile constituents and also variation in the amount of material removed by the vapour determine the composition of the residue. This would explain the extreme variation encountered in the pegmatitic phase of the mariupolite.

Emmons (1953, p.71) described dykes of syenite and nepheline syenite which are intrusive into a granite aplite in the Wausau area in central Wisconsin. The aplite grades into granite and probably represents the hood-facies of the granite. He also concludes that the dykes do not extend downwards below the aplite and is of the opinion that the dykes were evolved from the aplite under "dilitant structural control". Shearing of the aplite took place when the aplite still contained interstitial liquid. Sodium feldspar exsolved from potassium feldspar is, according to him, very mobile and will, together with the interstitial fluid, lead to the crystallization of syenite and nepheline syenite.

The development of a quartz syenite from a granite by a process whereby the addition of feldspar to a residual granitic liquid causes a reduction in the silica content is conceivable, but a change to a nepheline syenitic liquid involves the removal of some silica. Emmons (1953, p.76) concludes that the "escape of volatiles with their silica burden" appears to be responsible for the removal of silica.

In the Vredefort rocks where albite is the predominant feldspar, a process of the nature visualized by Emmons, namely the movement of sodic feldspar to areas of low pressure, is apparently not applicable, because then nearly the whole rock, at least on the walls of the fractures, should have been mobile. However, the process of desilication described above for the Vredefort rocks may also be applied to the Wausau rocks.

F. The Bronzite Granophyre

1. Distribution

The intrusion of dykes of bronzite granophyre was the last event in the igneous activity which occurred during the development of the Vredefort Dome. These dykes cut across the faults in the Dome. Displacement along the dykes is of the order of about 25 metres. The bronzite granophyre is not cut by pseudotachylyte, whereas all the rocks which are older than the granophyre are traversed by veins of pseudotachylyte. On Spitskop 1090 the tapering end of a dyke of granophyre cuts through and peters out in a coarse breccia having a pseudotachylyte "cement". The bronzite granophyre must therefore be regarded as younger than the pseudotachylyte (Plate I, Sheet 2).

The largest dykes of granophyre tend to follow the contact between the Witwatersrand System and the Archaean granite (Plates I, III, IV). Smaller dykes are intrusive into the Archaean granite in a belt about 5 kilometres away from the contact between the Archaean granite and the Witwatersrand System, in the vicinity of Vredefort, where they strike north-east and on Lesutaskraal 72 where they strike north-west. The largest dyke is about 16 kilometres long and attains a width of about 50 metres. The end of this dyke thins out to a width of a few centimetres on Rietpoort 66. This phenomenon has also been observed at the ends of the two offshoots of this dyke on Koppieskraal 89. (Plate I, sheet 4).

The dykes of bronzite granophyre contain numerous xenoliths which range from microscopic sizes to about 50 cm in diameter. In some areas the xenoliths are not very conspicuous, but in others (e.g. on Holfontein and on Lesutaskraal) the dykes are crowded with inclusions. Most of the inclusions are angular and are composed of quartzite. Inclusions of granite are few, even where granite is the only country-rock, and they are usually in a partly digested condition. The dykes in the Archaean granite are composite with spherulitic bronzite granophyre composing the margins and a granular type forming the central parts of the dykes. The granular parts of the dykes are intrusive into the spherulitic parts.

2. Petrography

Three textural types of bronzite granophyre can be distinguished:

(1) A fine-grained granular rock which is the principal type of all the dykes.

(2) A spherulitic type in which the spherulites are 2-3 cm in

diameter and which forms a marginal facies of the dykes around Vredefort and on Lesutaskraal.

(3) A spherulitic type with small spherulites about 0.5-1.0 cm in diameter which is found in the thin ends, offshoots, and the chilled margins of dykes.

Pyroxene composes 15-20 per cent of the bronzite granophyre and is mainly an orthopyroxene with $2V_x$ = 65°-66° which corresponds to the optic axial angle of bronzite with a composition of FS_{26-28}. The pyroxene of the granular type usually forms stout prismatic crystals. The pyroxene of the spherulitic types is usually elongated and has a length up to 20 times or more the width of the crystals. The bronzite crystals in the rock-type with the large spherulites have a subradial arrangement. The small spherulites of the chilled type usually show a black cross between crossed nicols. The bronzite is frequently zoned as is shown by the increase in birefringence towards the margins of crystals. Augite and hornblende are found locally in the granular type. Biotite and magnetite are common accessory contituents.

The plagioclase is strongly zoned (An_{60-35}) and forms subhedral lath-shaped crystals. Between 30 and 45 per cent of the bronzite granophyre is composed of micropegmatite. The micropegmatite has apparently grown from the plagioclase crystals which served as nuclei.

3. Petrogenesis of the Bronzite Granophyre

Hall and Molengraaff (1925, p.112, 166) regard the bronzite granophyre as a "glorified form of pseudotachylyte" which orginated by the ultratrituration and fusion of different rocks. Nel (1927, p.104) considers the bronzite granophyre to be a recrystallized pseudotachylyte which was generated in greater amounts than the pseudotachylyte. The reason why these authors consider the bronzite granophyre to be a "glorified" pseudotachylyte are the following :

(1) The spherulitic bronzite granophyre (type c) in the offshoots and terminations of dykes has a close textural resemblance to spherulitic types of pseudotachylyte (Hall and Molengraaff, 1925, p.111).

(2) Both the bronzite granophyre and the pseudotachylyte contain numerous inclusions which these authors regard as crushed rock fragments (Nel, 1927, p.103, Hall and Molengraaff, 1925, p.59).

(3) The bronzite granophyre and the pseudotachylyte are in places closely associated (Nel, 1927, p.103).

(4) The bronzite granophyre and the pseudotachylyte are of the same age or the granophyre is the younger of the two (Hall and Molengraaff, 1927, p.111).

(5) The granophyre is not connected with any igneous rock in the area (Nel, 1927, p.104).

The following must also be taken into account when considering a possible genetic relationship between the bronzite granophyre and the pseudotachylyte :

(1) Apart from aegirine, pyroxene, which is an essential mineral of the granophyre, is never developed in the pseudotachylyte. Amphibole is a constituent of some of the recrystallized types of pseudotachylyte. The reason for this difference was probably caused by a difference in temperature and water content of the bronzite granophyre magma and the pseudotachylyte during crystallization. Nel (1927, p.97) described pseudotachylyte from Abel 652 which is composed of "hornblende, plagioclase, biotite, quartz, enstatite and magnetite". Examination of Nel's thin section (kindly placed at the disposal of the writer by the late Dr. F.C.Truter,

then Director of the Geological Survey of South Africa) proved that the small crystals of pyroxene are part of an inclusion of poikilitic hyperite which normally contains numerous small crystals of pyroxene.

(2) The inclusions in the pseudotachylyte and the bronzite granophyre, which are composed of fine-grained mosaics, mainly of quartz, are actually the result of recrystallization rather than crushing,as was stated by Hall and Molengraaff and by Nel. It is difficult to visualize how more or less equidimensional "crushed inclusions" will remain undeformed in a fluid medium, i.e. the ground-mass of the granophyre and the pseudotachylyte.

(3) The bronzite granophyre is younger than the pseudotachylyte. There is no determinable genetic relationship between the bronzite granophyre and the pseudotachylyte. Crushing is usually associated with the pseudotachylyte and is present in most rocks in the Vredefort Dome. Where the bronzite granophyre cuts across crushed areas (pseudotachylyte is usually present in such areas), it does not necessarily imply a genetic relationship.

(4) The composition of the bronzite granophyre is very constant and does not show a variation related to the country-rock as the pseudotachylyte does.

(5) There is a possible relation between the dykes of bronzite granophyre and the inferred central pluton. On the contact between the Archaean granite and the Witwatersrand System the dykes have a concentric disposition towards this pluton and the smaller dykes in the Archaean granite radiate from the rim of this inferred pluton.

(6) If, as Nel (1927, p.104) states, the bronzite granophyre is derived from the "Old granite and its many basic intrusions", it should have a composition intermediate between gabbro and granodiorite. A mixed powder of these rocks will not produce so much orthopyroxene with practically no clinopyroxene. Willemse (1937, p.113) states that according to k and mg values the bronzite granophyre does not occupy an~~y~~ intermediate position between granite and gabbro.

(7) Manton (1964??, p.80) counted more than 5000 inclusions in a dyke on Lesutaskraal 72 and found that 99 per cent of them are quartzite and 1 per cent granite. The nearest outcrop of quartzite is about 5 km from this dyke. Because shale and quartzite are closely associated in the Lower Division of Witwatersrand System which is composed of about equal amounts of shale and quartzite, it can be expected that inclusions of shale should be nearly or just as abundant as quartzite, especially in the dykes on the contact between the Witwatersrand System and the Archaean granite. Granite should outnumber all inclusions in the bronzite granophyre in the Archaean granite. The dykes are apparently vertical, but if they are regarded as cone-sheets which dip towards the inferred central pluton, granite should have been the principal material forming the inclusions. It can then be concluded that xenoliths of granite and shale must have been assimilated by the magma.

Willemse (1937, p.112) compared the composition of the bronzite granophyre with the composition of some of Niggli's magma types and concluded that a magma with this composition is very abnormal. If the normative orthopyroxene and plagioclase An_{65} are subtracted from the norm of the average bronzite granophyre (Appendix B, No.50) about half of the bronzite granophyre is composed of a norite (40 per cent of orthopyroxene and 60 per cent of plagioclase) and the other half of a quartz-rich granite (21 per cent of albite, 25 per cent of orthoclase and 54 per cent of quartz).

Assimilation of solid rock which amounts to about half the volume of either a granitic or noritic magma is doubtful. Because the bronzite granophyre magma was probably nearly completely liquid, as is indicated by the spherulitic chilled rock (type c), the granitic magma could not have melted the solid norite but could only have reacted with it. A noritic magma can melt granitic material but then a large volume of noritic magma must be postulated, i.e. one of which only the roof and the sides were contaminated. This contaminated magma will then be emplaced as bronzite granophyre. A process of this nature fails however to explain the high quartz content of the rock. In the system $Ab\text{-}Or\text{-}SiO_2\text{-}H2O$ (Tuttle & Bowen, 1958, Fig. 30) the composition of the granitic portion of the granophyre falls in the quartz field some distance away from the minimum on the quartz-feldspar boundary (quartz about 15 per cent too high for P_{H_2O} = 0.5 kilobar). For the granitic portion to have a normal composition, i.e. if it should fall in the low-temperature area on the quartz-feldspar boundary near the minimum, this extra quartz must be subtracted and if it is added to the norite, an abnormal norite is created.

The assimilation of shale by a basaltic or andesitic magma suggests the reaction :

$$\text{clinopyroxene} + Al_2O_3 + SiO_2 = \text{anorthite} + \text{orthopyroxene}.$$

Such a reaction would explain the presence of orthopyroxene, but would also increase the anorthite content of the rock. As in the case of a noritic magma, the uncontaminated basaltic or andesitic magma would not alter the situation ~~in~~ as regards the excess of quartz. Selective melting or even complete melting of Archaean granite could not produce the excess quartz, which must therefore have been derived from rocks with a very high quartz content e.g. shale and quartzite. For the development of a quartz-rich granitic portion which would fall in the quartz field a rise in temperature to the level at which the noritic or dioritic portion would be liquid would probably be necessary. Here also, as in the case of a noritic magma, a large volume of basaltic or dioritic magma must be postulated. Alternatively, a fluidized system, like that postulated for the pseudotachylyte,could supply the extra heat. The bronzite granophyre must then be considered as derived from a magma which was contaminated by pseudotachylytic material.

Willemse (1937, p.113) concluded that the bronzite granophyre originated from an alkali lamprophyric magma which was modified by the assimilation of granite and quartzitic material. A lamprophyre which could develop from the alkali granite should be peralkaline, i.e. it should contain no normative anorthite. Furthermore, peralkaline rocks usually do not contain normative hypersthene. Assimilation of Archaean granite and quartzite by such a magma cannot produce the bronzite granophyre, because the average anorthite content of the plagioclase of the Archaean granite is about half that of the bronzite granophyre. On the other hand, if this lamprophyric magma contains a large amount of potential diopside, and if shale is involved in the assimilation, a bronzite granophyre could be produced provided that the diopside content is high enough to produce sufficient anorthite to increase the anorthite content of the resulting magma to such a value that plagioclase (An_{50}) can crystallize from it. A lamprophyric magma of dioritic composition is more suitable than an alkali lamprophyric magma to produce the bronzite granophyre by the assimilation of granitic and quartzitic material. It is possible, in the light of this conclusion, that some of the lamprophyric rocks of the dioritic series could be younger than postulated above. Pseudotachylyte has been found in the lamprophyric rocks in the Vredefort Dome but so far not in the rocks of the Lindequesdrift Intrusion. The possibility that the Lindequesdrift rocks are cut by pseudotachylyte cannot be completely ruled out, because these rocks are poorly exposed and the Lindequesdrift Intrusion lies outside the area of high concentration of pseudotachylyte.

A further problem in connection with the dykes of bronzite granophyre is the origin of the sedimentary xenoliths in the smaller dykes in the Archaean granite. On the present erosion surface the nearest sedimentary rocks are about 5-6 kilometres away from the dykes. If these xenoliths were derived from a possible cover of Witwatersrand rocks shortly after the formation of the dome, the xenoliths must have moved downwards. The question that arises is whether these xenoliths would sink in such a magma. If the xenoliths were derived from below, the dip of the Witwatersrand System must decrease with depth and the axis of overfolding must be at least 5 kilometres from the present outcrop of sedimentary rocks towards the central part of the Dome. A third possibility is that the granophyric magma originated in the vicinity of the large dykes near the contact between the Witwatersrand System and the Archaean granite and was emplaced laterally to produce the smaller dykes near Vredefort and on Lesutaskraal.

V. MUTUAL RELATIONSHIPS OF THE IGNEOUS ROCKS

When comparing the gravity anomalies (Gravity map of the Union of South Africa 1958, 1:1,000,000) over the Vredefort, Pretoria-Johannesburg, Heidelberg-Devon and Grootvlei Domes, it is evident that a high anomaly exists only over the Vredefort Dome, whereas the anomalies over the other domes are low. Only the Vredefort Dome is underlain by rocks of high density (probably mafic) and the others by rocks of low density (probably granite). The presence of a pluton of mafic rocks lying eccentrically under the Vredefort Dome was inferred from gravity anomalies determined by Maree (1944, Fig. 1). The existence of such a central pluton must be accepted in order to explain the igneous and metamorphic phenomena in the Vredefort Dome.

It is reasonable to accept the possibility that this central pluton played an active rôle in the development of the Vredefort Dome. The question arises, is it related to the tholeiitic suite and/or the alkali suite of igneous rocks in the Vredefort Dome? If it is composed of tholeiitic rocks alone it could not have been responsible for the overturning of the Witwatersrand System, because the tholeiitic suite was emplaced before the Witwatersrand System was tilted to a vertical attitude. If this central pluton is composed of rocks related to the alkali suite alone, the igneous activity must have continued over an extended period, i.e. at least from the stage of overturning of the Witwatersrand System, through the periods of extensive faulting, intrusion of the alkaline suite, development of the pseudotachylyte and, finally, the emplacement of the bronzite granophyre.

Inclusions of plagioclase (An_{80}) are frequently found in the Annas Rust dolerite sill and a similar dolerite sill near Vredefort. These inclusions have probably been derived from an unexposed body of anorthosite.

Such an anorthosite can be expected from the differentiation of a tholeiitic magma rather than from one similar to the mafic rocks of the Rietfontein Complex where the plagioclase has an anorthite content of less than 40 per cent.

It would thus appear that this central pluton is probably composed of rocks of both suites and that it is probably layered. The postulation of such a pluton offers the best explanation for the polymetamorphism of the rocks in the Vredefort Dome, i.e. the first stage of contact-metamorphism was caused by the magma of the tholeiitic suite and the later, superimposed metamorphism by the magma of the alkaline suite. (This will be discussed later.) There was a probable time gap between the emplacement of the two rock suites. This gap is represented by the stage of overturning of the strata and the faulting. Such a gap between the peaks of progressive metamorphism is also necessary for the production of the polymetamorphism. Moreover, a differentiated pluton is in harmony with the different compositions of the mafic sills and the variation of the rocks of the alkaline suite.

The distribution-pattern of the intrusions of the alkaline suite probably has a bearing on a possible genetic relation between these intrusions and the central pluton:

a) The Roodekraal Complex, the Rietfontein Complex, and the Lindequesdrift Intrusion form an outer arc which is concentrically disposed with respect to the central pluton.

b) The inner arc is roughly parallel to the outer arc and is formed by the dykes of bronzite granophyre which more or less follow the contact between the Witwatersrand System and the Archaean granite.

c) The major axes of the plutons of alkali granite are also roughly parallel to these arcs.

d) The major strike-faults, including those along which the plutons of the alkaline suite were emplaced, strike parallel to these arcs.

e) The smaller dykes of bronzite granophyre which are intrusive into the Archaean granite and the dykes of alkali granite aplite are radially disposed with respect to the central pluton.

The post-Transvaal igneous rocks in the Vredefort Dome and the Potchefstroom Synclinorium represent a group of rocks showing a large range in mineralogical and chemical composition (Fig. 8 and Appendix B). These rocks constitute a petrographic province, and because of certain similarities in composition and age, they can be considered as a subprovince of the larger Bushveld province.

The relative ages of the different complexes and intrusions in the Vredefort area are as follows :

(1) the tholeiitic suite,

(2) the Rietfontein mafic intrusion and the related wehrlite on Koedoesfontein 12,

(3) the dioritic series (Roodekraal, Lindequesdrift?),

(4) the peralkaline granite and mariupolite and,

(5) the bronzite granophyre.

It is possible that some of the lamprophyric rocks are related to the mafic portion of the Rietfontein Complex.

Each of these groups shows its own variation (Fig. 8) which can be attributed to magmatic differentiation and assimilation. Thus each group shows an enrichment in iron and alkali in the later stages. This phenomenon is mainly due to fractional crystallization and crystal settling under the influence of gravity in the mafic magma. The enrichment in

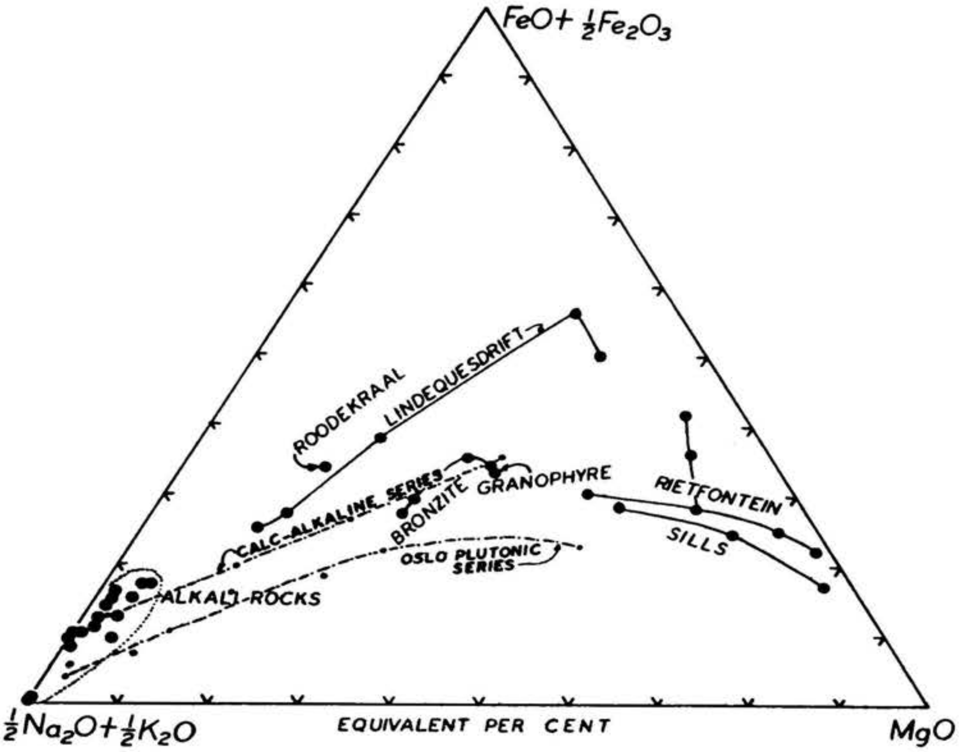

Figure 8. Diagram showing variation in the composition of the igneous rocks of the Vredefort Dome and also curves for the variation in the plutonic rock series of Oslo (Barth, 1945), and the calc-alkaline series (Daly, 1933).

iron and alkali is also a feature of the province as a whole.

If the different intrusions are considered as derived from a common magma (Hall and Molengraaff, 1925, p.92, Nel, 1927, p.60), the major problem is to explain the following sequence of rocks as the result of differentiation : tholeiite ⟶ olivine sodagabbro ⟶ diorite ⟶ peralkaline granite ⟶ bronzite granophyre. Such an explanation, to be acceptable, must effectively bridge the large gaps between the different magma types and must also be justifiable on physico-chemical grounds.

Normally differentiation of a tholeiitic magma produces oversaturated differentiates and the development of a highly undersaturated olivine basaltic magma from a tholeiite is highly improbable. It is possible that the tholeiitic magma and the olivine basaltic magma were derived from a common source-material but they represent two independent primary magmas. The association of theoleiitic and alkali olivine basaltic magmas in comagmatic provinces is frequently encountered in nature (see Turner and Verhoogen, 1960, p.217).

The exact relationship between the dioritic magma and the olivine gabbroic magma is not clear. The close association of the lamprophyre with olivine gabbro and the broad correspondence ~~to~~ with the pegmatite of the olivine gabbro which is actually a leucodiorite, point to a possible genetic relationship. Water and other volatile constituents probably played an important rôle in the differentiation of diorite from olivine gabbro if the olivine gabbroic magma was the parent of the dioritic series. The dioritic rocks of the Roodekraal Complex were relatively "dry" before the later hydrothermal alterations took place. However, it is possible that the dioritic rocks crystallized from a primary dioritic magma (see Turner and Verhoogen, 1960, p.433, 286). The large andesitic provinces e.g. the Ongeluk lava and the Ventersdorp lava point to the possible existence of such dioritic magmas.

The origin of the peralkaline syenite has been discussed above and it is concluded that it crystallized from an independent primary trachytic magma. The bronzite granophyre is considered to have crystallized from a contaminated dioritic magma.

VI. STRATIGRAPHY OF THE METAMORPHIC ROCKS

A. Nomenclature of the Metamorphic Rocks

The nomenclature which will be used for the metamorphic rocks of the Vredefort Dome is largely based on definitions suggested by Williams, Turner and Gilbert (1954, p.174). The metamorphic rocks of the Swaziland System in the Vredefort Dome are products of regional metamorphism and can be classified as granulite and amphibolite.

A granulite is an even-grained rock which is not obviously schistose and is a product of the highest grade of metamorphism.

Amphibolite includes the medium-grade metamorphic rocks which are composed mainly of plagioclase and amphibole. Schistosity is not prominently developed.

Hornfels and slate are the principal metamorphic rocks in the Witwatersrand System. The term hornfels is used for medium- to fine-grained, granoblastic rocks which are frequently porphyroblastic and are products of contact-metamorphism. Some of the amphibole-bearing metamorphic rocks contain acicular or long, slender prisms of cummingtonite and are therefore not granoblastic. The cummingtonite-bearing rocks originated under the same conditions as the granoblastic types but do not have the hornfelsic texture because of the growth-habit of cummingtonite. These rocks will also be termed hornfels. All the hornfelses in the Vredefort Dome are quartz-bearing, and all of them, with the exception of the amphibole-bearing varieties, are mica-bearing. To avoid the use of too many mineral names prefixed to the term hornfels, in order to distinguish between different varieties, only the non-alkali-bearing minerals will be used, i.e. the minerals used in the A M F and A C F diagrams (Fig. 10 f.159), e.g. a hornfels composed of andalusite, cordierite, biotite, muscovite, and quartz will be termed an andalusite-cordierite hornfels, or one composed of cummingtonite and quartz will be termed a cummingtonite hornfels. A type which does not contain any of these minerals, but only mica and quartz, will be termed hornfels only.

The term slate will be used for a fine-grained metamorphic rock with a slaty cleavage but with no segregation-banding. It is a product of low-grade regional metamorphism of fine-grained, clastic sediments. Spotted slates are products of contact-metamorphism, in which the spots represents embryonic porphyroblasts. Types with all the properties of slate but containing recognisable porphyroblasts, for example andalusite or garnet, will also be included here.

The mafic rocks younger than the Archaean granite but older than the Transvaal System are all metamorphosed and are termed epidiorite. Epidiorite will be used in the sense proposed by Williams, Turner and Gilbert (1954, p.243), i.e. for metamorphosed mafic igneous rocks which do not show any preferred orientation of the constituent minerals and are composed of amphibole and plagioclase. The low-grade chlorite-bearing type will also be termed epidiorite.

B. The Basement-complex

The petrology of the rocks of the Basement complex has been described by Willemse (1937, p.43-119). He (p.69) subdivides the rocks older than the Archaean granite into ortho- and para-rocks and differentiates between mineral assemblages characteristic of the epi-, meso- and katazones of metamorphism. Rocks of the katazone are found on Steynskraal 129, Pretoriuskraal 987 and near Vredefort, and consist mainly of garnet-hypersthene and garnet-plagioclase granulites. To the occurrences mentioned above the pyroxene granulite of Kliprug 334 and the charnockitic rocks of the Parys industrial area can be added. This group represents the granulite facies and the mineral assemblages are outlined in Table 3. The different assemblages are numbered for easy reference to Fig. 10(p.159).

Table 3.

Minerals assemblages of the granulite facies

Assemblage number	Mineral assemblage
43	Almandine, plagioclase, biotite, quartz
44	Almandine, quartz
45	Almandine, hypersthene, magnetite, quartz
46	Plagioclase, hypersthene, diopside, quartz
46a	Plagioclase, hypersthene, diopside, hornblende ± biotite
47	Plagioclase, orthoclase, quartz
48	Diopside, plagioclase
48a	Diopside, plagioclase, hornblende

The rocks which Willemse (1937, p.69) considered as characteristic of the mesozone, i.e. schists and amphibolites, represent the amphibolite facies of metamorphism.

The metamorphism responsible for the development of these two groups of rocks is related to the intrusion of the Archaean granite and the accompanying regional metamorphism. As Willemse (1937, p.70) justly remarks, the rocks of the katazone (granulite facies) are xenolithic bodies and are also found on the immediate contacts of the Archaean granite and the country-rocks, whereas rocks of the mesozone (amphibolite facies) form small xenoliths in the granite and are also present in the area around Avondale 600 and Blaauwboschpoort 16 in the south-eastern sector of the Vredefort Dome.

Within the epizone Willemse (1937, p.69) distinguishes the effects of regional and retrogressive metamorphism and points out that the latter may have taken place at a later stage than the progressive metamorphism. The retrogressive metamorphism probably took place during the period of low-grade metamorphism which affected the Witwatersrand and Ventersdorp Systems (greenschist facies) and the contact-metamorphism to be described later.

In texture the Archaean granites ranges from equigranular to porphyritic and in composition from granitic to granodioritic and tonalitic (cf. Willemse, 1937, p.84-101).

C. Dominion Reef System

This system is represented by the Basal Amygdaloid which is described by Hall and Molengraaff (1925, p.24 & p.131) as a hornblende granulite. In terms of the facies classification this designation is, however, not a very fortunate one, as the grade of metamorphism attained by this lava is not higher than that of the amphibolite facies. In the area of intense contact-metamorphism the amygdaloid shows a more pronounced degree of recrystallization than elsewhere. The amygdaloid represents a lava which was probably subjected to low-grade, regional metamorphism (equivalent to the greenschist facies) and subsequently to contact-metamorphism. Directive structures are absent in the amygdaloid. This rock should be termed an epidiorite.

Highly metamorphosed sedimentary rocks form isolated blocks of garnet-amphibole-cordierite and amphibole hornfels near the top of the Basal Amygdaloid on Rietpoort 66 (Plate I, Sheet 3). These bodies are elongated parallel to the strike of the amygdaloid.A cordierite-amphibole hornfels on Dampoort 327 and S-klip 496, halfway up in the successions forms a thin sheet about 1.5 kilometres in length (Plate I, Sheet 1). In a band of amphibole-garnet hornfels between the Basal Amygdaloid and the Orange Grove quartzite on Spitskop 1060 (Plate I, Sheet 2), the thin lamination (an original sedimentary feature) is still preserved in the upper part. A muscovite schist is developed on the same horizon on Koppieskraal 89 (Plate I, Sheet 2).

The hornfels bands and "blocks" indicate short periods of sedimentation between the different lava flows during which irregularities on the lava surfaces were filled with sediment before the commencement of the following flow, especially towards the end of the Dominion Reef period.

D. Witwatersrand System

1. Hospital Hill Series

The Orange Grove quartzite (O.G.Q.) consists of four to five bands (usually four) of pure quartzite with intercalated impure quartzite or slate and hornfels (Plate I). Of the intercalated pelitic bands, the upper is the most persistent. The pelitic types grade into arenaceous types, e.g. on the eastern part of Rietpoort 66 and on Rensburg's Drift 432. On Brakfontein 40 and the eastern part of Rietpoort 66, four quartzite bands alternate with three pelitic bands (garnet-amphibole hornfels) (Plate I, Sheet 4). Westwards the three pelitic bands grade into impure quartzite (Plate I, Sheets 3 and 4). From Rensburg's Drift 432 south-eastwards, only one pelitic band, composed of garnet-amphibole hornfels and a ferruginous slate on top, is present between the upper quartzite bands, but grades into quartzite on Deelfontein 19 (Plate I, Sheets 1 and 2).

The Orange Grove quartzite is followed by the ferruginous Water Tower slates (Plate I, Sheet 5). Directly on top of the upper band of Orange Grove quartzite is a band of garnet-amphibole hornfels which is followed by a band of highly ferruginous slate (magnetite hornfels), about 10-15 feet thick which produces fairly good outcrops. This band is marked W.T.S. on Nel's (1927) map. Next in the succession is a thick group of ferruginous slates (amphibole-magnetite hornfels with scattered garnet) and a poorly exposed non-ferruginous slate (cordierite hornfels).

The Speckled Bed (S.B.) consists of a feldspathic quartzite which is developed only on Rietpoort 66 and farther to the east. It is absent in the area between the Potchefstroom-Parys road and the Vredefort-Viljoenskroon road.

The argillaceous rocks between the Speckled Bed and the Lower Hospital Hill quartzite (H.H.Q.1) consist of ferruginous slate (amphibole hornfels) and banded ironstone in the lower half and a non-ferruginous slate (andalusite-cordierite hornfels) in the upper half. The banded ironstone, about 100 feet above the Speckled Bed, is highly contorted in the upper part and is known as the Contorted Bed (C.B.). The non-ferruginous slate becomes more arenaceous owing to the conspicuous development of thin lenses of impure quartzite. Variation in the composition of the pelitic layers causes the hornfelses developed from them to have a banded appearance. A poorly exposed, nearly monomineralic cummingtonite hornfels is found more or less in the middle of the banded andalusite-cordierite hornfels.

The banded andalusite-cordierite hornfels is followed by the three Hospital Hill quartzites and the argillaceous beds in between. The Upper Hospital Hill quartzite (H.H.Q.3) forms a prominent white ridge which is an outstanding scenic feature in the area. About halfway between the Upper and Lower Hospital Hill quartzites a bed, approximately 100 feet thick is found which consists of ferruginous slate (amphibole-magnetite hornfels) which has a banded appearance in some places. This slate is followed by aluminous slate (cordierite hornfels) and a thin, poorly exposed band of quartzite (H.H.Q.2) which is separated from the Upper Hospital Hill quartzite by slate (cordierite hornfels). Some of the argillaceous bands above the Lower Hospital Hill quartzite vary considerably in chemical composition as is evident from their metamorphic equivalents, e.g. the band directly above the Lower Hospital Hill quartzite grades from a garnet hornfels into a cummingtonite hornfels which in turn grades into a cordierite hornfels.

2. Government Reef Series

The lowermost bed of the Government Reef Series consists of a slate and a cordierite hornfels with a thin band of quartzite (G.R.Q.1) above it. In the western part of the Dome on Steenkampsberg 127, and Deelfontein 19 the cordierite hornfels between the Upper Hospital Hill quartzite and the first Government Reef quartzite grades into an impure quartzite. This results in a thick quartzite of which the upper third is taken as the lower part of the Government Reef Series. The line of demarcation of the two series in this area is however distinct owing to the difference in topographic expression of the pure Hospital Hill quartzite and the impure Government Reef quartzite.

The lowermost Government Reef quartzite (G.R.Q.1) is followed by a ferruginous slate containing a thin band of hornfels which is usually poorly exposed. The thick andalusite hornfels overlying the ferruginous slate forms prominent outcrops and is a useful marker in the field. A cordierite hornfels above this andalusite hornfels is overlain by the poorly exposed impure second Government Reef quartzite (G.R.Q.2). In the Steenkampsberg-Deelfontein area and the eastern part of Rietpoort 66 the cordierite hornfels and the andalusite hornfels grade into slate.

The slate between the second and third Government Reef quartzites is not as thoroughly recrystallized as the argillaceous rocks below the Upper Hospital Hill quartzite. In some places, e.g. in the north-western corner of Rietpoort 66, the upper part of this slate displays a fine lamination. Where this slate is recrystallized, e.g. on Koedoeslaagte 59, Helena 780, Eliza 972, and Goedgedag 971, it is represented by cummingtonite hornfels which overlies the second Government Reef quartzite. The latter is followed by a garnet hornfels and a very fine-grained amphibole hornfels which in turn is overlain by the third Government Reef quartzite (G.R.Q.3).

The third Government Reef quartzite is the thickest quartzite in this series and forms a prominent rounded ridge. A gritty rock near its base is well exposed on Goedgedag 971 and Steenkampsberg 127. A similar rock-type, especially well developed on the top of this quartzite, occasionally contains scattered pebbles, e.g. in the south-western corner of Buffelshoek 83 and on Aasvogelkop 426. Next in the succession is a thin band of andalusite hornfels which grades northwards (e.g.in the south-western corner of Buffelshoek 83) and southwards (on Deelfontein 19) into andalusite slate and slate. On Rietpoort 66, west of the road between Potchefstroom and Parys, the trace of a strike-fault follows the outcrop of this slate, which was metamorphosed to an andalusite schist.

The slate above the fourth Government Reef quartzite (G.R.Q.4) is poorly recrystallized. In the vicinity of the alkali granite on Koedoeslaagte 59 only a garnet hornfels is developed above this quartzite, and the rest of the succession between the fourth and the fifth quartzite (G.R.Q.5) consists of slate and occasionally intercalated bands of fine-grained hornfels.

The fifth Government Reef quartzite (G.R.Q.5) is poorly developed in the eastern part of the Dome (about 5 feet thick) but increases in thickness towards the west in the Orange Free State. The thin band of slate between the fifth and the sixth quartzite (G.R.Q.6) disappears in some areas (i.e. it probably grades into quartzite).

The sixth Government Reef quartzite (G.R.Q.6) is thicker in the Transvaal than in the Orange Free State. On this quartzite a thick succession of slates (approximately 1000 feet thick) follows with a fine-grained hornfels near the middle of the succession in some areas, e.g. on Koedoesfontein 12 and Koedoeslaagte 59. The seventh is a thin quartzite band with a grit band on top (G.R.Q.7). This grit is persistent throughout the mapped area and is a useful marker in the Government Reef Series. This grit is overlain by a ferruginous slate and then the eighth quartzite (G.R.Q.8) which is the second thickest quartzite in the Government Reef Series. The upper half of the slate between the eighth and the ninth quartzite (G.R.Q.9) is metamorphosed to a fine-grained hornfels. The ninth is the purest of the Government Reef quartzites and it usually forms a sharp ridge.

3. Jeppestown Series

The uppermost band of Government Reef quartzite is succeeded by a thin band of slate and a still thinner band of quartzite (J.Q.1) which is usually poorly exposed owing to a cover of debris from the ninth Government Reef quartzite. This is succeeded by some 800-900 feet of slate containing a fine-grained hornfels near the alkali granite. The second Jeppestown quartzite (J.Q.2) is an impure one which does not form prominent landscape features. The middle part of this quartzite is even more argillaceous than the lower and the upper bands. Where this middle band is metamorphosed, it usually weathers to rounded boulders and blocks and then it has an appearance very similar to the dark grits referred to in the description of the Government Reef Series. In some areas a thin band of conglomerate known as the Velschoen Reef, is found at the base of this quartzite, e.g.on Rebok Kop 290 and Nooitgedacht 89, where it was mined, and in an old prospecting pit on the boundary between Thesensrust 296 and Reidsrust 468.

The third Jeppestown quartzite (J.Q.3) is about 1200 feet thick and forms a prominent ridge in the Vredefort Dome. The slate below this quartzite is not recrystallized to a hornfels and the one above it is converted to a garnet hornfels only near the contact with the alkali granite. The two upper quartzites (J.Q.4 and J.Q.5) are impure and not well exposed. The Jeppestown Amygdaloid which is intercalated between these two bands of quartzite is also poorly exposed except in an area east of the major fault on Buffelshoek 83. The uppermost Jeppestown slate separates this series from the overlying Main-Bird Series.

4. Main-Bird and Kimberley-Elsburg Series

The Main-Bird Series and the Kimberley-Elsburg Series have roughly the same thickness and are separated from each other by a longitudinal valley in which the bedrock is seldom exposed. According to Nel (1927, p.46) the bedrock appears to be largely ~~and~~ argillaceous sandstone which grades into a slate (Kimberley-Elsburg slate). The best known occurrence of this slate is on Rooderand 26 in a cutting on the Potchefstroom-Venterskroon road.

A zone of conglomerate close to the base of the Kimberley-Elsburg Series is known as the Amazon Reefs. Some of the bands below, in, and above the conglomerate horizon, are argillaceous quartzites. From Rooderand 26 to Koedoesfontein 12 these bands have a knotted appearance owing to the development of more or less spherical aggregates consisting of kyanite and andalusite. The original bedding is still preserved and, as these rocks display no directive textures or structures, they can be described as andalusite-kyanite hornfelses (Plate IX B).

E. Ventersdorp System

The Ventersdorp System, which consists only of lava in the Vredefort Dome, overlies the Witwatersrand System with an apparently conformable relationship. Jansen (Nel and Jansen, 1957, p.21) however, found sediments on Welgedacht 282 in the eastern sector of the Dome.

F. Transvaal System

1. Black Reef Series

This series is poorly exposed around the Vredefort Dome. In the Rietfontein area the Black Reef Series forms a quartzite "koppie" on Rietfontein 54 south-west of the alkali granite and also a succession of conglomerate and shale on Rietfontein 163 near the trigonometrical beacon 56. In the last-named area the Black Reef Series is exposed on the slopes of a ridge which strikes east. The basal conglomerate is actually a boulder-conglomerate which represents an old channel-filling in the Ventersdorp lava. The boulders and pebbles of the different conglomerate bands consist mainly of fragments of Ventersdorp lava, indicating that the Black Reef in this area was derived from a Ventersdorp terrain.

2. Dolomite Series

Outcrops of dolomite are comparitively rare in the Rietfontein area. The chert becomes more prominent in the upper part of this series and is reasonably well exposed. There are a few bands of shale near the base of the dolomite. A conglomerate at the contact between the alkali granite and the dolomite in the northern part of Rietfontein 163 is well exposed in a gravel pit along the road to Lindequesdrift. The pebbles are poorly rounded and some of them are even angular. They consist mainly of recrystallized chert. Above this conglomerate, a sandy shale with a dip of approximately 85° to the north-west, is exposed in the gravel pit. This conglomerate is regarded as the Bevet's conglomerate which is found in this position (several hundred feet below the top of the dolomite) owing to a major strike-fault.

VII. METAMORPHISM OF THE SEDIMENTARY ROCKS

A. Mineralogy

1. Sillimanite

Two varieties of sillimanite are present in some rocks in the Vredefort area, namely a prismatic and a fibrous variety. The prismatic variety is found only on Rietfontein 163 together with the fibrous variety (fibrolite) in a cordierite-sillimanite hornfels in the Dolomite Series near the contact with the alkali granite. Fibrolite is also a constituent in some hornfelses near the contact with the alkali granite on Koedoeslaagte 59 and Helena 780 and in a xenolith in the alkali granite on Schurwedraai 382.

The prismatic variety forms crystals up to 1.25 mm in length which are square in cross section owing to the development of prism faces. A perfect (010) cleavage is present in the larger crystals and also a basal parting in nearly all crystals. The refractive indices are, $\alpha = 1.654$, $\gamma = 1.675$. The sillimanite prisms are frequently enclosed by fibrolite and sometimes show a corroded contact with the fibrolite. Sillimanite prisms are also included in biotite or the longer prisms cut across biotite without showing any signs of corrosion of either the biotite or the sillimanite.

Where the sillimanite prisms are small, fibrolite is quite abundant, but specimens with larger prisms contain only small amounts of fibrolite, indicating that the prismatic sillimanite was probably derived from fibrolite by recrystallization.

In a hornfels above the third Government Reef quartzite on Helena 780, the fibrolite grows from the faces of andalusite crystals, often where two porphyroblasts of andalusite are in contact with each other, or where biotite and quartz form a narrow zone between the andalusite porphyroblasts. In rare cases the fibrolite grades into stout prisms of sillimanite. Fibrolite is also found in close association with the biotite in the ground-mass of the rock. This is also the case with the small amount of fibrolite in the impure Jeppestown quartzite (J.Q.2) near the contact with the alkali granite on Koedoeslaagte 59.

A xenolith composed of sillimanite hornfels, in the alkali granite on Schurwedraai 382, contains abundant fibrolite in nodular aggregates which are visible to the naked eye. Under the microscope these nodular aggregates consist of units of parallel to subparallel fibres. The central parts of these units have the appearance of large "crystals" from which the outer fibres radiate. The fibrous nature of the "crystals" is still distinct. They are brownish in colour and there is a parting perpendicular to the length of the fibres. The biotite and the fibrolite are closely associated.

If the fibrolite were derived from the breakdown of biotite, one would have expected to find a non-aluminous mineral or minerals closely associated with the biotite and the fibrolite. Chinner (1961, p.319) has pointed out that the most serious problem in this case is the fate of the Na, K, Mg, and Fe.

Tozer (1955, p.313) states that as the ratio of fibrolite increases, the colour of the biotite becomes progressively paler, and the rocks which contain the fibrolite contain no other Al_2SiO_5 polymorph from which it could have developed. According to him fibrolite results from the dissociation of biotite with the expulsion of K, Mg, Fe, F, and H_2O, with the iron sometimes remaining as grains of magnetite. The occurrence of fibrolite, partly as outgrowths from biotite and partly in the adjacent ground-mass, is regarded by Tozer (1955, p.318) to be the result of a certain amount of diffusion of the elements of which sillimanite is composed.

Francis (1956, p.357) suggests that the iron-member in biotite breaks down first, leaving the biotite enriched in magnesium and precipitating the iron as magnetite and the potassium as microcline. No potassium feldspar is associated with the fibrolite in the Vredefort rocks, nor is magnetite closely associated with the fibrolite.

Chinner (1961, p.320, Table III) shows that there is no significant change in the Mg/Fe ratio in biotite with progressive increase in the amount of sillimanite in the gneisses of Glen Clova, and potassium feldspar is absent from the sillimanite-bearing rocks. He rejects the possibility of the metasomatic removal of Fe, Mg, K and Na from the system, as such a postulate involves metasomatic losses of a high order and because of the fact that rocks having 20 per cent or more sillimanite are not unusual for pelitic rocks. Furthermore, there is no indication in the Glen Clova rocks that any spectacular metasomatism of this type was involved in the formation of the sillimanite-bearing rocks. Chinner (1961, p.321) concludes that the impression that biotite is replaced by sillimanite may therefore be illusory, and that the greater part of the silicon and aluminium which is required for the growth of sillimanite must be sought outside the biotite.

Chinner (1961, p.322) ascribes the rôle of biotite in the formation of sillimanite to that of a nucleating agent. The trigonally arranged chains of oxygen tetrahedra and octahedra in the alternate mica sheets act as nuclei for the growth of the tetrahedral and octahedral chains of the sillimanite structure. The nucleation was probably dominantly epitaxial, and the constituents for the formation of sillimanite was mainly derived from unstable kyanite and transferred to the sillimanite nuclei through the medium of a fluid phase. Chinner (1961, p.321) also believes that the nucleation and growth of sillimanite was aided by some form of temporary instability in the mica as a result of changes in pressure and temperature and the partial pressures of water and oxygen to which ferruginous micas are especially sensitive.

The sillimanite of the hornfelses of the Vredefort Dome forms outgrowths on biotite, fibrolite nodules with radiating fibres, and outgrowths on andalusite. It also forms independently of biotite or any other Al_2SiO_5 polymorph. There are no signs of metasomatism in the hornfelses which would indicate a source of aluminium outside the hornfelses or the removal of other constituents from the hornfelses which would leave a residue rich in aluminium.

The sillimanite developed from the constituents of the rocks themselves, through transformation of andalusite to sillimanite (the hornfels directly above G.R.Q.3), or directly from the aluminous sediment under appropriate metamorphic conditions (possibly the sillimanite hornfels on Rietfontein 163). The nodular sillimanite in the xenolith on Schurwedraai 382 can be interpreted as andalusite which was completely transformed to sillimanite. Willemse (1959, p.liii) has given a similar interpretation for the origin of the sillimanite nodules in a hornfels from Apiesdoorndraai 162 in the eastern Transvaal.

The presence of sillimanite in a metamorphic rock which constitutes a mineral assemblage in equilibrium, indicates an excess of aluminium after the formation of the other aluminosilicates. It is however, difficult to accept the hypothesis that all the sillimanite associated with biotite involves metasomatism. The most serious part of the problem is not the source of the aluminium, but rather the close association of the sillimanite with biotite. In some rock-types biotite appears to be actively involved (i.e. by breakdown) in the formation of sillimanite, but in others it serves as a nucleus on to which sillimanite fibres grew (i.e. where biotite shows no signs of alteration). Where there is a breakdown of biotite during the formation of sillimanite, it is probably the result of the formation of a mineral assemblage of higher grade from a pre-existing assemblage of lower grade in which biotite as well as other minerals are involved.

2. Kyanite

Abundant kyanite is present in several bands of kyanite-andalusite hornfels just above and below the conglomerate zone in the Kimberley-Elsburg Series on Koedoesfontein 12, Buffelskloof 44, Leeuwfontein 81, Buffelskloof 24 and Rooderand 26 (Plate IV). Kyanite-andalusite hornfels, or knotted quartzite as Nel (1927, p.76) has termed this rock, is seldom seen below the Kimberley shale. The most conspicuous development of this rock-type is found on Buffelskloof 24, i.e. where these bands are nearest to the pluton of alkali granite on Schurwedraai 382 and Koedoeslaagte 59. Towards Koedoesfontein 12 and Rooderand 26, the knotted appearance of the rock becomes less conspicuous, until it eventually disappears on these two farms.

The knots are mostly spherical and range in size from a few millimetres to about 2.5 cm in diameter. The kyanite-andalusite hornfels hardly shows any signs of directed structures, but has a banded appearance owing to a variation in the abundance and the size of the knots in the alternating bands (Plate IX B).

Nel (1927, p.76) found that these knots consist of kyanite. However, examination of thin sections cut from specimens taken at different localities in the area of knotted quartzite also reveals the presence of andalusite. In some places, e.g. in the north-western corner of Buffelshoek 44, only small quantities of andalusite are present whereas on the outer limit of the zone of metamorphosed quartzites, andalusite is the dominant Al_2SiO_5 polymorph.

The knots (glomeroporphyroblasts) are of different varieties:

(1) knots composed of large porphyroblasts of kyanite and small sparsely distributed fine-grained aggregates of andalusite;

(2) knots composed of large porphyroblasts of both kyanite and andalusite and fine-grained aggregates of andalusite (Plate X A);

(3) fine-grained knots of andalusite which seldom include large porphyroblasts of kyanite; and

(4) sparsely distributed, small fine-grained knots of andalusite, without any kyanite, which are not clearly revealed on weathered surfaces.

The above is also more or less the order in which the knots vary from the area nearest to the alkali granite to the outer limit of metamorphism of the quartzites.

The matrix of the kyanite-andalusite hornfels consists mainly of clastic grains partly or completely surrounded by fine-grained aggregates of sericite which form the "cement" of the rock. The large porphyroblasts of kyanite and andalusite enclose the original clastic quartz grains which show different degrees of corrosion. The quartz grains range from sizes similar to those of the unaffected grains of the ground-mass to very small serrated relicts which represent only a small fraction of the original grains. The corrosion of quartz is more evident in the kyanite than in the andalusite, probably as a result of the stronger tendency of kyanite to be idioblastic compared with andalusite.

Some bands of knotted quartzite on Buffelskloof 44 and Leeuwfontein 81 contain chloritoid together with andalusite and kyanite. It is particularly abundant in thin lenses of slate within the quartzite in the north-western corner of Buffelskloof 44. The kyanite found in a thin quartz vein in this slate has grown beyond the walls of the vein into the fine-grained slaty ground-mass. Large porphyroblasts of andalusite are seldom seen in the slaty rock, but fine-grained aggregates of andalusite are associated with kyanite in the knots or glomeroporphyroblasts. Chloritoid is usually found in the ground-mass and to a lesser extent in the knots.

The fine-grained aggregates of andalusite between the porphyroblasts of kyanite and andalusite frequently form narrow rims which surround clastic grains of quartz. Large parts of these fine-grained aggregates of andalusite are often in optical continuity. Where the porphyroblasts of kyanite and andalusite are well developed, the fine-grained aggregates of andalusite form a small part of the knot, whereas knots near the outer limit of the aureole of metamorphism consist only of aggregates of andalusite with or without porphyroblasts of kyanite. This indicates that at least the porphyroblasts of andalusite originated from the fine-grained aggregates of andalusite which represent the incipient crystallization of the Al_2SiO_5 polymorphs.

On Leeuwfontein 81, on the outer limit of the aureole of metamorphism, where the knots consist for the greater part of andalusite, coarse kyanite is found in a vug or a small shear-plane approximately 20 cm long and about 1 cm thick.

Small amounts of kyanite are also constituents of hornfels in the lower part of the Government Reef Series near its contact with the alkali granite on Helena 780 (Plate X B). This kyanite usually forms small crystals on the margins of andalusite porphyroblasts and are seldom present in the central part of andalusite crystals or in the ground-mass of the hornfels. It is usually well developed between andalusite porphyroblasts, where the latter are nearly in contact with one another. Where more than one crystal of kyanite is associated with one porphyroblast of andalusite the kyanite crystals do not have a common orientation. There is also no relation between the orientation of the kyanite and that of the andalusite. Kyanite is also closely associated with staurolite in the same hornfels in the Government Reef Series. This is probably due to their simultaneous development and a partial similarity of internal structure. It is evident that the material from which kyanite developed was derived from andalusite and that this process represents a reconstructive transformation (Buerger, 1948, p.106).

Nel (1927, p.77) described a kyanite-ottrelite schist from Kromdraai 142, near the base of the Main-Bird Series. The kyanite in this schist, as described by Nel, is lath-shaped and different from the kyanite of the knotted quartzites which has an irregular form and a strongly poikiloblastic habit.

Kyanite is considered to be a stress mineral by Harker (1939, p.151). Hietanen (1956, p.25) states that the occurrence of kyanite in quartz veins shows that kyanite can be formed at low temperatures without stress, and that Verhoogen has shown that during the formation of minerals, hydrostatic pressure can substitute for stress. The hornfelsic character of the kyanite-bearing rocks in the Vredefort Dome indicates that here kyanite did not crystallize under stress conditions.

3. Andalusite

Stratigraphically the first development of andalusite in the Witwatersrand System, is above the ferruginous slate which overlies the Contorted Bed, in the banded andalusite-cordierite hornfels below the Lower Hospital Hill Quartzite (H.H.Q.1). Several bands between the Lower and the Upper Hospital Hill quartzite (H.H.Q.3) contain andalusite. Above the lowermost Government Reef quartzite (G.R.Q.1) a thick band of andalusite hornfels is found, which served as a useful marker during the mapping of the area. Higher up in the succession the only andalusite-bearing hornfels is one between the third and the fourth Government Reef quartzite.

Owing to the resistance of andalusite to weathering, rectangular crystals usually stand out on weathered surfaces. The andalusite ranges in size from microscopic grains to crystals having a length of 5 cm (on the eastern part of Rietpoort 66). The prism (110) is generally well developed and occasionally also the (011) face, whereas (100) and (101) faces are seldom seen. The mineral is usually strongly poikiloblastic, especially the larger crystals, although parts of some crystals are nearly free from inclusions. Quartz is the most abundant type of inclusion, but magnetite, biotite and garnet are also frequently present. Prismatic cleavages are usually well developed in the non-poikiloblastic parts of crystals. Occasionally porphyroblasts consist of small rectangular "blocks" which are optically continuous.

In exceptional cases the andalusite is xenoblastic, e.g. in a hornfels on the contact of the alkali granite on Helena 780 which contains abundant andalusite. In rocks where andalusite is an accessory constituent it is usually also xenoblastic. This type of andalusite is not strongly poikiloblastic and does not form porphyroblasts. In the first-named example the andalusite probably resulted from the recrystallization of original porphyroblasts, as the same hornfels contains idioblastic porphyroblasts of andalusite with a zonal structure about 100 metre away from the contact (Plate XI A). This zonal structure is also evident in other andalusite hornfelses. The core of the crystal is separated from the outer part by a narrow zone which is practically free from inclusions, thus producing an "idioblastic crystal" within another crystal which is also idioblastic, both having the same orientation. Another type of zonal growth consists of a strongly poikiloblastic core and a margin which is relatively free from inclusions.

Andalusite is the first mineral which crystallized in the andalusite hornfels, as is evident from andalusite slate which grades into andalusite hornfels. The andalusite forms short prismatic porphyroblasts up to 0.5 cm in length in the slate which is composed of fine-grained quartz, chlorite, and sericite. With increase in the grade of metamorphism, fine-grained aggregates of biotite appear. An interesting example of the development of andalusite is found in a slate directly above the thick Government Reef quartzite (G.R.Q.3) on Aasvogelrand 293 in which andalusite has developed along cracks more or less perpendicular to the lamination of the slate (Plate XI B). The ground-mass consists of sericite and quartz; metamorphism did not reach the stage in which biotite begins to develop. The andalusite along the crack is practically free from inclusions, but farther away from the crack it is strongly poikiloblastic with more than 60 per cent of inclusions. There is no sharp boundary between the poikiloblastic and non-poikiloblastic parts of the andalusite. Where the crack crosses the quartz-rich laminae, the band of andalusite is narrow, whereas in the darker, clayey laminae it becomes much wider. This indicates that the interstitial pore-fluid, probably mainly water, was an effective agent in the transportation of aluminium to the centers of crystallization and that the shale began to recrystallize at very low temperatures.

The andalusite in the hornfelses with a ground-mass of quartz and chlorite (penninite) often shows a narrow clear border which is composed of cordierite. This border is relatively, and in some cases practically, free from coloured ferromagnesian minerals. In one exceptional example from Ebenhaezer 498, the andalusite exhibits stout prismatic crystals up to 2 cm in length. These crystals are surrounded by a zone, about 3 to 4 mm wide, which contains a relatively small amount of coloured ferro-magnesian minerals, compared with the ground-mass, which consists of a dense felt of chlorite, quartz and scattered porphyroblasts of biotite (Plate XII A). A very narrow zone, less than 0.5 mm wide, on the margin of the andalusite crystals consists of magnetite and penninite. This is followed by a zone, about 3 to 4 mm wide, which is composed mainly of small grains of cordierite and accessory biotite, penninite, magnetite, and quartz. The cordierite decreases in quanitity outwards from the andalusite, owing to an increase of quartz.

Where this zone is in contact with the ground-mass, a fair amount of magnetite is developed. The magnetite in these zones forms pseudomorphs after a flaky mineral, probably chlorite. It is different from the magnetite enclosed in the andalusite and elsewhere in the ground-mass, where it forms more or less equidimensional crystals which are steel grey in reflected light. The magnetite which forms the pseudomorphs appears black in reflected light (probably cryptocrystalline) with a few small spots which show steel-grey reflections. Occasionally part of the chlorite aggregates are replaced by this type of magnetite.

In this hornfels from Ebenhaezer the strongly poikiloblastic porphyroblasts of cordierite are partly altered to a type of magnetite similar to that which forms the zone around andalusite. It thus appears that two generations of cordierite are present in the rock: the large porphyroblasts which crystallized more or less simultaneously with the andalusite, and a second generation which developed by reaction between the chlorite of the ground-mass and the andalusite. That the andalusite crystals are partly replaced by cordierite is indicated by the preservation of faces of the original andalusite crystal by the outer margin of the cordierite zone and also the more or less concentric disposition of the outline of the andalusite to the outer margin of the cordierite zone. Owing to the larger area which was exposed on the margins of the andalusite crystal to reaction, the remaining andalusite developed into subrounded bodies. The biotite in the cordierite zone, and probably also the cordierite in the chlorite-rich ground-mass, developed more or less simultaneously with cordierite of the second generation, i.e. subsequent to the crystallization of the andalusite, because the andalusite does not contain inclusions of biotite.

In an andalusite-cordierite hornfels from Deelfontein 19, the original idioblastic outline of andalusite porphyroblasts is still preserved in the ground-mass, which is composed of quartz and sericite. In the central parts of the areas bounded by the original crystal faces of andalusite, xenoblastic remnants of andalusite are still preserved. The zone between the andalusite and the ground-mass consists of quartz grains larger than those of the ground-mass, as well as small crystals of biotite. As the andalusite in this rock and in other andalusite hornfelses seldom contains inclusions of biotite, it is evident that the small biotite crystals resulted from the reaction between the andalusite and the ground-mass material, and also that the xenoblastic andalusite did not result from shrinkage owing to the elimination of inclusions.

The last stage in the disappearance of andalusite can be observed in a staurolite hornfels near the contact of the alkali granite on Helena 780, where only pseudomorphs after andalusite indicate the former presence of this mineral (Plate XII B) . These pseudomorphs show a zonal structure, with a core consisting of quartz, surrounded by a zone rich in biotite, followed by a quartz zone and an outer zone of quartz and chlorite. The quartz and the chlorite of the pseudomorphs are much coarser than those of the ground-mass.

In some cases porphyroblasts of biotite have grown around andalusite crystals thus partly or completely surrounding them. In other examples, clear crystals of cordierite have developed on the margins and in the outer zones of the andalusite porphyroblasts.

The examples described above indicate that under conditions of low grade metamorphism andalusite crystallized in excess of its stoichiometric ratio for conditions of high-grade metamorphism. With the increase of metamorphic grade other aluminous silicates become stable phases and react with andalusite to form new aluminous minerals, e.g.

chlorite + andalusite = cordierite.

The chlorite is a magnesian type (penninite) which would be an ideal base for the formation of cordierite. At a still higher grade of metamorphism, the andalusite is replaced by staurolite. This is fully described under staurolite. Occasionally the andalusite is altered to sericite, the aggregates of which form partial or complete pseudomorphs after andalusite.

On a strike-fault above the thick Government Reef quartzite (G.R.Q.3) on Koedoesfontein 12 (Plate 1, Sheet 3) an andalusite schist is found. The andalusite idioblasts are up to 1 cm in length, are turbid under the microscope owing to alteration to sericite, and are usually surrounded by a narrow zone of chlorite. The sedimentary laminae in the rock are finely folded. Crystals of andalusite cut across the lamination of the rock, but the included part of the lamination is not folded. It therefore appears that the andalusite crystallized before the folding of the laminae, thus representing resistant knots in the rock during the folding.

4. The Physical Conditions of Formation of Al_2SiO_5 Polymorphs

In the metamorphic rocks of the Vredefort Dome only two of the Al_2SiO_5 polymorphs are present simultaneously in the same rock namely, andalusite + kyanite and andalusite + sillimanite.

Andalusite is stable under quite a large range of temperature conditions, i.e. it started to crystallize before biotite in some of the slates and is found up to the contact with the alkali granite together with sillimanite. As already noted above, it probably recrystallized on the contact, which indicates that both andalusite and sillimanite were stable phases under the physical conditions prevailing at the granite contact.

Kyanite on the other hand, is associated with chloritoid and andalusite in the knotted quartzite. It is also found together with andalusite and staurolite in hornfels a few hundred yards away from the contact with the alkali granite where it has developed by the transformation of andalusite. The transformation of andalusite to kyanite and to sillimanite is probably a sluggish process as only small amounts of sillimanite and kyanite have developed from the andalusite. From the occurrence of kyanite it is evident that it is stable in nearly the same temperature range as andalusite, except that it begins to crystallize at a slightly higher temperature than andalusite. According to Francis (1956, p.354), kyanite is known in the almandine zone, i.e. at a higher temperature than that of the biotite zone in the Barrovian type of metamorphism.

As all three polymorphs of Al_2SiO_5 are found near the alkali granite and probably also developed during the same metamorphic event, one can assume that the temperature and pressure conditions in the vicinity of the alkali granite were very near to triple-point conditions, i.e. those conditions under which all three polymorphs are stable.

Several workers have constructed a phase diagram for the Al_2SiO_5 polymorphs (see Newton, 1966, Fig. 2). Pressure values for the triple point, according to different workers, range between 2.5 and 9 kilobar and the temperature range between 300°C and 500°C. The diagram constructed by Newton is preferred, because the values for the triple point (4 kilobar and 500°C) closely correspond to the pressure and temperature conditions under which subsolvus granite crystallizes, i.e. above P_{H_2O} = 4 kilobar and below 650°C (Tuttle and Bowen, 1958, p.71 and Fig. 17; Luth, Jahns and Tuttle, 1964, p.764). These are the conditions under which the alkali granite of the plutons along the Vaal River have crystallized.

According to Halferdahl (1961, p.99) and Francis (1956, p.326) chloritoid is replaced by staurolite with increase in temperature. The association of andalusite, kyanite, and chloritoid then represents a lower temperature assemblage than the andalusite-kyanite-staurolite assemblage. The curve for the temperature-pressure gradient for the metamorphism caused by the alkali granite in the Vredefort Dome (Fig. 15, curve A. p·196) begins in the andalusite field at a temperature below the chlorite-biotite curve (lowest grade). With increase in grade of metamorphism towards the alkali granite, this curve follows the andalusite-kyanite boundary-curve in the chloritoid field and cuts the chloritoid- staurolite curve, and still follows the andalusite-kyanite curve in the staurolite field, until eventually it leaves this boundary curve and cuts the andalusite sillimanite curve near the triple point. This P T curve is based on the following mineral assemblages :

(1) chlorite-andalusite,
(2) chlorite-biotite-andalusite,
(3) chloritoid-andalusite-kyanite,
(4) andalusite-staurolite-kyanite-biotite,
(5) andalusite-staurolite-sillimanite-biotite,
(6) biotite-sillimanite.

Field and petrographic evidence indicates that the triple point for Al_2SiO_5 lies in the stability field for staurolite, as all three polymorphs are found within a short distance from the alkali granite in the staurolite zone. Staurolite begins to develop under slightly lower-grade conditions than those for the triple point. The transformation of andalusite to kyanite takes place at slightly lower temperature than its transformation to sillimanite.

A problem arises from the fact that kyanite is abundantly developed in the andalusite-kyanite hornfels(knotted quartzite) in the Upper Division of the Witwatersrand System and is practically absent in the Lower Division of the Witwatersrand System except for small amounts in the lower part of the Government Reef Series on Helena 780, where it is a product of a higher grade of metamorphism. Andalusite is the polymorph which is abundant in the Lower Witwatersrand rocks.

Field evidence indicates that the alkali granite was emplaced after the formation of the dome or at least during the closing stages of the main tectonic event. As the isograds of metamorphism have a zonal distribution around the alkali granite plutons, it is possible that similar conditions of pressure and temperature as those that obtained in the Upper Division of the Witwatersrand System could also have prevailed in certain parts of the Lower Division of the Witwatersrand System. If so, the question that arises is, why was kyanite-andalusite the stable assemblage in one area and only andalusite in the other?

Pitcher (1965, p.334) refers to several cases which suggest that the composition of the rock has a controlling influence on the development of andalusite. Contact-metamorphic rocks from Donegal which contain andalusite are richer in Mg and Fe than rocks which contain its polymorphs. A chemical analysis (Appendix B, No.40) of the chloritoid-andalusite-kyanite hornfels (knotted quartzite) shows that it is poor in Mg and Fe and extremely rich in Al, whereas both Mg and Fe are major constituents in the hornfelses of the Lower Division of the Witwatersrand System. It is possible that Mg and Fe have a stabilizing influence on the formation of andalusite under conditions where both andalusite and kyanite should be stable if they were formed from pure constituents without the intervention of foreign ions.

Another possible explanation is that andalusite developed in the Lower Division of the Witwatersrand System during a low-grade contact-metamorphism caused by the central pluton. At a later stage the plutons of alkali granite were intruded and caused a further or superimposed contact-metamorphism in the Lower Witwatersrand rocks and an extension of the metamorphic aureole into the Upper Witwatersrand quartzites which had been only slightly influenced, or not at all, by the first stage of metamorphism. In the Lower Division of the Witwatersrand System andalusite already existed, but recrystallization of the rocks was probably not complete so that, although physical conditions were such that both andalusite and kyanite could have crystallized, andalusite underwent only further growth and where the temperature was high enough (e.g. in the staurolite zone) it was mostly taken up in the formation of staurolite or the andalusite began to transform to kyanite, e.g. on Helena 780. In the Upper Division of the Witwatersrand System both polymorphs began to nucleate simultaneously from the original low-temperature sedimentary material and thus crystallized together. This possibility of polymetamorphism is discussed later.

5. Cordierite

With the exception of biotite, cordierite is the most abundant metamorphic mineral in the different hornfelses of the Witwatersrand System. Stratigraphically, the first development of cordierite is found in a band between the ferruginous Water Tower slates and the Speckled Bed and in the banded hornfels below the Lower Hospital Hill quartzite. Between the Upper and Lower Hospital Hill quartzites (H.H.Q.3) cordierite hornfels is the most common rock-type. A light-coloured coarse-grained cordierite hornfels follows directly above the Upper Hospital Hill quartzite. Higher up in the Government Reef Series, cordierite is found as an accessory constituent in the thick andalusite hornfels above G.R.Q.1 and again abundantly in a thick cordierite hornfels on top of this andalusite hornfels. Directly above the thick Government Reef quartzite (G.R.Q.3) cordierite is found in an andalusite hornfels.

The crystals of cordierite are usually round or oval and can easily be recognized in the field where, owing to weathering, a pitted surface is produced on the surface of the rock. The size of the cordierite crystals ranges from microscopic dimensions to about 1 cm in length. The cordierite usually forms strongly poikiloblastic porphyroblasts, containing in some specimens up to about 75 per cent of inclusions, a feature which renders the determination of optical constants practically impossible. The inclusions consist mostly of quartz with smaller amounts of magnetite, chlorite, and biotite.

A hornfels developed from a slate in the dolomite on Rietfontein 163 consists mainly of cordierite which forms small interlocking grains, about 0.1 mm in diameter, as well as scattered porphyroblasts, about 1.0 mm in diameter. Simple and lamellar twinning are frequently shown by the porphyroblasts and occasionally trillings are present. The cordierite in the ground-mass is usually untwinned except for the occasional occurrence of simple twins and trillings. As the rock contains only accessory amounts of quartz, the cordierite is remarkably free from inclusions.

In the Vredefort Dome the cordierite porphyroblasts invariably show different degrees of alteration. Alteration is especially marked on the margins of crystals where biotite is in contact with cordierite. The most common product of alteration is a greyish mineral with a very small grain-size which usually forms small prismatic crystals up to 0.1 mm long and 0.02 mm thick. It was identified by Hall and Molengraaff (1925, p.146) as ottrelite. This mineral is length-slow, whereas ottrelite is length-fast. Owing to the smallness of the grains it is difficult to determine optical properties. Under high magnification this mineral has a pale greenish-yellow colour. Where the cordierite contains abundant inclusions of biotite, crystals of this mineral are also abundantly developed and are grown on to the biotite which is frequently corroded. In some rocks the andalusite is partly replaced by a similar greyish mineral which forms prisms up to 0.25 mm in length. It is also length-slow and shows parallel extinction. In rare cases it shows a very feeble pleochroism in colours similar to that of staurolite. It is possible that this mineral is staurolite.

In a coarse-grained andalusite hornfels above the first Government Reef quartzite (G.R.Q.1) on Koedoeslaagte 59 pseudomorphs after cordierite consist of muscovite and small crystals of staurolite and garnet. In the formation of these pseudomorphs a potassium-bearing mineral (biotite) would have had to break down to supply the potassium for the formation of muscovite. As both staurolite and muscovite are richer in aluminium than cordierite and biotite, extra aluminium was probably derived from andalusite. Such a reaction can be represented as follows :

$H_4K_2(Mg,Fe)_6Al_2Si_6O_{24}$ + $(Mg,Fe)_2Al_4Si_5O_{18}$ + 6 Al_2SiO_5
(biotite) (cordierite) (andalusite)
+ 2 H_2O = $H_4K_2Al_6Si_6O_{24}$ + 2 $H_2(Fe,Mg)Al_4Si_2O_{12}$ +
(water) = (muscovite) + (staurolite)
2 $(Fe,Mg)_3Al_2Si_3O_{12}$ + SiO_2
(almandine) + (quartz)

As both staurolite and almandine are usually iron-rich minerals, the biotite and cordierite are probably also iron-rich.

Frequently large porphyroblasts of cordierite are traversed by cracks along which abundant prisms of the greyish mineral mentioned above are developed. In some instances the cordierite is recrystallized to a fine-grained aggregate with a fibrous habit; the fibres are orientated more or less perpendicular to the cracks. Some pseudomorphs after cordierite contain smaller pseudomorphs after a micaceous mineral (probably biotite) and consist of quartz, sericite, chlorite, and magnetite.

Two generations of cordierite are present in some hornfelses:

(1) large strongly poikiloblastic porphyroblasts which are usually altered, and

(2) small clear round to oval crystals (Plate XIII A) which are frequently zoned and not strongly poikiloblastic.

The last-named cordierite crystals form inclusions in the large cordierite porphyroblasts and also independent crystals in the ground-mass or inclusions in some crystals of andalusite. The hornfels from Ebenhaezer 498 described above, also contains two generations of cordierite. The first generation of cordierite is represented by the highly altered porphyroblasts in the hornfels and the second generation forms a zone of small crystals around the andalusite. This cordierite developed by reaction between the andalusite and the chlorite of the ground-mass.

Occasionally cordierite porphyroblasts are intergrown with biotite. The cordierite in a garnet-amphibole hornfels in the Dominion Reef System on Rietpoort 66, west of the road between Potchefstroom and Parys, shows a distinct (010) cleavage and lamellar twinning. It is not poikiloblastic but is partly altered to the greyish mineral described above.

The alteration of cordierite and the development of a second generation of cordierite indicate changes in the physical conditions during metamorphism or, as is probably the case, these phenomena are the result of polymetamorphism.

6. Chlorite

Chlorite is a constituent of several hornfelses in the Vredefort Dome, usually in accessory amounts, but it is an essential constituent in some hornfelses where it forms the ground-mass together with quartz. In the first case it is usually closely associated with biotite. The chlorite has a low birefringence (sometimes nearly isotropic) or it shows anomalous indigo-blue interference colours (penninite) which indicates that it must be a magnesium-rich variety. Chlorite is not only restricted to the zone of low-grade metamorphism, but is also present in the staurolite zone. Yoder (1952, p.576, 579) has shown from experiments on the system $MgO-Al_2O_3-SiO_2-H_2O$, that clinochlore is stable at temperatures up to 520°- 680°C and aluminous serpentine below 520°C, both at pressures between 2,000 and 30,000 psi. These correspond to temperatures within the sillimanite zone. Chlorite can therefore no longer be regarded as a mineral which is characteristic only of low-grade metamorphism.

7. Garnet

Garnet is a constituent of the more ferruginous rocks in the Water Tower slates, the ferruginous bands between the Lower and Upper Hospital Hill quartzites, and also of ferruginous rocks in the Government Reef Series, and the Jeppestown Series. It is also frequently found in more aluminous hornfelses, but here it is not as spectacularly developed as in the ferruginous rocks. Thin bands of hornfels in the Orange Grove quartzite and directly above it, as well as a thick band above G.R.Q.2, contain more than 50 per cent of garnet. A poorly exposed band, a few inches thick, below the Upper Hospital Hill quartzite contains about 80 per cent of garnet.

The garnet has a refractive index of 1.79 to 1.80. Owing to the abundant inclusions in the garnet a reliable value for its specific gravity could not be obtained. On freshly broken surfaces and in thin sections it has a light pink colour. Partial chemical analyses of the garnet from the garnet hornfels between G.R.Q.2 and G.R.Q.3 indicate that the almandine content ranges from 57.8 to 66.8 per cent and the spessartine content from 0.63 to 3.77 per cent (analyses No. 47, 48, and 49 Appendix B.). Almandine-rich garnet is apparently the rule in calcium-poor pelitic metamorphic rocks.

The garnet usually forms round grains or idioblastic crystals showing (110) faces. The diameters of crystals range from a fraction of a millimetre to about 0.75 cm with an average value between 2 and 3 mm. Occasionally cleavages are developed. Frequently the cores of crystals are strongly poikiloblastic whereas the marginals zone contain relatively few inclusions.

Zonal structure due to the arrangement pattern of the inclusions is often seen. In some garnets narrow zones parallel to the margins of crystals contain abundant inclusions, whereas the outer parts and the cores are relatively free from inclusions, but in other cases poikiloblastic crystals have thin zones which are practically free from inclusions arranged parallel to the crystal faces, giving the impression of a crystal within a crystal (Plate XIII B). A similar phenomenon is also seen in andalusite. The impression is gained that the crystal has grown to a certain stage, followed by an interruption in its growth, after which it underwent further growth to the present form. In the more aluminous types of hornfels, e.g. the thick andalusite hornfels above G.R.Q.1, the garnet porphyroblasts show secondary growths (Plate XIV A) of small garnet crystals on the margins of the large crystals, whereas in the ground-mass individual garnet crystals of a size similar to that of the secondary growths are present. Crystals which show no secondary growths and have sizes of the same order as the large garnet crystals in the ground-mass are enclosed in biotite and andalusite porphyroblasts. Where the garnet is partly included in other porphyroblasts only that part of the garnet crystal which is in contact with the ground-mass shows secondary growths. In the same rock the garnet replaces some biotite and may even be elongated parallel to the cleavages of the biotite, thus forming a partial pseudomorph after biotite (Plate XIV B). This appears to substantiate the interpretation that there was an interruption in the crystallization of the garnet.

According to Sturt (1962, p.65, Fig.3), who plotted the weight percentages of CaO + MnO against FeO + MgO for garnets from pelitic metamorphic rocks, the FeO + MgO increases with increase in metamorphic grade. He also considers this variation to be a more sensitive indicator of metamorphic grade than the presence or absence of one of the index-minerals. In metamorphic terrains where Ca-poor garnets are found, e.g. in the Gosaiyo-Takanuki area in Japan, the decrease in the manganese content is more marked with rising metamorphic grade, whereas in Mn-poor garnets, e.g. the Moines and Dalradian areas, rising metamorphic grade is indicated by a decrease in Ca.

The partial analyses of garnet mentioned above, indicate that with the increase of the metamorphic grade there is a decrease in both the almandine and the spessartine content of the garnet. Miyashiro (1953, p.202) regards this systematic variation in the composition of garnet as related to the decreasing molar volume of garnet with increasing grade of metamorphism. With the decrease in the molar volume, the larger Mn^{++} and Ca^{++} are replaced by the smaller Fe^{++} and Mg^{++}. He also found that with the increase in the grade of metamorphism Mn^{++} is first replaced by Fe^{++} and then by Mg^{++}. Engel and Engel (1960, p.43 and Fig. 9) came to a similar conclusion for the garnets from the Adirondack

Mountains.

Almandine is usually regarded as a typical mineral of pelitic rocks which have undergone regional metamorphism of the middle and higher grades and when it is found in hornfels it is usually manganese-rich. The garnet in the hornfelses of the Vredefort Dome is almandine and is especially abundant in the ferruginous rocks, i.e. those that do not contain biotite. According to Chinner (1962, p.317) the occurrence of almandine in contact-metamorphic aureoles is regarded as the result of abnormal rock compositions (Eskola, 1914, Willemse, 1938), or special physical conditions (Harker, 1939, Tilley, 1926). In the first case the development of almandine is considered to be related to the Mg/Fe ratio of the host-rock.

In the Vredefort rocks almandine is stable from the lowest to the highest grade of metamorphism, i.e. from slate to hornfels on the contact of the alkali granite. Furthermore it is also found in an almandine-hypersthene-magnetite hornfels (pyroxene-hornfels facies) on the contact of a thick dolerite sill on Rebok Kop 290 where the highly ferruginous nature of the rock has been the controlling factor in the development of the almandine.

8. Staurolite

Staurolite is not abundant in the hornfelses of the Vredefort Dome. Megascopic staurolite forms dark porphyroblasts, up to about 0.75 cm in length, in a thin band of garnet-staurolite hornfels between G.R.Q.2 and G.R.Q.3 on Koedoeslaagte 59 not far from the alkali granite. Abundant staurolite is developed in the lower part of the Government Reef Series between G.R.Q.1 and G.R.Q.3 on Helena 780, near the southern contact of the alkali granite, where it forms light straw-yellow porphyroblasts in the hornfels. In the field this staurolite may easily be mistaken for weathered andalusite, but when both minerals are found together the difference is apparent. Megascopic staurolite is also found in a thin band of andalusite-staurolite hornfels near and on the contact of the alkali granite directly above G.R.Q.3 on Helena 780 and Koedoeslaagte 59.

The crystals of staurolite vary from xenoblastic to idioblastic with well developed prism faces; (110) and (010) are frequently seen in cross-sections. When the staurolite is idioblastic,it occasionally shows cruciform twinning.

The staurolite is usually poikiloblastic and contains inclusions of quartz, magnetite and sometimes garnet. Small round and six-sided garnet crystals are abundantly included in the staurolite in the hornfels between G.R.Q.2 and G.R.Q.3 on Koedoeslaagte 59.

The rocks containing staurolite display a hornfelsic texture but occasionally a poorly developed incipient schistosity is shown by the parallel alignment of biotite and sometimes elongated quartz near the porphyroblasts of staurolite. This is not evident in the hand-specimen but only under the microscope.

The development of staurolite can be traced in the hornfelses between G.R.Q.1 and G.R.Q. 4. Staurolite increases in abundance towards the alkali granite. The first staurolite to appear forms small crystals in pseudomorphs after cordierite, but nearer to the outcrop of the alkali granite small skeletal crystals become evident. It is difficult to determine the distance from where staurolite makes its first appearance to the contact of the alkali granite because the configuration of the granite pluton below the surface is not known. Nearer to the alkali granite more fully developed crystals of staurolite appear. Abundant sericite is associated with the skeletal staurolite but disappears again where the staurolite is fully developed near contact of the alkali granite.

During the early stages in the development of the staurolite it often forms rims around andalusite (Plate XV A) which shows a pronounced alteration to sericite. Biotite, which is abundant in the ground-mass, disappears in the immediate vicinity of the xenoblastic crystals of staurolite. This indicates that biotite and andalusite were involved in the formation of the staurolite. As already mentioned above, (p.134) staurolite probably also developed from the reaction between cordierite, biotite and andalusite with muscovite and garnet as additional products.

In the hornfels between G.R.Q.1 and G.R.Q.2 on Helena 780 biotite and andalusite are partly replaced by staurolite which shows the following interesting features (Plate XV B): The crystals are strongly poikiloblastic and contain pseudomorphs after biotite which are practically free from inclusions. These pseudomorphs after biotite have similar sizes and density of distribution within the staurolite porphyroblasts as the biotite in the ground-mass, which is also practically free from inclusions. Although these pseudomorphs after biotite have a random orientation within the porphyroblasts, they are optically continuous with one another and with that part of the crystal which is pseudomorphous after andalusite. In some examples faces of the staurolite cut biotite crystals or the staurolite partly replaces andalusite. In a staurolite-andalusite hornfels on Helena 780, about half a mile from the Vaal River on the western slopes of the ridge formed by the upper quartzite of the Hospital Hill Series, the xenoblastic crystals of staurolite consist only of replaced biotite crystals without the additional replacement of other minerals in the ground-mass. Where andalusite is partly replaced by staurolite, that part of the staurolite porphyroblast which is pseudomorphous after andalusite has morphological features which are similar to that of the original andalusite. In this rock there is no sericite associated with the staurolite. The hornfels on

Helena 780 which contains pseudomorphs after andalusite (Plate XII B) also contains staurolite similar to that of other hornfelses on Helena but this staurolite is not closely associated with the pseudomorphs.

The features of the staurolite described above indicate that on Helena 780 it developed at different crystallization centres in the ground-mass and that the material needed for its formation was extracted from other minerals by diffusion to the nuclei of the staurolite.

The rocks which contain the staurolite described above, also contain cordierite and andalusite. The amount of andalusite ranges from a few scattered crystals to about 20 per cent in areas away from the alkali granite, where no staurolite is developed. Where staurolite is abundant, cordierite is absent or is only an accessory constituent. This indicates that cordierite is also involved in the formation of staurolite. Staurolite, however, is absent from a hornfels consisting mainly of cordierite, biotite and quartz, and which lies adjacent to the hornfelses described above. This is probably due to too low an aluminium content, and possibly also too low an iron content of the rock.

Staurolite, then, develops in rocks which have an appropriate bulk composition, provided that the physical conditions are such that it is a stable phase. It is also evident that staurolite does not develop owing to a possible instability of the original minerals of the rock, because the original minerals, e.g. cordierite, biotite, chlorite and andalusite in rocks which do not have the appropriate composition, persist under the stability conditions of staurolite. These minerals become unstable owing to the development of staurolite. A high aluminium content and a high Fe^{++}/Mg ratio is necessary for the development of staurolite.

9. Chloritoid

An alteration product of cordierite was described by Hall and Molengraaff (1925, p.146) as chloritoid, but as already shown above this identification is doubtful. In a hornfels from the lower part of the Government Reef Series on Koedoeslaagte 59, grains up to 0.3 mm in length can definitely be identified as chloritoid. These crystals show lamellar twinning, a birefringence of 0.007, oblique extinction, large $2V_z$, and pleochroism from nearly colourless to pale bottle-green. Here it is not an alteration product of cordierite, but seems to have developed from biotite and chlorite in the ground-mass. A further search for chloritoid in this vicinity was unsuccessful.

Megascopic chloritoid is present in small lenses of slate in some of the knotted quartzites and in the quartzites of the Kimberley-Elsburg Series below the conglomerate. The (001) cleavage is well developed, pleochroism is weak, and lamellar twinning is common. The associated minerals are andalusite, kyanite and muscovite. The reason for the development of chloritoid and muscovite, and not biotite, is probably ~~due to~~ the low magnesium content of the rock (Appendix B No. 40).

10. Cummingtonite

This mineral is a constituent of the ferruginous hornfelses and is usually associated with garnet especially in the lower part of the Hospital Hill Series. It is also a major constituent in a nearly monomineralic rock which forms a band in the banded cordierite-andalusite hornfels which underlies the Lower Hospital Hill quartzite, and in another thick band in the Government Reef Series directly above G.R.Q.2. It is also present in the hornfelses of the Jeppestown Series.

The cummingtonite ranges in size from grains with a diameter of a fraction of a millimetre to prisms having a length of over 2 cm. Its pleochroism is weak, from a pale yellow to slightly greenish or a darker yellow. Some of the amphibole forms sheave-like bundles showing a bow-tie structure or rosettes of prisms. Usually it does not contain many inclusions but it can be strongly poikiloblastic. The prism faces are usually well developed. Locally the prisms may show a parallel arrangement and impart a schistose structure to the rock.

The cummingtonite grades into green hornblende in some hornfelses, with the hornblende forming the outer rims of the crystals. Twinning on (100) is present. β = 1.662, $2V_z$ = 82°. This indicates that it is a cummingtonite with 55 per cent of grunerite. In a few specimens the amphibole is nearly colourless or very pale green, $2V_z$ = large, $Z^\wedge c$ = 17° indicating tremolite.

11. Anthophyllite

Orthorhombic amphibole was found in only one specimen of hornfels from Koedoesfontein 12 near the small dykes of wehrlite not far from the school. The value $2V_x$ = 80°, indicates anthophyllite. The crystals are xenoblastic with poorly developed cleavages and they are associated with cummingtonite to which they appear to have altered or transformed.

12. Hornblende

Hornblende is usually found in the ferruginous rocks of the Water Tower slates, in thin bands in the Government Reef Series, and in a hornfels in the upper part of the Dominion Reef System on Spitskop 706. Its pleochroism is strong, from straw yellow to apple green. Prism faces and a basal parting are developed in some crystals. Usually, the hornblende has a small grain-size but porphyroblasts up to 4 mm were observed, some of which are twinned on (100). Compared with garnet, cordierite, or andalusite, inclusions are absent or very few. $2V_z$ = 60°, and $Z^\wedge c$ = 16°. This corresponds to values found by Willemse (1937, p.66) for this amphibole. He also noted that a similar amphibole is found in the eastern part of the Mesabi Range for which he quotes a chemical analysis, which when plotted on a AMF diagram gives a position very near to almandine.

13. Biotite

Biotite is a constituent of all the hornfelses in the Vredefort Dome with the exception of the ferruginous types containing amphibole. It often forms large prophyroblasts up to 0.5 cm in diameter, but usually has a small grain-size and is limited to the ground-mass. The pleochroism is intense from straw yellow to orange brown or olive green. Where detrital grains of zircon are included in the biotite, they cause intense pleochroic haloes around the zircon. The porphyroblasts are usually more poikiloblastic than the crystals of the ground-mass and in rare cases may contain up to about 50 per cent of inclusions. Minerals enclosed in the biotite are quartz, magnetite, muscovite, chlorite and zircon. Some porphyroblasts show a parting which makes an angle of about 35°with the(001)cleavage.In a hornfels from the lower part of Government Reef Series on Koedoeslaagte 59 a reddish-brown biotite shows a thin margin of chlorite on the (001) faces of the crystals with the (001) of the chlorite perpendicular to the (001) faces of the biotite. In some hornfelses biotite is found as both porphyroblasts and as a component of the ground-mass. It then probably represents two generations, just like the garnet in the same rock.

Small amounts of phlogopite is found in a recrystallized chert in the dolomite on Rietfontein 54.

14. Muscovite

In some of the more aluminous hornfelses muscovite usually forms small sericitic flakes. Porphyroblasts are rare and they are relatively small in comparison with the biotite porphyroblasts. Muscovite is a conspicuous component in the mica schist between the Orange Grove quartzite and the Dominion Reef lava on Koppieskraal 89 and in small lenses in the upper part of the third Government Reef quartzite.

A sparsely disseminated chromium-bearing muscovite in the Hospital Hill quartzites imparts the greenish tinge so often seen in these quartzites. Occasionally thin lenses, a few millimetre thick occur on the bedding planes in the quartzite. One lens of this type contains green tourmaline associated with the muscovite.

15. Plagioclase

Plagioclase is seldom found in the hornfelses except for small amounts in some of the nearly monomineralic cummingtonite hornfelses. The composition of the plagioclase is An_{50-60}. A cummingtonite-almandine hornfels which was analysed by Willemse (1937, Table 111, No. 14) also contains plagioclase. The calcium content of these rocks is probably too low for the formation of tremolite instead of cummingtonite.

16. The Iron-oxide Minerals

Iron oxides are common accessory minerals of the hornfelses. They are mostly magnetite. In some bands in the Water Tower slates magnetite is an essential constituent. It is also abundant in most of the amphibole-garnet hornfelses.

17. Quartz

Quartz is an essential constituent of all the varieties of hornfels in the Vredefort Dome except in the nearly monomineralic cummingtonite hornfelses. Quartz usually has a small grain-size but becomes slightly coarser in grain in the hornfelses of the highest grade.

B. Metamorphism Caused by Mafic Sills

The metamorphism caused by the mafic sills (epidiorite, dolerite etc.) is very inconspicuous in the Vredefort Dome. In the zone of high-grade metamorphism its effects on the country-rock was obliterated by the later metamorphism. Outside this zone, metamorphism which resulted from the intrusion of sills is limited to a narrow zone of induration on the contacts of these intrusions. The only exception is the thick dolerite sheet on Rebok Kop 290 and Nooitgedacht 89 which is intrusive into the Jeppestown Series. Within a few yards from the contact the grade of metamorphism attained corresponds to that of the pyroxene hornfels facies. Nel (1927, p.79) describes the rock as a hypersthene granulite. It is a fine-grained dark-coloured hornfels composed of garnet, orthopyroxene (ferrohypersthene-eulite), magnetite and quartz. In some bands garnet is absent.

C. Texture of the Pelitic Metamorphic Rocks

An isotropic fabric is characteristic of the hornfelses in the Vredefort Dome. A porphyroblastic texture is common owing to the development of porphyroblasts of cordierite, andalusite, garnet, staurolite, and in places also biotite and amphibole. When a mineral forms porphyroblasts it is seldom also a constituent of the ground-mass. The porphyroblastic texture is not so prominent in the ferruginous types of hornfels, but when the rock contains garnet it is usually porphyroblastic and in a few places porphyroblasts of hornblende are also present.

The more sandy (quartzose) hornfelses are fine-grained and not porphyroblastic owing to the absence of cordierite, andalusite and other typical metamorphic minerals. This type of hornfels usually consists of biotite and/or muscovite and quartz. The andalusite-kyanite hornfels (knotted quartzite) of the Kimberley-Elsburg Series has a glomeroporphyroblastic texture; the knots are composed of several crystals of kyanite or andalusite and kyanite.

The original sedimentary features, such as laminar stratification, are well preserved in the different hornfelses and also in the knotted quartzite. These features are actually accentuated during the metamorphism because the small differences in the composition of alternating bands are shown up by variation in the mineral composition and the abundance of constituent minerals. This proves that deformation and homogenization played subordinate rôles during metamorphism.

In rare cases signs of deformation during recrystallization were observed, e.g. in the andalusite schist on top of G.R.Q.3 along a fault on Koedoesfontein 12 where the deformation probably post-dates the formation of the andalusite. This may also be the result of renewal of the movement along an already existing fault. In some examples there was slight deformation on a limited scale during recrystallization as is shown by the small second-generation cordierite crystals with helicitic structure (Plate XVI A) in a hornfels from the Hospital Hill Series on Rietpoort 66, or by the biotite which "flows" around staurolite porphyroblasts in a garnet-staurolite hornfels on Koedoeslaagte 59.

D. Progressive Metamorphism of the Pelitic Rocks

1. General

There is a progressive increase in the grade of metamorphism towards the alkali granite. The slates of the different horizons in the Witwatersrand System were not all equally susceptible to recrystallization. Those of the Hospital Hill Series, lower part of the Government Reef Series, and some of the bands of impure quartzite in the Kimberley-Elsburg Series were recrystallized to fairly coarse-grained rocks. The grain-size of the different varieties of hornfels is partly a function of the original composition of the rock, e.g. where ferruginous beds alternate with more aluminous ones, the last-named are usually much coarser-grained then the ferruginous types. This phenomenon has been observed in areas where both types can safely be considered to have been subjected to similar conditions of temperature and pressure.

To study progressive metamorphism the best results will be obtained by selecting a bed which has a nearly constant bulk chemical composition. Such rocks should also be sensitive to changing physical conditions, i.e. the chemical composition should be such that minerals which are stable only under limited physical conditions would develop from it. In the Vredefort Dome some of the aluminous types are best suited for this purpose. However, poor exposure and rapid variation across the bedding renders the selection of such beds difficult. Lateral variation militates against some of the beds which would otherwise be suitable, as they are not found near or in contact with marker-beds of quartzite. Furthermore, as the highest grade of metamorphism is attained on the contacts of the alkali granite which outcrops only in small areas, the aluminous beds which are in contact with the alkali granite are also limited in number. Extensive faulting also complicates matters.

However, two bands, one a thick cordierite-andalusite hornfels in the lower part of the Government Reef Series, which forms prominent outcrops along the middle slopes of the ridge of Upper Hospital Hill quartzite and the other a narrow band of andalusite hornfels overlying the thick Government Reef quartzite (G.R.Q.3) proved to be the most suitable. In both of them, however, small variations across the stratification do occur. A third band which was also found to be suitable is a garnet-amphibole hornfels between G.R.Q.2 and G.R.Q.3.

2. Andalusite Hornfels above the Third Government Reef Quartzite

Andalusite was the first mineral to crystallize and forms sparsely disseminated porphyroblasts of about 5 mm in diameter in the slate. Small flakes of sericite are quite common but biotite is not present. At a higher grade small porphyroblasts of cordierite and aggregates of biotite develop more or less simultaneously. The andalusite porphyroblasts have at this stage increased in size (about 10 mm in length) and abundance, and sericite has a larger grain-size than in the first stage.

When the hornfels stage is reached, andalusite has decreased in size (about 2.5 mm) and so has the number of inclusions in the mineral. Biotite forms distinct flakes, whereas the grain-size of muscovite remains small and has also diminished in amount. Cordierite has increased in grain-size and the number of inclusions in it has decreased. Cordierite is also partly altered to the greyish mineral described above (p.133). Biotite in contact with cordierite is partly digested in this process and chlorite appears as a by-product. A few small crystals of staurolite have developed at the expense of biotite and andalusite. Quartz has a larger grain-size than in the slate.

Towards the contact of the alkali granite staurolite increases in abundance. In a hornfels about 50 yards from the contact, staurolite is one of the major constituents. Here muscovite is an accessory constituent but the crystals are larger than those of biotite. Sillimanite (fibrolite) has developed from andalusite and is in places closely associated with biotite. Some andalusite crystals show a zonal structure owing to a thin zone which is practically free from inclusions and which is parallel to the crystal faces (Plate XI A). Cordierite has disappeared nearly completely.

A hornfels on the contact with the alkali granite consists of andalusite, staurolite, biotite, and quartz. The andalusite (about 0.5 mm in diameter) is xenoblastic and does not form distinct porphyroblasts as in the previous stage. Cordierite has completely disappeared, but the sillimanite is similar to that of the hornfels about 50 yards away from the contact.

3. Hornfelses between the First and Second Government Reef Quartzites

In some of these hornfelses cordierite is a conspicuous constituent and andalusite is either absent or present as a minor constituent only. Where andalusite is abundant, cordierite is not so prominently developed. Biotite and quartz are essential minerals. Some of the hornfelses contain chlorite and garnet. Staurolite is only developed in the higher grades.

Owing to poor exposures and extensive strike-faulting the change from slate to hornfels could not be followed, but changes from hornfelses of low grade to rocks of higher grade are well displayed on Koedoesfontein 12, Koedoeslaagte 59, and Helena 780.

In the hornfelses of the lower grades biotite is only a constituent of the ground-mass, but with increase of the metamorphic grade it also forms large porphyroblasts together with the biotite of the ground-mass. When staurolite is prominently developed both the porphyroblasts and the biotite of the ground-mass are replaced by biotite with an even grain-size. This biotite is coarser than the biotite in the ground-mass of the hornfels of the lower grade. The colour of the biotite has changed from a dark brown or greenish brown to a reddish brown in the staurolite hornfels, which indicates that its composition has changed with increase in the grade of metamorphism.

Cordierite is abundant in the rocks of the lower grades of metamorphism. It forms large poikiloblastic crystals which are in places associated with round to oval, clear crystals of cordierite. With increase in the grade of metamorphism cordierite is replaced by muscovite and staurolite which are closely associated with small crystals of garnet, When staurolite is abundant cordierite has decreased to a few small, clear, unaltered crystals or it has disappeared completely.

Garnet is stable in the hornfels from the lowest to the highest grade of metamorphism and is found together with or without staurolite. However, the larger crystals show secondary growths (Plate XIV A) or zonal structure as already described (cf. p.137) and are associated with small crystals of garnet in the ground-mass.

Chlorite is a constituent of some of the garnet-andalusite hornfelses but it is greatly reduced in abundance as the grade of metamorphism increases. Quartz shows an increase in grain-size with an increase in the grade of metamorphism.

Andalusite forms large porphyroblasts in rocks of the lower grade and is in places partly replaced by sericite. In such examples andalusite is represented by partial pseudomorphs consisting of small optically continuous "squares" of andalusite with sericite in between. With an increase in the metamorphic grade andalusite is partly replaced by staurolite or by quartz, biotite, and chlorite (Plates XV A, XII B). When staurolite is abundant the associated andalusite is no longer represented by large idioblastic crystals but by small xenoblastic crystals which represent the excess of aluminium after staurolite had formed. Here andalusite shows incipient transformation to kyanite. Kyanite is found only near the alkali granite. In the initial stages of staurolite development sericite is usually closely associated with it, but in the higher grades of metamorphism it disappears.

In both the hornfels bands described above it is evident that staurolite develops at the expense of biotite, cordierite, and andalusite. The reaction can be represented as follows :

$H_4K_2(Mg,Fe)_6Al_2Si_6O_{24}$ + $(Mg,Fe)_2Al_4Si_5O_{18}$ + 16 Al_2SiO_5 +

(biotite) (cordier~~t~~ite) (andalusite)

8 H_2O = 8 $H_2(Fe,Mg)Al_4Si_2O_{12}$ + $H_4K_2Al_6Si_6O_{24}$ + 5 SiO_2

(staurolite) (muscovite) (quartz)

The muscovite eventually disappears through reaction with the chlorite of the ground-mass to form biotite and probably also additional staurolite:

2 $(OH)_8(Mg,Fe)_5Al_2Si_3O_{10}$ + $H_4K_2Al_6Si_6O_{24}$ + 4 Al_2SiO_5 =

(chlorite) (muscovite) (andalusite)

$H_4K_2(Mg,Fe)_6Al_2Si_6O_{24}$ + 4 $H_2(Fe,Mg)Al_4Si_2O_{12}$ + 4 H_2O + 2 SiO_2

(biotite) (staurolite) (quartz)

4. Garnet Hornfels between the Second and Third Government Reef Quartzites

The following changes in the mineralogical composition can be observed from the low-grade hornfels to the high-grade type (Fig. 9): The relative abundance of garnet and cummingtonite increases at the expense of chlorite. The grain-size of garnet increases to a maximum with progressive metamorphism but decreases again in the highest grade. The almandine and the spessartine content of the garnet decrease with progressive metamorphism. The detrital quartz in the low grade has also recrystallized and shows an increase in grain-size towards the alkali granite. Furthermore the number of garnet crystals also increases per unit area in the higher grades.

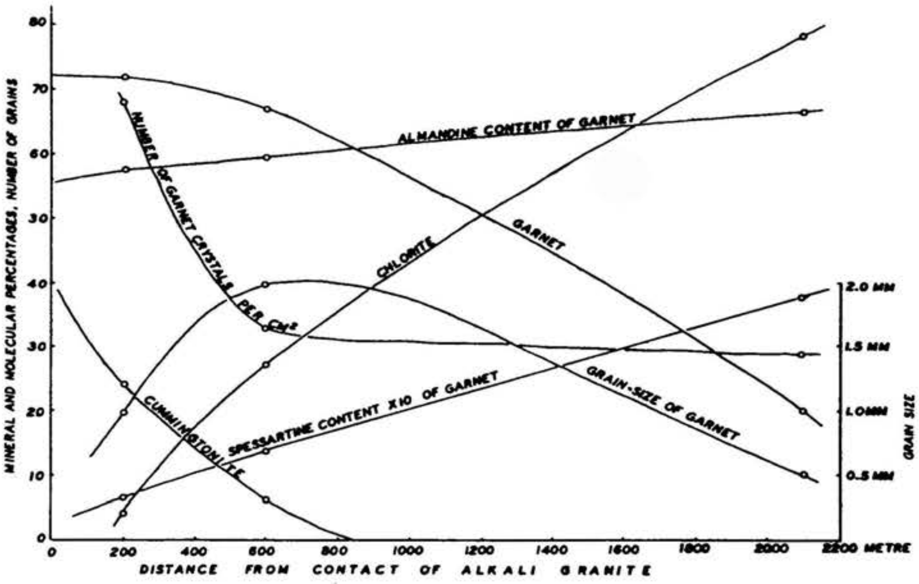

Fig. 9. Variation in the volumetric mineral composition (chlorite, cummingtonite, and garnet recalculated as 100 per cent), chemical composition of garnet, and rate of nucleation of garnet, of the hornfels between G.R.Q.2 and G.R.Q.3.

A phenomenon which is associated with the increase of metamorphic grade is the increase in grain-size of the mineral components, especially the porphyroblasts, e.g. garnet, biotite, andalusite etc.,up to a maximum after which it decreases again. The maximum grain-size for the different minerals is attained in different grades of metamorphism, e.g. andalusite attains its maximum grain-size in a lower grade than garnet. This phenomenon is probably related to the paragenetic sequence of the different minerals.

The relation between crystal growth and nucleation of minerals in metamorphic rocks is apparently different from that of crystallization and nucleation in a liquid. In a liquid (Eitel, 1965, p.15) the maximum rate of crystal growth is at a higher temperature than the maximum rate of nucleation. In metamorphic rocks the opposite seems to be applicable, namely that the maximum rate of crystal growth is at a lower temperature than the maximum rate of nucleation. In this sense then, grain-size will be an indication of an increase in metamorphic grade. Whether the above principle will be applicable to areas where deformation is an important factor during metamorphism is difficult to tell.

The staurolite zone does not form a complete concentric zone around the outcrops of alkali granite (Plate IV), but forms an arcuate zone north-east of the plutons. On the western side the staurolite grade is not attained. This is probably due to the underground configuration of the plutons themselves. Their roofs probably dip eastwards at a low angle. The finer-grained portions of the alkali granite are only on the western side of the plutons, so that the western side represents parts the floor and the eastern side the roof. On Koedoeslaagte 59 the roof is visible in the field (Plate I Sheet 2). Such an interpretation is also in accord with the distribution of the mariupolite dykes which are believed to have developed only in the roof portions of the plutons.

E. Metamorphism of the Dolomite

Calcite and dolomite are the only carbonate minerals in the marbles forming the contact aureole around the alkali granite on Rietfontein 54 and Rietfontein 163. Dolomite is the most abundant of the two carbonate minerals. The dolomite forms interlocking grains about 1.5 mm in diameter. The pure varieties of marble consist nearly entirely of dolomite. The calcite forms small veins or small coarse-grained patches. In such cases it probably was a constituent of the dolomitic limestone before metamorphism.Most of the calcite,however,resulted from dedolomitization, i.e. from the formation of forsterite at the expense of dolomite and quartz, as the calcite forms narrow zones around the forsterite and tremolite in a dolomite ground-mass.

The forsterite is xenoblastic and ranges from 0.1 to 1.5 mm in diameter. It is partly altered to serpentine. Diopside forms thin bands up to about 4 cm thick in the dolomitic marble and, where the original composition allowed it, these bands consist almost entirely of diopside. Diopside forms crystals up to 0.5 cm in length. Some bands contain large crystals of diopside (2-3 mm in diamter) which are surrounded by aggregates of small crystals of diopside (0.1 mm in diameter). Some of the diopside consists of radiating prisms with a prominent salite parting.

On both sides of diopside bands tremolite is present between the diopside and the dolomite ground-mass. The tremolite is separated from the dolomite ground-mass by a thin zone of calcite.

The chert in the dolomite is recrystallized, and has changed to a medium-grained quartzite with a sugary texture. Recrystallization of quartz also occurred in thin laminae and patches in the dolomitic marble.

The chemical reactions which result from the metamorphism of the dolomitic limestone correspond to Bowen's first, second, and third steps in the progressive metamorphism of impure limestones (Turner and Verhoogen, 1960, p.518).

Step 1

$$\underset{\text{(dolomite)}}{5\ \mathrm{CaMg(CO_3)_2}} + \underset{\text{(quartz)}}{8\ \mathrm{SiO_2}} + \mathrm{H_2O} = \underset{\text{(tremolite)}}{\mathrm{H_2Ca_2Mg_5Si_8O_{24}}} + 7\ \mathrm{CO_2} + \underset{\text{(calcite)}}{\mathrm{CaCO_3}}$$

Step 2

$$\underset{\text{(dolomite)}}{2\ \mathrm{CaMg(CO_3)_2}} + \underset{\text{(quartz)}}{\mathrm{SiO_2}} = \underset{\text{(forsterite)}}{\mathrm{Mg_2SiO_4}} + \underset{\text{(calcite)}}{2\ \mathrm{CaCO_3}} + 2\mathrm{CO_2}$$

Step 3

$$\underset{\text{(dolomite)}}{\mathrm{CaMg(CO_3)_2}} + \underset{\text{(quartz)}}{\mathrm{SiO_2}} = \underset{\text{(diopside)}}{\mathrm{CaMgSi_2O_6}} + 2\ \mathrm{CO_2}$$

The formation of forsterite and diopside is dependent on the amount of silica available as both are found together in the same hand-specimen; diopside in bands and forsterite as patches in the dolomitic ground-mass.

F. Classification of the Hornfelses

If ACF diagrams are used as a basis for the classification of the hornfelses in the Vredefort Dome, several difficulties arise. Firstly, the hornfelses are calcium-poor and nearly all minerals present are those lying near the AF side of the triangle. Secondly, in most examples which contain more than one (Mg,Fe)-bearing phase, there is no evidence of disequilibrium. For these reasons Mg and Fe, or more accurately (Mg,Fe) and (Fe,Mg) must be considered as separate components and AMF diagrams are best suited to represent the mineralogical variation of the Vredefort hornfelses. In this type of diagram $A = \mathrm{Al_2O_3}$, $M = \mathrm{(Mg,Fe)O}$, and $F = \mathrm{(Fe,Mg)O}$.

The components A,M, and F can be represented in molecular or equivalent proportions. In Fig. 10 the molecular proportions are used.

Calcium is grouped with the alkalis. Potassium is a component of biotite and muscovite, sodium of hornblende and plagioclase, and calcium of plagioclase and tremolite. Plagioclase and tremolite are rare constituents of the hornfelses. Biotite is present in all the hornfelses except in the highly ferruginous types where hornblende appears instead of biotite. Biotite, muscovite and hornblende can be considered to represent alkali-bearing phases and the amount of (Mg,Fe) extracted from the system is dependent on the amount of alkali present. Similarly the amount of (Mg,Fe) and Al in tremolite and plagioclase respectively, extracted from the system, will be determined by the amount of Ca present and they are calcium-bearing phases.

After allowance is made for the alkali- and calcium-bearing minerals the following are left over : andalusite, kyanite, sillimanite, chloritoid, almandine, cummingtonite, chlorite and cordierite. It is evident from chemical analyses of the above minerals from pelitic metamorphic rocks that they can be subdivided on the basis of their Mg/Fe ratios into magnesium-rich phases (chlorite and cordierite) and iron-rich phases (staurolite, chloritoid, almandine, and cummingtonite).

There are however, a few assemblages which probably represent disequilibrium, i.e. 26, 27, 32 and 33 in the low grade (chloritoid zone), and 28, 29, 30 and 31 in the staurolite zone (Appendix C and, Fig. 10), because there are either two magnesium-rich or two iron-rich phases which are in contradiction to the phase rule, or minerals with a low aluminium content are found together with andalusite in rocks in which a mineral with an intermediate aluminium content could also be a stable phase.

The different mineral assemblages for the metamorphic rocks in the Vredefort Dome and the Rietfontein area are shown in Appendix C, and are

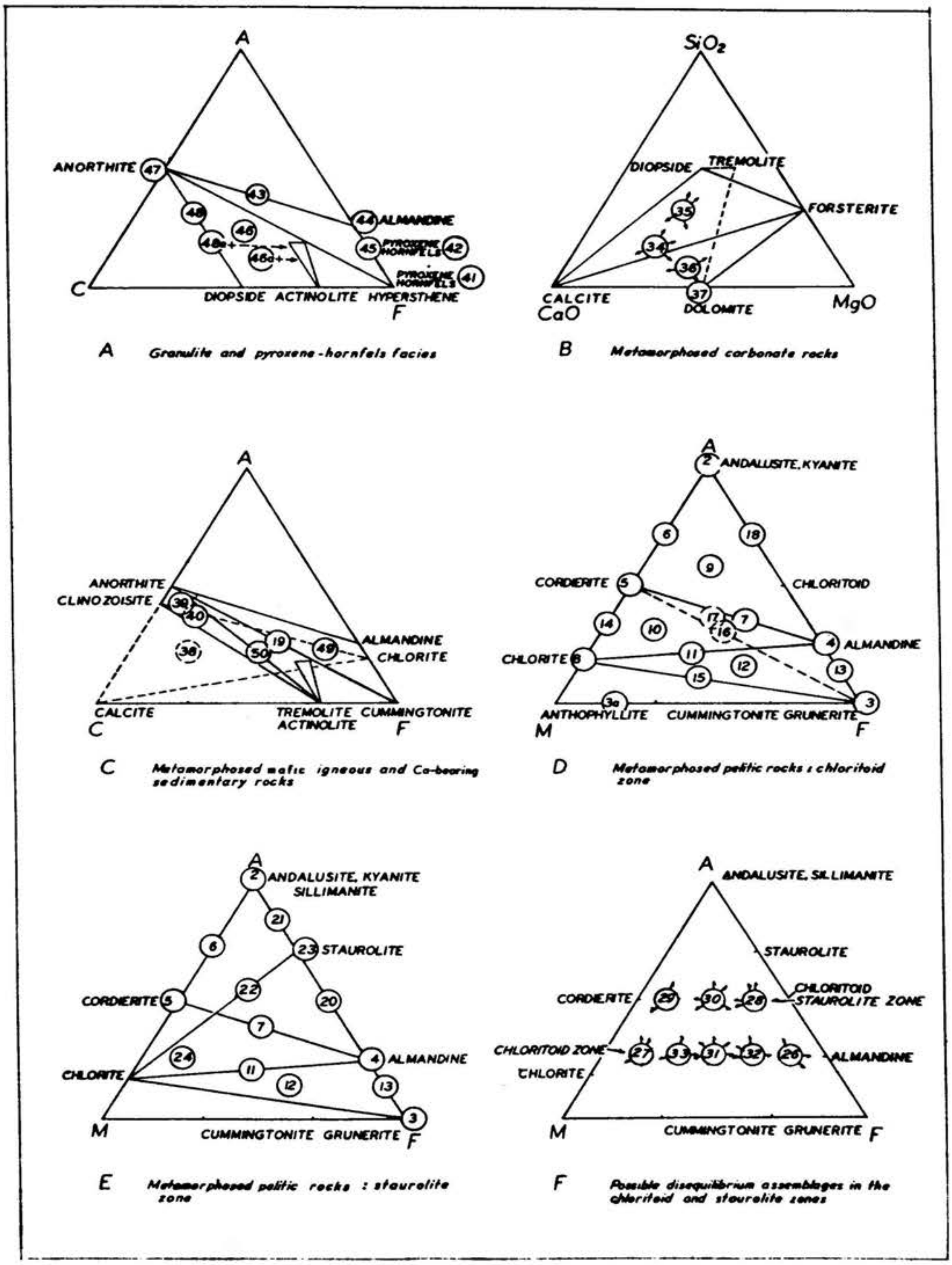

Fig. 10. AMF and ACF diagrams presenting the mineral assemblages of the metamorphic rocks of the Vredefort Dome. The numbers in circles are the assemblage numbers (Appendix C). The arrows point to minerals of which the assemblage shown in the circle is composed.

represented in ACF and AMF diagrams in Fig. 10, which also serve as a classification of the hornfelses.

G. The Chemical Composition of the Metamorphic Rocks

Nine chemical analyses of hornfelses from the Vredefort Dome are represented in Appendix B. Of these, six are new analyses and three are taken from the literature (Willemse, 1937, p.67). Two of Willemse's analyses (No. 42 and 43, Appendix B) and one of the new analyses (No. 38, Appendix B) represent highly ferruginous types (non-biotite-bearing) whereas the others are aluminous types (biotite-bearing). The absence of biotite or muscovite in the highly ferruginous types must be ascribed to the low aluminium content of these rocks. In the ferruginous types, sodium preponderates over potassium, a relationship which is reversed in the aluminous types. This is, no doubt, related to the composition of the original sedimentary rocks.

A linear diagram in which mg, k, and c/10 are plotted against t = al - (c+alk) (Fig. 11) shows that mg slowly increases with an increase in t, whereas c decreases with an increase in t. The curve for k portrays the above-mentioned relation between potassium and sodium clearly. From a t-value of about 25, k decreases sharply with a decrease in t, whereas c increases rapidly. In the analysed rocks, those with a t-value above 25 contain biotite and/or muscovite but both are absent from rocks with a lower t-value. The minerals with a high aluminium content, e.g. cordierite, staurolite and andalusite are only developed in rocks with a t-value higher than 20-25. To substantiate this, analyses of the almandine-cummingtonite-cordiertie assemblage will be necessary. Almandine is the only aluminium-bearing mineral in rocks with a t-value between 0 and 25 but is absent when the analysis of the hornfels has a negative *t*-value.

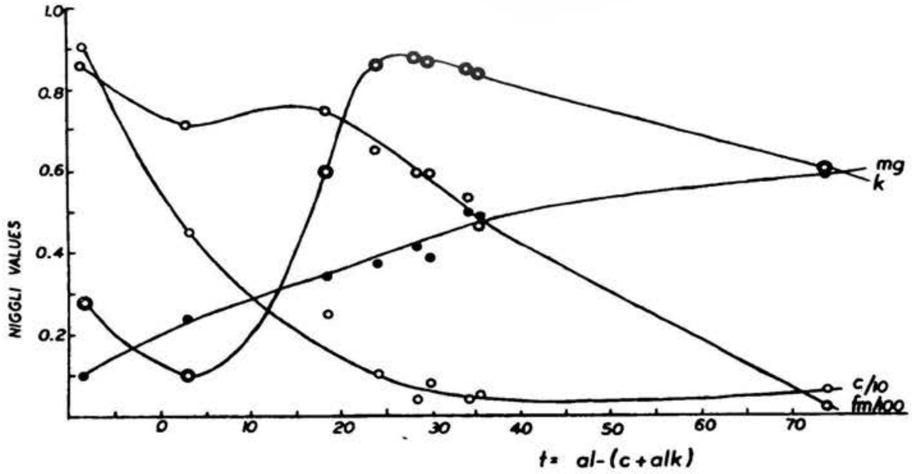

Fig. 11. Linear variation diagram showing *mg*, *k*, *c*/10 and *fm*/100 against *t* = *al* - (*c*+*alk*) of the analysed hornfelses of the Vredefort Dome.

There are several possible ways of calculating the A, M, and F values. The ideal condition would be if a subtraction could be made for the iron-ore-minerals (magnetite, ilmenite and hematite), the alkali-bearing minerals (biotite, muscovite and feldspar) and the calcium-bearing minerals (feldspar and amphibole) so that the remaining Al_2O_3, MgO, and (Fe,Mn)O are represented in the aluminium-, magnesium-, and iron-bearing phases. For such a correction it would be necessary to know the modal percentages of the minerals to be subtracted as well as their chemical composition. However, the strong poikiloblastic nature of some of the constituent minerals makes modal analyses difficult and even unreliable.

Because the metamorphic rocks of the Vredefort Dome do not contain feldspar, a correction for potassium, sodium and calcium in terms of feldspar cannot be effected. As biotite is a major alkali-bearing phase and generally belongs to the siderophyllite-~~annite~~ eastonite series, a correction for A = $Al_2O_3 - 2\ K_2O$ will give a closer approach to the true value for A. However, because muscovite is in places associated with biotite, it will be necessary to estimate these two micrometrically.

The Mg/Fe ratio for biotite will also affect the values for M and F, depending on the composition of the biotite. A correction for biotite is, however, not easily effected because the composition of biotite varies considerably, depending on the associated minerals and probably also on the grade of metamorphism. In ACF diagrams where MgO and FeO are considered to be one component, the discrimination between magnesian and ferroan minerals is not made and therefore a correction for biotite is not absolutely necessary.

Schwellnus (1956, p.49) calculated with the aid of the Niggli norm and from the micrometric determination of staurolite and garnet that the biotite associated with these two minerals has a <u>mg</u> value of 0.43, or $Fe^{++}/Mg = 2.4$ (weight). In his calculations he accepted that staurolite contains practically no magnesium. Juurinen (1956) has collected a considerable number of chemical analyses of staurolite, but unfortunately for only a few the rock-type from which the analyzed staurolite comes is stated. For 12 analyses obtained from the literature, the molecular value for FeO/MgO ranges between 2.0 and 3.9 or the molecular value for MgO/MgO + FeO = 0.2 - 0.33 with an average of about 0.25. Hounslow and Moore (1967, p.16) present seven new analyses from the Grenville schists near Fernleigh, Ontario, in which the total Fe is taken as FeO. The molecular value of MgO/MgO + FeO for these staurolites range from 0.13 to 0.32. This varying Mg/Fe ratio of staurolite will eventually affect the final Mg/Fe ratio for biotite.

To test the assumed constant Mg/Fe ratio for biotite which is by Phinney (1963, p.124), namely that there is a relation between the garnet/staurolite ratio (by volume) and the MgO/MgO+FeO ratio for biotite. This is well illustrated in his Fig. 13 (p.126.) The lowest garnet/staurolite ratios are associated with the lowest Fe^{++} content of the biotite and the highest garnet/staurolite ratio with the highest Fe^{++} content of the biotite. Hounslow and Moore (1967, p.15) show that as the oxidation ratio of the rock increases the Mg^{++} and Fe^{+++} in biotite from the staurolite zone also increases.

The bulk composition of the rock appears to have an influence on the composition of the biotite e.g. a recrystallized chert from the Dolomite on Rietfontein 53 contains phlogopite, whereas the pelitic rocks in the Vredefort Dome and also on Rietfontein 163 contain biotite.

From the above discussion it is evident that the composition of biotite in metamorphic rocks is dependent on a number of factors which include the following : the associated ferromagnesian minerals, the relative amounts of these minerals, the grade of metamorphism, the oxidation ratio of the rock and the bulk composition of the rock. It is possible that the composition of biotite will vary with the grade of metamorphism, but to study such a variation it will be necessary to choose a rock-type with a more or less constant bulk composition which shows different grades of metamorphism. Such a variation in the composition of biotite is shown by the hornfels between G.R.Q.1 and G.R.Q.2 where the colour of biotite changes from greenish brown in the lower grade to reddish brown in the staurolite zone.

Schwellnus (1956, p.17 and Plate 2) describes and illustrates a hornfels similar to the staurolite hornfels between G.R.Q.1 and G.R.Q.2 on Helena 780, referred to above, in which biotite is replaced by staurolite. In this hornfels from Helena, biotite is the only potassium-bearing phase. In both these rocks biotite crystallized before staurolite.

If then biotite should remain constant in composition throughout progressive metamorphism the low-grade biotite must then necessarily be in equilibrium with staurolite in the higher grade. If so, it is difficult to explain why staurolite replaces biotite which is in equilibrium with it. Furthermore, as biotite is a member of a solid-solution series, variation in composition is to be expected under varying conditions of temperature and pressure.

It thus appears that at the stage where staurolite develops the biotite which was originally present changed in composition to produce a new equilibrium with the newly developing staurolite. The development of staurolite takes place under physical conditions more or less similar to those of the transformation of andalusite to kyanite and sillimanite. The aluminium appears to diffuse towards the biotite where the latter is being replaced by staurolite. As staurolite structurally consists partly of kyanite layers,the physical conditions under which andalusite transforms to kyanite should be ideal for the formation of staurolite,if the necessary iron and magnesium are available.

Chemical analyses of minerals from pelitic metamorphic rocks were collected from the literature and plotted on a molecular AMF diagram (Fig. 12). The aluminium contents of the different minerals are taken as those present in the ideal formulae so that only the variation in $MgO/MgO+FeO+MnO$ is presented. However, for biotite the aluminium content was also taken into account. One cordierite analysis, represented by point X, falls a considerable distance away from the cordierite field which represents the range in 27 analyses. The same applies to two analyses of biotite represented by points Y_1 and Y_2. In the case of cordierite this does not necessarily imply the presence of a gap in the cordierite field. Judging from cordierite in the low-grade metamorphic rocks in the Vredefort Dome such cordierites, which are

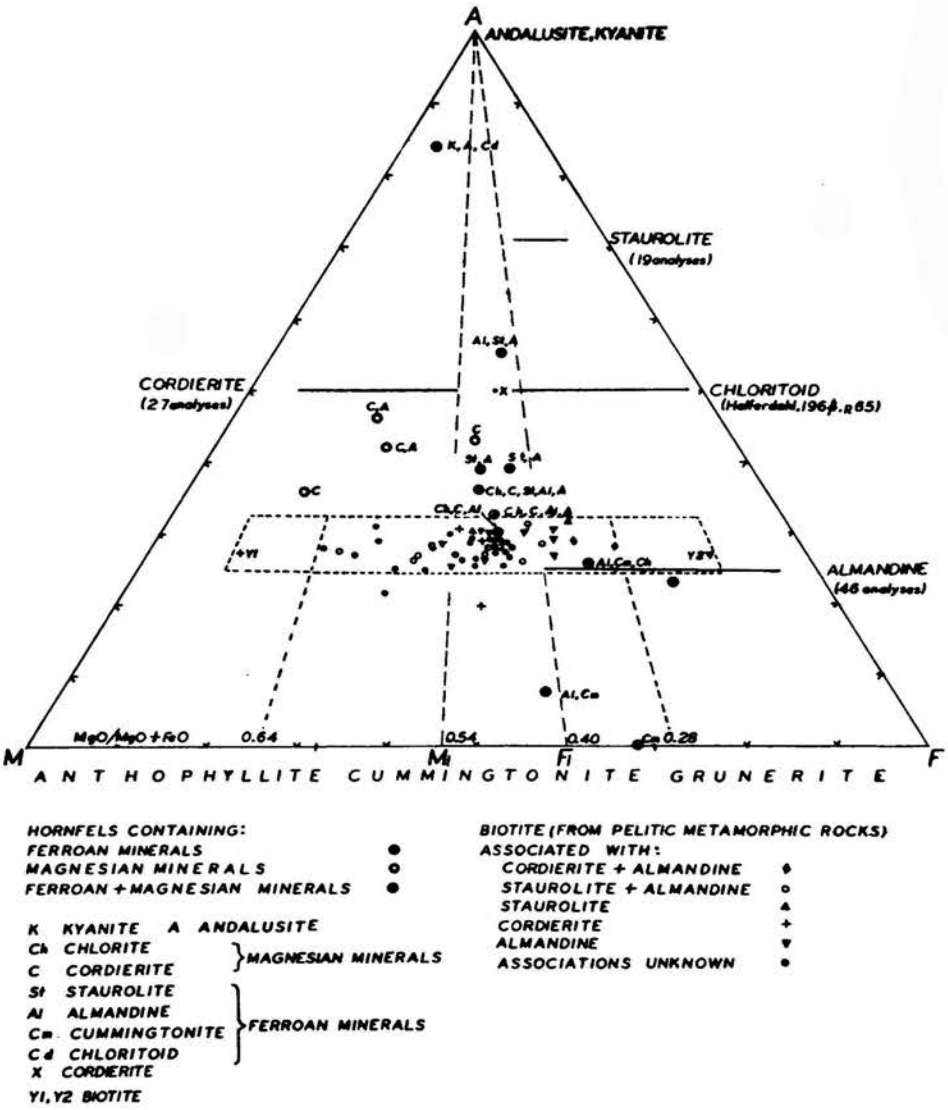

Fig. 12. AMF diagram illustrating variation in MgO/MgO+FeO+MnO (molecular) for analyses of metamorphic minerals from pelitic rocks and analysed hornfelses from the Vredefort Dome as well as other South African examples.

probably iron-rich, are so crowded with inclusions that purifying samples for chemical analysis would be difficult. It thus appears probable that such cordierite will seldom be used for analysis. X probably represents such a cordierite from a low-grade metamorphic rock. A similar situation probably also holds for the biotite Y_2. Y_1 represents a biotite from a magnesium-rich rock which has undergone high-grade metamorphism.

From Fig. 12 it is evident that biotite normally occupies an intermediate position between the ferroan and the magnesian minerals, and has an average MgO/MgO+FeO+Mno ratio of 0.5 for 48 analyses. It thus appears that the presence of biotite in a rock will in most cases not too seriously affect the position of a point in its relation to the MgO/MgO+FeO+MnO ratio of the rock. For practical purposes then (mainly owing to the difficulty of estimating the composition of biotite) the MgO/MgO+FeO+MnO ratio for biotite can be neglected. Where both biotite and muscovite are constituents of the analysed rock a micrometric determination of these two minerals will be necessary in order to correct for them.

The amount of Fe_2O_3, and to a certain extent TiO_2, in the rock will have a pronounced influence on the Mg/Fe ratio of the ferromagnesian silicate minerals, and therefore a correction for magnetite, ilmenite and possibly hematite must also be made.

For the metamorphic rocks of the Vredefort Dome the following procedure was followed after the molecular proportions for the different oxides of the analysis were computed :

$A = Al_2O_3 - 2(K,Na)_2O$ for biotite and $- 3(K,Na)_2O$ for muscovite,

$M = MgO$,

$F = (FeO+MnO) - (Fe_2O_3+TiO_2)$.

For analysis 40 (Appendix B) no Fe_2O_3 was subtracted because the rock contains no magnetite but only haematite. For 43 a correction for plagioclase $Al_2O_3 - (CaO + Na_2O)$ was made. The rocks represented by analyses 35, 37 and 39 contain accessory muscovite which was neglected.

The analyzed Vredefort rocks which contain ferroan minerals, fall within the AFM_1 field (Fig. 12) and those containing magnesian minerals fall in the AMF_1 field. A few other analyses of hornfelses (Willemse, 1959, Table 10, and Schwellnus, 1956, p.44) are also plotted on this diagram (Fig. 12). The rocks containing both ferroan and magnesian minerals mainly fall in the overlap area of the two fields AMF_1 and AFM_1. The subdivision of the AMF triangle is according to the maximum limits of substitution of Fe^{++} for Mg^{++} in magnesian minerals and Mg^{++} for Fe^{++} in ferroan minerals. Of the 48 chemical analyses of biotite from pelitic metamorphic rocks which are plotted on the AMF diagram (Fig.12), 46 have MgO/MgO+FeO ratios between 0.64 and 0.28.

Willemse (1937, p.72, Fig. 10) has plotted c/fm values against mg values for cordierite and garnet-bearing metamorphic rocks. From this diagram it is evident that cordierite is the only ferromagnesian phase when mg is greater than 0.51 and almandine when mg is less than 0.22. The field between mg = 0.22 and mg = 0.51 represents rocks containing almandine alone or both almandine and cordierite. Schwellnus (1956, Fig. 5) has constructed a similar diagram for staurolite and garnet and staurolite-garnet rocks.

Fig. 13 is compounded from the above-mentioned diagrams of Willemse and Schwellnus and a few of the analysed hornfelses of the Vredefort Dome are also plotted. This diagram shows that there is no definite field for staurolite- and staurolite-garnet-bearing rocks. However, these rocks have mg-values below 0.51. It is also evident from Willemse's diagram, as he states, that an increase in calcium favours the development of garnet. For a constant c/fm value, say 0.1, the mg value appears to be a major controlling factor. Both cordierite and garnet are stable between mg = 0.22 and mg = 0.51. In this part of the field the mg value is apparently not the major controlling factor

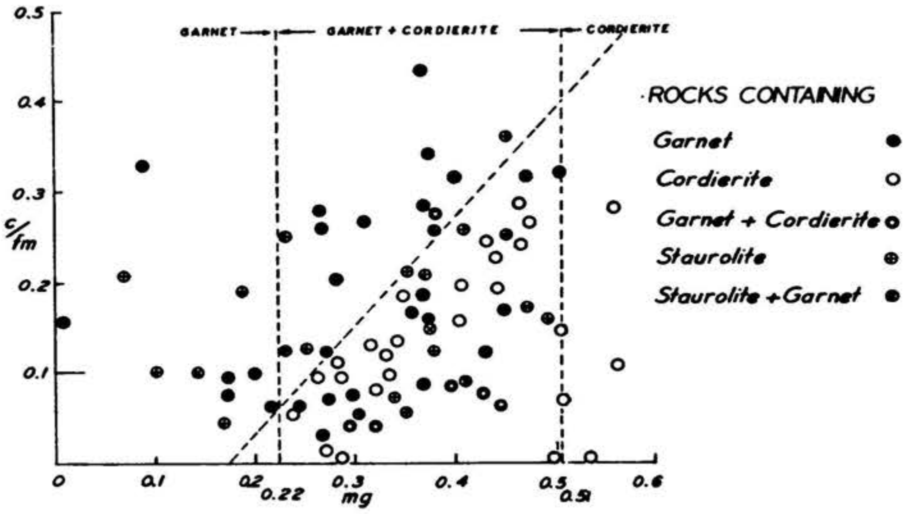

Fig. 13. Variation diagram compounded from Willemse (1937, Fig. 10) and Schwellnus (1956, Fig. 5) with some of the hornfelses of the Vredefort Dome also plotted.

in the formation of cordierite and garnet. Here physical conditions must have a major controlling influence. It is difficult to tell what the physical conditions are, as the stability fields of garnet and cordierite for the different conditions of temperature and pressure are unknown.

The increase in the amount of mutual replacement of Mg^{++} and Fe^{++} with an increase in the grade of metamorphism appears to hold for most ferromagnesian metamorphic minerals. Engel and Engel (1960, p.31) found that there is a decrease in the iron and an increase in the magnesium content of biotite in the Adirondack paragneiss with increasing temperature of metamorphism. They also recognized a similar condition for garnet in the same rocks. Miyashiro (1953, p.192) concluded that the stability field for garnet is enlarged with a rise of metamorphic grade because high-grade garnets are more magnesium-rich than low-grade garnets (see his Figs.6 and 7). According to Woodland (1963, p.364) Wones has shown that at high temperatures the biotite produced has a higher Mg/Fe ratio than at low temperatures. In the high-grade metamorphic facies, e.g. the pyroxene hornfels and granulite facies, Mg^{++} and Fe^{++} appear to substitute for one another to such an extent that Mg^{++} and Fe^{++} can be treated as one component. For a particular ferromagnesian mineral the species containing the higher amount of Mg is the high-grade one, whereas the low-grade species will be the ferroan one. This shows correspondence to the sequence of fractional crystallization in igneous ferromagnesian minerals, e.g. pyroxene and olivine.

Acceptance of the above statement implies that magnesian and ferroan minerals can co-exist as separate phases under low-grade conditions and that one of them can disappear at higher grades owing to an increase in the mutual substitution of Mg^{++} and Fe^{++}. Furthermore the Mg/Fe ratio will have a controlling effect on the formation of magnesian and ferroan minerals up to a certain stage and thereafter physical conditions become the controlling factors.

VIII. METAMORPHISM OF THE MAFIC IGNEOUS ROCKS

A. Nomenclature

A group of mafic rocks described by Hall and Molengraaff (1925, p.48-50) as epidiorite is intrusive into the Archaean granite (their "interior marginal intrusions") and the Witwatersrand System (their "exterior marginal intrusions"). The Basal Amygdaloid, the Jeppestown Amygdaloid, and Nel's (1927, p.59) "slaty looking igneous rocks" can also be included in this group.

The Basal Amygdaloid is a fine-grained rock which Hall and Molengraaff (1925, p.24) described as a hornblende granulite because of its "pronounced granulitic micro-structure". The texture is not similar to that of typical granulites as amphibole usually forms elongated prismatic or irregular crystals. Furthermore this rock is not the result of high-grade metamorphism which is characteristic of the granulite facies. It is therefore more appropriate to include it with the epidiorites because it represents only a fine-grained variety of epidiorite and fits the definition given by Hall and Molengraaff (1925, p.50) for epidiorite better than that of granulite. Turner (Williams, Turner and Gilbert, 1954, p.243) uses the term epidiorite for rocks with a composition similar to that of amphibolite and which are weakly foliated or not foliated so that they can hardly be distinguished from igneous diorites. Tyrrell (1938, p.311) also includes altered mafic lava with altered mafic intrusive rocks under epidiorite, provided that the original texture is not completely destroyed.

B. Age of the Epidiorite Intrusions

The relative age of the Basal Amygdaloid and the Jeppestown Amygdaloid leaves no doubt about their position in the stratigraphic sequence, but there are problems attached to the relative age of the epidiorite intrusions. Hall and Molengraaff (1925, p.92) and Nel (1927, p.60) consider all the mafic intrusions and the alkaline rocks as belonging to the same period of magmatic activity i.e. of the same age as the Bushveld Complex. Hall and Molengraaff (1925, p.48-51) find it difficult to explain why a high pressure such as they postulated should leave a gabbro unaltered in one place and convert another close by into epidiorite. They distinguish six stages in the process of epidioritization. Occasionally small amounts of alteration are displayed by some of the unaltered rocks of the tholeiitic suite described above, and rarely a few remnants of pyroxene may be found in the epidiorite, thus giving the impression that there is a possible relation between them. Their first three stages of epidioritization are seldom encountered, the first two being the result of autometamorphism of the unaltered tholeiitic intrusions and the third representing the rare examples in which a few remnants of pyroxene are present in amphibole. Their fourth and fifth stages are typical epidiorites.

During the course of mapping in the Vredefort Dome it was possible to distinguish in the field between epidiorite and the unaltered mafic rocks. The epidiorites are green on weathered and darker green on freshly broken surfaces, whereas the unaltered mafic rocks are brown on weathered and dark brown to black on fresh surfaces. Furthermore, the strongly poikilitic texture which is characteristic of some of the unaltered mafic rocks is absent in the epidiorites. The feldspar in some of the epidiorites, especially those in the Archaean granite, has a sugary appearance owing to recrystallization. The development of joints in the epidiorite intrusions is more prominent than in the unaltered mafic intrusions and this leads to angular debris in the case of the epidiorites whereas the unaltered mafic rocks are usually characterized by rounded "boulders".

There is a difference in age between the epidiorite intrusions and the intrusions of the tholeiitic suite described above. On Koedoesfontein 12, and Koedoeslaagte 59 (Plate I, Sheet 3) inclusions of epidiorite are found in a poikilitic hyperite which also cuts across the epidiorite.

Both the epidiorites and the rocks of the tholeiitic suite display features characteristic of overturned sills. Some of the sills of epidiorite show an increase in colour-index towards the lower stratigraphic contact and an increase in grain-size towards the upper contact. The epidiorite intrusions are mostly concordant with the sediments of the Witwatersrand System and the thick epidiorite intrusion in the Archaean granite a short distance away from the Dominion Reef lava also follows a course concentric to the strike of the Witwatersrand System. Faults displace the epidiorite intrusions and the intrusions of the rocks of the tholeiitic suite alike, thus indicating that these intrusions were emplaced before the major faulting in the Dome took place. The above evidence also indicates that the epidiorite intrusions were emplaced before the Witwatersrand rocks were overturned during the formation of the Dome.

If the rocks of the tholeiitic suite are regarded as having the same age as the Bushveld Complex, the only period of igneous activity succeeding the Witwatersrand sedimentation and preceding the Bushveld magmatism is that which took place during the formation of the Ventersdorp System. Another possibility to consider is the correlation of the epidiorite intrusions with the sill phase of the Bushveld Igneous Complex and the unaltered mafic rocks with the main plutonic phase. If this is accepted, there must have been a considerable lapse of time between the two phases, or else the two phases are separated from one another by a period of quite intensive diastrophism which caused the older phase to be altered to low-grade metamorphic rocks (greenschist facies) on which was superimposed a later high-grade metamorphism during the intrusion of the central pluton and the alkali granite. A similar situation is encountered in the Rustenburg district, and according to Willemse (personal communication) also elsewhere in the Bushveld Igneous Complex, where some of the sill-phase intrusions are epidiorites.

The "slaty looking igneous rocks" described by Nel (1927, p.59) form dykes in the Upper Division of Witwatersrand System or dyke swarms in some areas, e.g. on Buffelskloof 44 and Buffelskloof 24, where more than a dozen of these dykes are found within a distance of 3 miles along the strike of the Witwatersrand rocks. These dykes cut the Witwatersrand rocks more or less perpendicular or at high angles to the strike of the Witwatersrand System. Some of the dykes split into two or more branches which sometimes join each other again on higher stratigraphic horizons, e.g. on Buffelshoek 83 near the large fault in the Witwatersrand System.

These dykes are composed of fine-grained, highly jointed rocks which weather to a reddish-brown product. The weathered outcrops of these dykes are similar in appearance to some of the weathered slates of the Witwatersrand System, hence Nel's (1927, p.59) designation of "slaty looking igneous rock". In some places where erosion is rapid on the slopes of the quartzite ridges the dykes weather to rounded "boulders". Because the dyke-rocks weather easily, the dykes are responsible for the narrow depressions in the quartzite ridges of the Upper Division of the Witwatersrand System.

The contact area between the Witwatersrand and the Ventersdorp Systems is usually covered with soil, consequently the relation between these dykes and the Ventersdorp System cannot be determined with certainty. However, some of them can be followed for some distance into the Ventersdorp System. Two of the larger dykes can be followed from the Upper Division of the Witwatersrand System on Rooderand 26 to Tygerfontein 70 where they cut across the Ventersdorp System. Unfortunately the upper part of the Ventersdorp System and the lower part of the Transvaal System are not exposed so that the relation of these dykes to the Transvaal System could not be determined. The western dyke which forms a broad depression in the quartzite of the Upper Division of the Witwatersrand System is exposed only in a few places in the Ventersdorp System and is composed of dolerite which is partly altered. The dolerite is composed of augite, labradorite, micropegmatite, magnetite, and pseudomorphs of chlorite after pyroxene, probably orthopyroxene, and shows close similarities to the diabase sills in the Pretoria Series. The rock of the eastern dyke, however, is highly altered and is composed of highly altered feldspar (saussuritized), chlorite, epidote, actinolitic amphibole and leucoxene. This rock can be described as a low-grade epidiorite similar to the "slaty looking igneous rocks" of Nel (1927, p.59).

Nel (1927, p.60) and Rogers (1922, p.55) suggest that these dykes are related to the Ventersdorp System. Similar dykes are found in the Heidelberg area (Rogers, 1922, p.55), and are also known in the mines in the Witwatersrand System where they are considered to be related to the Ventersdorp System. These dykes probably represent feeders of the Ventersdorp lavas.

In the Vredefort Dome, dykes similar to these are seldom, if ever, found in the Lower Division of the Witwatersrand System and are unknown in the Archaean granite. Nel (1927, p.59) also states that they were found only in the Witwatersrand System. If it is accepted that the formation of the Vredefort Dome took place after the deposition of the Ventersdorp System and that these dykes are related to the Ventersdorp lava, the only plausible explanation for their prominent occurrence in the Upper Division of the Witwatersrand System is that they originated from sills lower down in the Witwatersrand System. Because they are highly altered they can be related to the sills of epidiorite. The rocks of the Lower Division of the Witwatersrand System are more argillaceous than those of the Upper Division. For this reason the latter was more ideal for sill intrusion than were the rocks of the Upper Division (mostly quartzite) into which the intrusion of dykes occurred.

Should these dykes be regarded as younger than the formation of the Dome, i.e. that they are not related to the Ventersdorp lavas, a more difficult problem arises, namely to explain why these dykes were emplaced almost exclusively in the Upper Division of the Witwatersrand System around the Dome and seldom, if ever, in the Lower Division of the Witwatersrand System.

Comparison of the equivalent norms of an epidiorite, a Basal Amygdaloid, and a Ventersdorp lava, shows striking similarities between the epidiorite and the Ventersdorp lava (Appendix B, No. 44, 45 and 46).

C. Mineralogy and Petrography

The different epidiorites of the Vredefort Dome can be divided into three groups according to the stages in their progressive metamorphism. The first stage is represented by the "slaty looking igneous rocks" which are abundantly emplaced as dykes in the Upper Division of the Witwatersrand System. Only one sill which is emplaced into the Kimberley slate, is found along the western part of the Dome in the Upper Division of the Witwatersrand System on Kromdraai 142 and Elandslaagte 28.

The epidiorite which represents the first stage of metamorphism is composed mainly of chlorite and epidote. The feldspar is usually altered to such an extent that it is scarcely recognizable. It is replaced by fine-grained aggregates of quartz, chlorite, and epidote. It is possible that albite forms part of these aggregates but it will be extremely difficult to distinguish it from the fine-grained quartz as no twinned crystals were observed. In one specimen plagioclase with a composition of approximately An_{15} was observed. Calcite is a constituent of some of these rocks and the iron-ore mineral is partly altered to leucoxene.

The second and third stages of metamorphism are represented by the sills of epidiorite which are intrusive into the Lower Division of the Witwatersrand System and the Archaean granite. In the epidiorite of the third stage the pyroxene is altered to amphibole and the feldspar is partly or completely recrystallized, whereas in the epidiorites of the second stage only the pyroxene is altered to amphibole and the feldspar remains practically unaltered. Clinozoisite is characteristic of both stages but it is more abundant in the second stage than in the third stage. In the third stage magnetite is frequently absent, and is replaced by sphene or is represented by small remnants of magnetite with a rim of sphene. In places biotite is found in the second stage but is absent in the third stage. In the third stage the amphibole consists of large crystals or aggregates of small stout prisms which project deep into the feldspar, whereas the amphibole in the second stage is usually fibrous.

Epidiorites belonging to the third stage include the intrusions south of a line which follows the strike of the lower part of Hospital Hill Series between Mooihoek 411 and Tweefontein 637 (Plate IV). Epidiorite belonging to this stage also forms a small intrusion in the

Jeppestown Series which forms a xenolith or roof-pendant in the alkali granite on Koedoeslaagte 59. Epidiorite of the second stage forms sills in the rest of the Lower Division of the Witwatersrand System.

Amphibole is the most prominent constituent of the epidiorites in the Lower Division of the Witwatersrand System and in the Archaean granite. It varies from weakly pleochroic types (straw yellow to light green), to types which are strongly pleochroic from straw yellow to bottle green. This increase in the intensity of pleochroism is probably due to an increase in the iron content and/or a possible increase in solid solution between actinolite and hornblende. Coarse-grained epidiorite which is found near the stratigraphic top of the epidiorite sills usually contains pseudomorphs of amphibole after pyroxene which show a stronger pleochroism than the amphibole lower down in the sills. This amphibole forms single-crystal pseudomorphs after the pyroxene and frequently shows morphological features inherited from the pyroxene, e.g. (001) and (100) partings. Lower down in the sills the amphibole is usually fibrous (bundles of these fibres have a random orientation in the pseudomorphs) in the second stage, but it forms large crystals intergrown with stout prisms in the third stage. In the second stage the pseudomorphs of fibrous amphibole are in places surrounded by narrow margins which are strongly pleochroic compared with the cores. A similar phenomenon was observed by Sutton and Watson (1951, p.28) in their second stage of epidioritization in the north-western Highlands of Scotland. They ascribe this phenomenon to the absorption of sodium during the reaction between pyroxene and feldspar when amphibole was formed. Some amphibole crystals in an epidiorite on Koedoesfontein 12 contain cores of brown hornblende.

It is difficult to establish the presence of orthopyroxene in the rocks from which the epidiorites have evolved as pyroxene is seldom found in them. The normative pyroxene of the analyzed epidiorite (Appendix B) contains 32 per cent of wollastonite (hypersthene and diopside are taken as one pyroxene) which is slightly lower than the values for clinopyroxene on the crystallization curve for mafic magmas (Deer, Howie and Zussman 1963, Vol. II, p.127), consequently it is possible that small amounts of orthopyroxene or pigeonite were present in the original rocks.

The plagioclase of the epidiorite of the second stage is mainly labradorite with an average composition of An_{65}. Zonal structure is frequently seen. The crystals are similar to those of dolerites, i.e. subhedral and elongated parallel to the twinning lamellae, and in some of the finer-grained varieties the plagioclase shows considerable elongation which produces lath-shaped crystals. In the epidiorite of the third stage the feldspar is partly or completely recrystallized to a fine-grained granular mosaic in which the feldspar is not very often twinned. Owing to the small grain-size of the plagioclase and the scarcity of twinned crystals in this mosaic the accurate optical determination of the composition of the feldspar is difficult. Where it was possible to determine the composition of the secondary feldspar an average composition of An_{45} was obtained. In an epidiorite on the contact between the Dominion Reef System and the Orange Grove quartzite, about a quarter of a mile west of the road between Potchefstroom and Parys, some of the crystals of original feldspar are deeply penetrated by small prisms of amphibole (Plate XVI B). A narrow zone of plagioclase on both sides of the row of amphibole crystals has a composition of An_{45} and the rest of the crystal has a composition of An_{65}. This indicates that some of the constituents of the feldspar, e.g. calcium and aluminium, were extracted during the formation of the amphibole.

Hall and Molengraaff (1925, p.48) describe zoisite as a constituent mineral of the epidiorites. Where crystals are large enough to allow of the determination of the optical properties, $2V_z$ is large (70°-80°) and the extinction oblique, indicating that it is clinozoisite. Clinozoisite is more abundant in the epidiorite of the second stage than in that of the third stage. In the rocks of the first stage epidote is characteristic. In some examples clinozoisite is absent. The clinozoisite usually forms small prisms or needles in the plagioclase, especially near the margins of the plagioclase crystals, i.e. close to the amphibole. In the average epidiorite, clinozoisite constitutes less than 10 per cent of the rock. Hall and Molengraaff (1925, p.49) are of the opinion that an increase in the amount of clinozoisite is characteristic of the more advanced stages of epidioritization and that in their last stage all the plagioclase is completely replaced by clinozoisite producing a "zoisite amphibolite". According to them only one of their specimens was representative of this stage. In some epidiorites fine-grained aggregates of zoisite cause the crystals of plagioclase to become turbid, but this does not indicate the absence of plagioclase. Their contention that there is an increase in the amount of clinozoisite in the more advanced stages of metamorphism could not be confirmed, rather the opposite appears to be true, i.e. there is a decrease in the amount of clinozoisite with increase in the grade of metamorphism. This is to be expected as the composition of the secondary feldspar is An_{45} which indicates an equilibrium above the "peristerite range" (Barth, 1962, p.55) and furthermore the anorthite content of plagioclase usually increases with progressive metamorphism. In the higer grades the amphibole becomes more hornblendic because components of feldspar are also taken up. Moreover, if zoisite is a characteristic mineral of the high grades, the amphibolites which are found in the Archaean granite should contain a high percentage of zoisite, but this mineral is absent in these rocks. The only rocks in which the feldspar falls within the peristerite range are probably some of the "slaty looking igneous rocks" which belong to the first stage of epidioritization in which epidote is a common constituent. According to Turner and Verhoogen (1960, p.533) plagioclase which is associated with epidote in metamorphic rocks, shows a sudden change in composition from An_{0-7} to An_{15-30}. The example referred to above, which contains plagioclase An_{15} appears to lie on the high temperature boundary of their greenschist facies.

Frequently micropegmatite remains unchanged in the epidiorite of the second stage, but in some examples the potassium feldspar is replaced by biotite. In the third stage biotite was not encountered and quartz forms part of the granular aggregates of light minerals between the amphibole. The biotite or the potassium feldspar was probably taken up in the formation of hornblende in this stage.

The accessory mineral in the epidiorite prior to alteration was probably ilmenite or titanomagnetite. Some biotite forms narrow rims around the iron-ore mineral. The sphene consists of round grains generally enclosed in the amphibole. Frequently it forms a rim around magnetite, especially in the second stage of epidioritization. In the third stage the iron-ore mineral is usually completely replaced by sphene. In some epidiorites of the second stage magnetite is found without any associated sphene and in places it consists of skeletal crystals in the amphibole. A possible reason for this is that the original iron-ore mineral was pure magnetite, or if small amounts of ilmenite were present, they were taken up by the amphibole.

During the second stage of epidioritization the original ophitic or subophitic texture of the rocks is still preserved, but in the third stage, though recognisable in some epidiorites, it is modified owing to the recrystallization of the feldspar and the deep penetration of the amphibole prisms into the recrystallized feldspar.

The mineralogy of the Basal and the Jeppestown Amygdaloids is very similar to that of the intrusive rocks just described. These rocks are, however, much finer-grained. The amygdales are recrystallized and consist mainly of quartz and amphibole (see Hall and Molengraaff 1925, p.129, and Plate 31).

D. The chemistry of Epidioritization

In Appendix B are shown the analyses and equivalent katanorms of an epidiorite and the Basal Amygdaloid. A norm was also calculated for the epidiorite in terms of its modal composition, without taking the water into consideration. It is evident that the formation of tremolite from diopside and hypersthene has a small effect on the plagioclase. In the formation of clinozoisite from anorthite, a small amount of sillimanite is formed:

20 An = 16 Zo + 3 Sil + Q . . . . A
6 Hy + 8 Di + Q = 15 Act . . . . B
A + B: 20An + 8 Di + 6 Hy = 15 Act + 16 Zo + 3 Sil . . . C

Niggli's ideal hornblende can be formed according to the following reaction :

20 An + 8 Di + 4 Hy = 15 Ho + 16 Zo + Q . . . . D

During epidioritization in the Vredefort Dome, reactions were not completed, as the amount of clinozoisite which developed was limited by the feldspar in equilibrium with it, i.e. An_{45}.

With an increase in the grade of metamorphism the amphibole becomes more hornblendic in composition. The zoisite was probably taken up by the amphibole in the more advanced stage. This is probably the reason for the decrease in the amount of zoisite. Wiseman (1934, p.378) also found that there is an increase in the amount of aluminium and sodium in the amphibole with progressive metamorphism.

E. Comparison with Epidioritization Elsewhere

The metamorphism of the mafic rocks described above shows a remarkable correspondence to that observed by Sutton and Watson (1951, p.27-30) for epidiorites of the north-western Highlands of Scotland but less so to the epidiorites of the south-western Highlands (Wiseman, 1934, p.357-392). In the south-western Highlands all the pyroxene is altered to chlorite and amphibole in the low grades of metamorphism, whereas amphibole and chlorite are not found together in the epidiorite sills of the Vredefort Dome. Wiseman (1934, p.371) showed that there is no indication that amphibole had developed from chlorite as was suggested by Tilley in 1923. Sutton and Watson (1951, p.27-29) also do not refer to any chlorite in the epidiorites of the north-western Highlands. In the Vredefort Dome chlorite is not present in the epidiorites of the middle grade but is a major constituent in those of the low grade.

Amphibole apparently developed directly from the pyroxene because it usually forms pseudomorphous aggregates and pseudomorphs after pyroxene. In the "slaty looking igneous rocks" the chlorite developed from the dark minerals but it is also a prominent constituent among the alteration products of the feldspar. Apart from the small amount of alteration to clinozoisite, the feldspar of the epidiorites of the second stage is still unaltered. If the rocks of the second stage had undergone alterations similar to those of the first stage, one would not have expected the preservation of the ophitic texture in the epidiorites of the sills in the Lower Division of the Witwatersrand System unless the pyroxene had been altered to chlorite without affecting the feldspar substantially. In this case then a rock consisting of slightly altered plagioclase and chlorite, or chlorite and amphibole, pseudomorphous after pyroxene, would represent the initial rock-type which was transformed into the epidiorite of the second and third stages.

Nel (1935, p.93)refers to earlier and later sills of mafic rocks which are intrusive into the Witwatersrand System in the Klerksdorp-Ventersdorp area. The rocks of the earlier group are much altered whereas those of the later group show less pronounced alteration. For comparison with the Vredefort rocks a few specimens of the more altered types were studied. The pyroxene is partly or nearly completely altered to chlorite and the feldspar is turbid owing to the development of zoisite, chlorite and small amounts of sericite. Quite coarse epidote is sometimes associated with the chlorite. The accessory iron-ore mineral is altered to leucoxene with lamellae of magnetite. Accessory calcite is frequently found in these rocks. These alterations show a close similarity to those of the slaty-looking igneous rocks described above. It is evident that the first stage of metamorphism of the mafic rocks in the Vredefort Dome mustbe ascribed partly to the low-grade regional metamorphism which affected the Witwatersrand System as a whole and also the Ventersdorp System. It is thus not improbable that the epidiorites of the second and third stages were also partly altered before they were subsequently subjected to contact-metamorphism.

A problem connected with the dykes of "slaty-looking igneous rocks" is that they were abundantly emplaced within the zone now characterized by the development of andalusite and kyanite in the Upper Division of the Witwatersrand System. In the kyanite zone in the south-western Highlands, according to Wiseman (1934, p.393), chlorite has disappeared and the plagioclase is recrystallized to a feldspar with a high anorthite content. The obvious conclusion in regard to the kyanite-bearing rocks of the Upper Division of the Witwatersrand System is that they represent a product of low-grade contact-metamorphism of rocks with a composition which was ideal for the formation of kyanite.

The second stage of progressive metamorphism of the mafic rocks of the Vredefort Dome is similar to that of the north-western Highlands described by Sutton and Watson (1951, p.28), with the exception that clinozoisite is developed in the rocks of the Vredefort Dome but is absent in the rocks of the north-western Highlands. In this respect the metamorphosed mafic rocks show similarities with those of the south-western Highlands where clinozoisite and albite are characteristic (Wiseman, 1934, p.353-392), except that albite is absent in the rocks of the Vredefort Dome. Sphene is characteristic of the rocks of the Vredefort Dome as well as of both areas of the Scottish Highlands.

The third stage of epidioritization in the Vredefort Dome is similar to that of the north-western Highlands, again with the exception of the clinozoisite in the Vredefort rocks. Up to this stage the blastophitic texture of the epidiorites is well preserved. In the north-western Highlands the original texture of the rocks is destroyed in the fourth stage and a directive texture, typical of amphibolite, is developed. Rocks similar to those of this stage occur in the Vredefort Dome but they belong to an earlier period of regional metamorphism which has been fully dealt with by Willemse (1937, p.57).

The problem in connection with the mafic intrusions in the Vredefort Dome, namely that some of them have been altered whereas others are unaltered (see Hall and Molengraaff, 1925, p.51, and Poldervaart 1962, p.245), especially the composite sills which are composed of both dolerite and epidiorite, can be explained as follows: The original rocks from which the epidiorites evolved have undergone a low-grade, regional metamorphism which affected both the Witwatersrand and the Ventersdorp Systems. At the time of the contact-metamorphism they were probably similar in mineral composition to their possible equivalents in the Klerksdorp-Ventersdorp area, as they appear at present, whereas the rocks of the tholeiitic suite which were emplaced prior to or simultaneously with the contact-metamorphism, were still unaltered. As a result of the contact-metamorphism of these regionally metamorphosed rocks, those representing the different stages of epidioritization developed, whereas the unaltered types were not affected.