THE DIORITES OF YZERFONTEIN, DARLING, CAPE PROVINCE

By

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ABSTRACT

The recent suggestion of the existence of a basaltic magma in the South-west Cape Province shortly before the intrusion of the Cape granites is corroborated by the occurrence of a gabbroic body of pre-granite age at Yzerfontein. A detailed study of the primary rhythmic banding and igneous lamination of this body indicates its original form as being sheet-like or laccolithic, and the differentiation appears to have been due to a combination of fractional crystallisation and gravitative crystal settling on to a sub-horizontal floor. The crystal settling process was probably later arrested by the viscosity of the rest magma, due to its enrichment in potash and alumina.

The Yzerfontein diorites proper represent a hybrid product resulting from the mixing, in depth, of the marginal contaminated facies of the Darling granite with gabbroic material. The present uniformity of the diorite is ascribed to the emplacement of the hybrid magma to a higher level.

Gabbroic xenocrysts are widely distributed in the diorites, these single crystals almost invariably being surrounded by rims of material later in the reaction series. Amongst the mafic minerals a uniform orientation relation is found to exist between the cores and rims of such reaction products.

Two different types of granite aplite and pegmatite, namely potash-rich and soda-rich varieties, have invaded both the diorites and gabbros along joints corresponding in direction to the joint system of the Darling granite pluton, while swarms of veins and dykes containing late hydrothermal minerals, which probably represent the final stages of the magmatic history of the granites, follow similar directions.

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I. INTRODUCTION

A suite of basic, igneous rocks is found along the Atlantic coast-line of the South-western Cape Province in the vicinity of Yzerfontein Point. Although the existence of these interesting rocks has long been known, little more than passing reference to their presence has previously been made.

In his first report to the Geological Commission of the Cape of Good Hope, A. W. Rogers (1896), while dealing with the south-western dolerite dykes, mentions that "at Yzerfontein . . . there is a large mass of doleritic rock which differs in important respects from the other basic rocks of this district". In a later publication (Rogers, 1905) the same author describes "a large mass of hornblendic rock, coarsely crystalline, with a banded structure; some thick layers are formed entirely of green hornblende, and others, usually thinner, have a fair proportion of plagioclase in them" and their dioritic character is indicated. Although the rocky coast-line around Yzerfontein was correctly mapped as "diorite" on Cape Sheet 4 of the following year (1906), these rocks were not differentiated from the "younger Cape granites" on the later 1 : 1,000,000 geological map published by the Department of Mines (1925).

In his report on the phosphates of Saldanha Bay, A. L. du Toit (1917) mentions that a sample of limestone, collected in this vicinity by Dr. Rogers, carried a fair proportion of phosphoric oxide, while W. Wybergh (1920) in a subsequent investigation, could find no such rich phosphate deposits. Neither of these reports mentions the nature of the underlying rocks.

"Cliffs of diorite, 40 feet high" are described as breaking the long, sandy beach of Saldanha by A. V. Krige (1927) in an examination of the physiographic characteristics of the South African coast, and in the same paper attention is directed to the raised beach deposits situated to the south-east of the Point.

The most recent reference to these rocks has been made by D. L. Scholtz (1946) who mapped them as a distinct and separate rock-type, and suggested their hybrid relation to the younger Pre-Cambrian Granites of the Cape Province. He further showed that the pyritic veins and dykes which traverse these hybrid rocks, belong to an extension of the north-west trending zone of mineralisation stretching from Helderberg through Kuils River and the Koeberg Hills, and concluded that these ore deposits are genetically related to the younger granites.

Two similar occurrences of basic rocks are known in the South-western Cape Province; The Brewelskloof Diorites and the Malmesbury Diorites. The latter comprise four composite stocks, intrusive into a dome structure in the Pre-Cape sediments along the western side of the Malmesbury-Paardeberg granite pluton, and have recently been described by P. J. van Zyl (1950). Although intimately associated with the Cape Granites, these diorites are believed to be older than the granite intrusions and are found to have had a pronounced contact metamorphic effect on the sedimentary country rocks. Petrologically the rocks vary from normal gabbros to quartz diorites and are shown to owe their origin to successive intrusions of a pre-Granite basaltic magma which had undergone different degrees of differentiation in depth.

The Brewelskloof diorites, now being investigated by P. J. Joubert, also invade the Pre-Cape sediments and occur about 6 miles north-east of Worcester. Their composite stock-like form may be indicated by a central, more basic portion surrounded by a more acid margin. The rocks have, however, been severely altered, presumably by regional metamorphism, no primary minerals remain and their original nature is therefore doubtful.

II. TOPOGRAPHY

Yzerfontein Point forms a small promontory protruding into the Atlantic Ocean approximately midway between Table Bay in the south and St. Helena Bay in the north. The nearest town, Darling, lies about 14 miles due east, while the important guano-collecting station, Dassen Island, is situated approximately 7 miles to the south-west. Along a narrow strip of the coast-line in the vicinity of the Point and for a short distance to both the north and the south are exposed rocks belonging to a complex igneous mass and varying in composition from basic olivine-gabbros, through more acid augite-diorites to aplites and pegmatites of granitic affinity.

Bold cliffs, often at least 40 feet high, have been cut into these rocks where they abut against the wild open sea. In addition, three distinct terraces, stepping the surface between the sea and the interior, are prominently developed. The lowest is definitely wave-cut and varies in height from 20 to 25 feet. This surface is most clearly seen cutting across "Die Eiland", a small peninsula to the south of the Point which is separated from the mainland by a narrow tidal channel. It may also be observed bevelling the four rocky outcrops along the beach stretching from Die Eiland towards the south-east, and it is on this level that the fishing factory at the Point and the holiday resort of Yzerfontein have been built. Comparable in height is the sandy terrace extending parallel to the coast for about a mile southwards from Die Eiland. Its width averages 100 yards and it is at least 26 feet high. This feature was noted by Krige (1927) who came to the conclusion that it "represents a true raised beach, as its surface is too uniformly flat to have been built up by storm waves during a considerable progression of the shore".

The second terrace varying from 40 to 60 feet above sea level is less prominent than the lower one, though comparable in area. It may best be seen cut in the dioritic cliffs to the south of the Point and it generally possesses a slight dip towards the sea. It is, however, by no means confined to this stretch, although its feeble development both towards the north and the south may be difficult to follow.

Rising fairly abruptly from this level, the land surface finally evens off to form the third and most distinct of the three terraces. This platform is remarkably flat and featureless, but possesses a very slight dip (less than 1°) towards the north-east. In this direction it attains its widest development and where it overlooks the resort it extends for approximately a mile inland with a constant height of 120 feet. From here it is prolonged in a south-easterly direction for almost two miles parallel to the coast-line, but before reaching its southern extremity its width narrows down to about 300 yards while its altitude increases almost imperceptibly to over 160 feet. (Plate I, No. 1).

All three platforms are blanketed by a veneer of sandy limestone or a covering of pale-coloured shelly sand, which conceals to a large extent the underlying igneous rocks. Frequently this unconformable cover displays basal lenses of dioritic pebbles and rounded boulders showing evidence of wear by wave action, and there is little doubt that they can be correlated with the raised marine deposits extending round the rest of the continent.

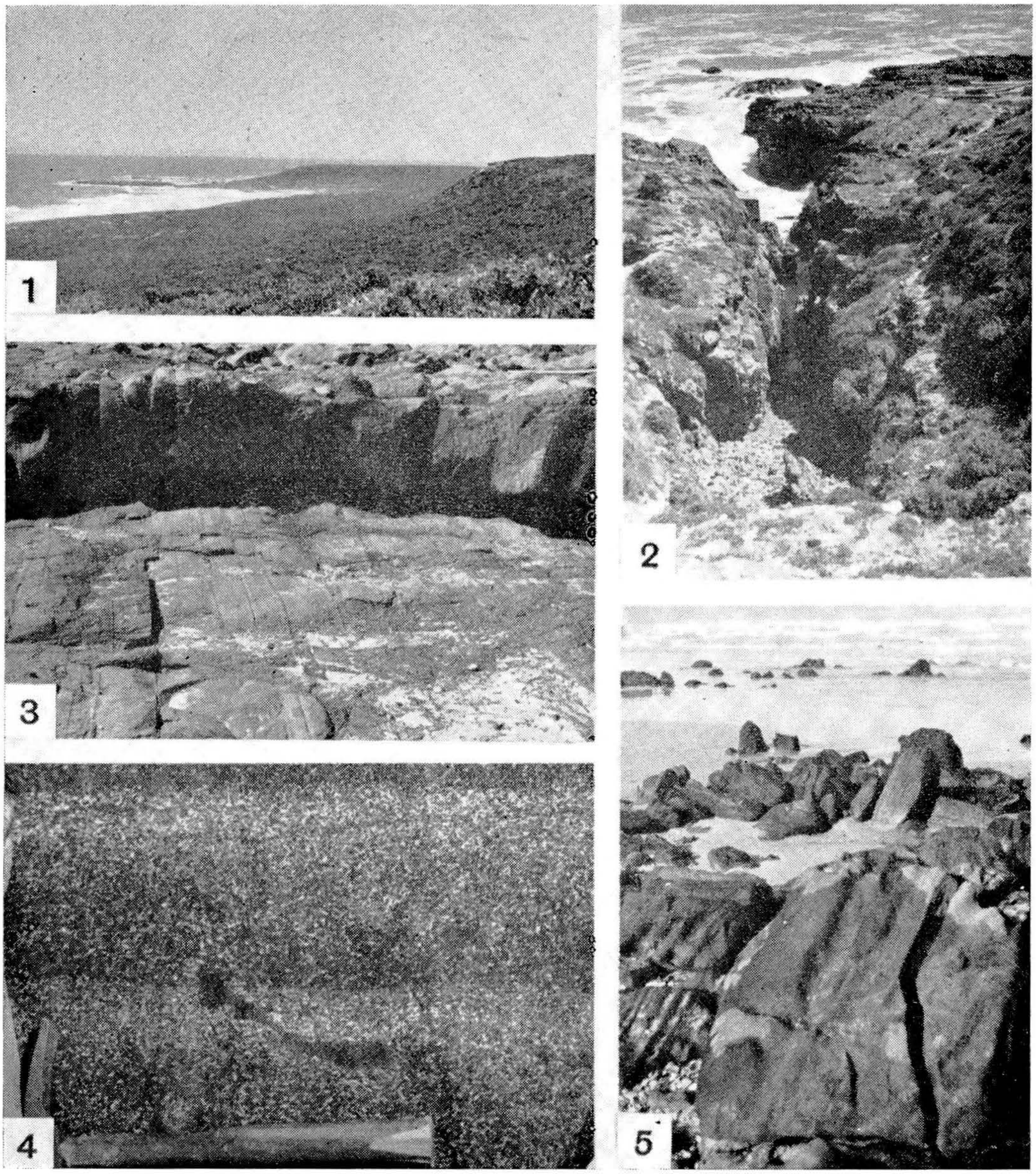


PLATE I.

1. View of Die Eiland from the south. The 120-foot platform is to be seen on the right, while the raised beach deposits occupy the foreground.
2. Duiwe Nes—a deep, narrow gulley, situated along a thick pyrite-tourmaline vein.
3. Swarm of parallel, closely-spaced, tourmalinised veins. Later, flat-lying joints visible in the background.
4. Banded gabbro, illustrating clearly the density gradient across the individual bands. The print has been cropped so as to demonstrate the original, horizontal attitude of the layering.
5. Banded gabbro outcrops at Gabbro Point showing the present, steeply-inclined attitude of the mineral banding.

The most prominent topographical feature in the vicinity is the conical hill, Vlaekop, which rises fairly abruptly from the 120-foot platform to a height of 280 feet. The summit of this low hill has been stripped of its concealing blanket of limestone and rocks belonging to the igneous complex are found surrounding the beacon which marks its crest.

Separating the high ground around Yzerfontein from the low granite hills of Slangkop and Koffiekop to the east, which are the nearest known exposure of the rocks of the Darling Pluton, is a 7-mile broad belt of level, sand-covered country, the elevation of which seldom exceeds 100 feet and averages less than 50 feet.

Although several traverses were made across this gap, not a single outcrop of rock was found and only occasionally were small rounded granitic pebbles encountered embedded in these sands. This sandy stretch continues towards the north-west and the south-east, and the nearest rock outcrops in these directions are respectively the granites at Geelbek and the rugged cliffs of Malmesbury rock at Bok Point. It will be shown later that most of this region, particularly the stretch between Vlaekop and Koffiekop, is probably underlain by the Younger Pre-Cambrian Granite of the Darling pluton, while the rocks of the dioritic complex are confined to the high ground around Yzerfontein and for a short distance to the north. Further, it appears that this high ground is built solely of diorite and its thin, recent limestone cover and there can be little doubt that the existence of this promontory, which is the only relief from the monotony of an otherwise smooth expanse of beach and sandy, often dune-covered, coastal plain extending for fully 25 miles from Saldanha Bay to Bok Point, is due to the superior resistance of the dioritic rocks to the forces of marine denudation when compared with the granite.

With the exception then of the summit of Vlaekop, rocks belonging to the basic Yzerfontein Complex are exposed only along the wave-washed coast in the vicinity of Yzerfontein itself. The most continuous exposure is that which forms the Point and extends in an almost uninterrupted sequence to the holiday resort on the one hand and to Die Eiland on the other, a distance of almost 3,000 yards, but the outcrop is nowhere more than 200 yards wide. Along the stretch of shelly beach further down the coast, four smaller exposures are found all within the first two miles from Die Eiland, while on the northern side of the resort a clump of rounded igneous boulders, 1,000 yards from the bathing shelter on the beach, form both an important and the only occurrence of these rocks in this direction.

III. THE GEOLOGY OF THE IGNEOUS ROCKS

Great variation exists in the grain size of the dioritic rocks. Generally the most basic varieties possess the coarsest grain with the average size of the crystals varying between 2·00 and 5·00 mm., while the colour index of these types in no way reflects the basicity of the rocks. This is due to the frequent development of primary mineral banding in these types. A much more uniform texture and homogeneous colour is displayed by the less basic varieties and these types possess a finer and more even grain. They are free from primary banding and do not display sharp intrusive contacts towards the more basic types. The change between the two types is, however, accomplished across a broad, transitional zone, but the frequent occurrence in the finer-grained type, near this transitional zone, of large, coarse-grained, ghostlike inclusions with either a lighter or a darker colour may be taken to reflect their younger age relative to the more basic types. The most acid rock-type found is a very fine-grained, pink, aplitic dyke-rock which always shows sharp intrusive contacts towards the darker, more basic varieties. Occasionally too, coarse-grained pegmatites, comparable in all respects with the aplites, are developed.

On the basis of the above variations, as well as on mineralogical grounds, it is possible to recognise the following suites of rock types at Yzerfontein:—

(i) A coarse-grained gabbroic suite.
(ii) A suite of heterogeneous, transitional rocks.
(iii) A fine-grained dioritic suite.
(iv) A suite of later aplitic and pegmatitic injections.

Phase petrology has played an important part in this distinction of the various rock types, but the variation of the phasal compositions of the different suites will be discussed only after their distribution and petrological characteristics have been described.

(i) **The Gabbroic Suite.**

Although it is believed that the gabbroic rocks must originally have constituted a fairly large body, the present outcrops of these rocks are very limited. Only at the clump of boulders on the beach to the north of the resort do they occur in any quantity, but similar gabbroic types are also found on the northern edge of the lone outcrop near the bathing shelter, on the seaward extremity of some of the rocks jutting into the sea below the resort, at the "Poikilitic Gabbro Promontory" and on Meeuw Rock, the bevelled, rocky, guano-covered island in the middle of the bay.

The rocks of this suite are characteristically coarse-grained gabbros, frequently banded and composed essentially of well-formed, tabular crystals of pyroxene and plagioclase, with flakes of biotite and interstitial orthoclase also visible in hand specimen.

The pyroxene grains, however, are very dark, almost black, particularly in slightly weathered specimens, and their general appearance in the field is more suggestive of hornblende than pyroxene with the result that these rocks have been erroneously referred to by Rogers (1905) as diorites.

Primary rhythmic banding is not universally developed in these rocks and at only two localities could the orientation of this structure be measured. Here the banding is seen to be due to the varying proportions of the essential minerals. (Plate I, No. 4.) Thus types vary from a dark, almost black rock, extremely rich in pyroxene, to a leucogabbro in which the mafic minerals are very subordinate to the feldspar. The thickness of the individual bands is remarkably constant and averages nine inches in width, while the boundaries between the bands are sharp and distinct. A density gradation is, however, developed across each band, whereby the lower side with reference to the dip of the banding is always dark and pyroxene-rich, while the lighter, felsic minerals appear to be concentrated in the upper portions of the layers. Also apparent in the field is the arrangement of the large crystals of plagioclase and pyroxene in such a way that their greatest dimensions parallel the plane of banding. This feature is described as "igneous lamination" by Wager and Deer (1939) and seems universally associated with primary rhythmic banding.

Occasionally too, as at the "Poikilitic Gabbro Promontory" and on Meeuw Rock, a distinct facies of the non-banded gabbro is developed which, when viewed from a distance, presents a peculiar mottled appearance. (Plate II, No. 1.) On closer inspection the dark spots responsible for this feature are found to be large, rectangular insets of orthoclase up to 2 inches long and 1½ inches wide, and possessing good crystal outlines. These insets are, however, not homogeneous but are liberally studded with

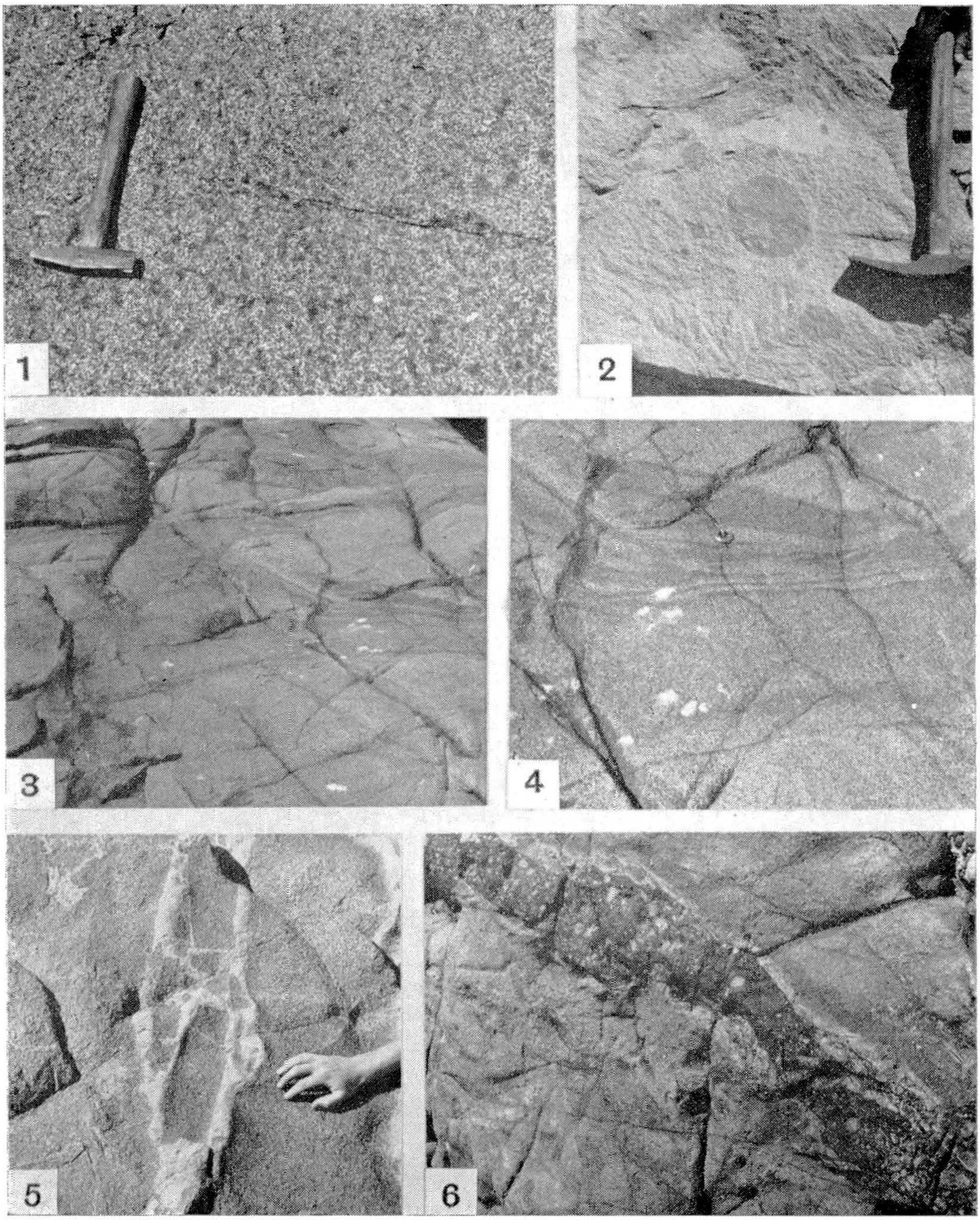


Plate II.

1. Mottled appearance of the poikilitic monzo-gabbro.
2. Rounded inclusions of the gabbro chill phase in diorite.
3. and 4. Mixed aspect of the transitional zone.
5. Aplite dyke containing scattered fragments of diorite.
6. Tourmalinised shear-zone.

inclusions of well-formed crystals of pyroxene, plagioclase, biotite and iron ore. On either side of the Promontory and on the south-western edge of Meeuw Rock, this facies grades imperceptibly into more normal gabbro by a decrease in the amount and size of the poikilitic orthoclase crystals, and this, coupled with the similar mineral assemblage and chemical composition, justifies our regarding this "poikilitic gabbro" not as a separate rock type but as a facies of the normal gabbro suite.

(ii) **The Transitional Suite.**

This zone occupies a belt situated between the gabbros and the diorites, the outcrop width of which varies from 10 feet in the north to at least 60 yards in the south. Two main occurrences are observed: the northern occurrence stretching from just below the offices of the Atlantic Ocean Industries for approximately 550 yards towards the north-east where it disappears beneath the sands just below the resort; and the western occurrence which may be traced along the westerly extremities of many of the promontories between Duiwe Nes and Die Eiland, a distance of 1,200 yards. As the rocks of these two belts are identical, they probably extend out to sea to join somewhere to the west of the Point around which they curve.

The rocks of the transitional suite may truly be referred to as "mixed rocks". In the field they have a patchy and uneven appearance and much variation from place to place is seen in the proportions of the constituent minerals, the colour and the grain size. Generally the coarse-grained types appear to belong to the gabbroic suite, while the finer-grained more homogeneous varieties cannot be distinguished from the dioritic rocks in hand specimen. These various types are intimately mixed. Sometimes large rounded ghostlike inclusions of the coarse gabbroic rocks are found in the finer-grained type, while at other times there is an intricately streaked and whorled relation between the types which may be likened to the pattern obtained on partially stirring up a mixture of thick, coloured paints. (Plate II, Nos. 3 and 4.) Although both gabbroic and dioritic types are distinguishable in these streaks and whorls, even here sharp contact between the types is absent and transition from one to the other is gradual.

The rocks of this suite are intermediate in character, both chemically and mineralogically, between the gabbros and the diorites.

(iii) **The Dioritic Suite.**

Practically all the remaining outcrops at Yzerfontein are formed by rocks of this suite. They are readily distinguished by their greater homogeneity, constant light grayish green colour, fine even grain (1-3 mm.) and total lack of any primary structures. Feldspar is by far the most abundant mineral in these rocks. The pyriboles appear in the form of relatively large, green, sugary grains which may occasionally reach a length of 5 mm. Less abundant are flakes of mica which have often been altered to green chlorite and are easily confused with the other dark minerals. Quartz is not visible in hand specimen.

The rocks of this suite are apparently the most resistant of the complex and the configuration of the coast reflects to some extent the trend of their junction with the transitional and gabbroic suites. The outcrops are prominently developed around the Point and extend south-eastwards to include the four smaller headlands lower down the coast. In addition, outcrops are found at various points below the resort while the rocks are well exposed around the Vlaekop beacon.

Although characteristically homogeneous, the dioritic rocks often contain inclusions of the older gabbroic suite. These are mainly confined to the coarse-grained ghost inclusions near the transitional zone, but at some localities a diorite is developed which is extremely rich in small, rounded inclusions averaging 4 inches in diameter. (Plate II, No. 2.) This "inclusion-bearing diorite" is well displayed in the quarries at the harbour where the inclusions are composed of a very fine-grained rock, slightly darker in colour than the surrounding diorite towards which they show sharp boundaries. On chemical and mineralogical grounds, these inclusions belong to the gabbroic suite. Their anomalous grain size and xenolithic development will be discussed later. Prolonged search of the quarries brought to light only two inclusions of coarser grain and darker colour which proved to be the more normal members of the gabbro suite.

(iv) **Aplite and Pegmatite injections.**

The aplite consists of a distinct pink rock with so fine a grain that the individual crystals cannot be distinguished with a hand lens. Occasionally it is possible to pick out extra large clusters of tourmaline, dark green hornblende or chlorite, but even these have sizes usually less than 0·5 mm.

The aplite injections are found to fill veins, fissures, dykes and irregular pockets in the rocks of all three other suites. Towards these rocks they show sharp contacts and they have also altered them for a distince of about three inches from these contacts, manifest either by a pink staining or by the whiter colour shown by hydrated feldspars. Injection has often been accomplished by the shattering of the intruded rock and the aplitic material may engulf angular chips and fragments up to 6 inches long of the adjacent rock. (Plate II, No. 5.) Sometimes these fragments show edges which may be pieced together after the style of a jig-saw puzzle. Although injections of this type are highly irregular along their length, some aplite dykes are found which have produced little shattering and have a more constant width and direction over long distances. They have exploited the two prominent sets of joints striking approximately 138°-144° M.N. and 6°-12° M.N. Still another mode of occurrence is displayed on the western side of the region where, roughly midway between the Point and Die Eiland, aplitic material has been injected into the diorite, not as dykes or veins but as a large irregular mass from which may radiate dykes and veins. Similar, though very much smaller, isolated aplite bodies are frequently encountered on Die Eiland and these aplite-filled "pockets" often carry large rounded foreign inclusions ranging up to 9 inches in diameter. Although mainly dioritic, many of these inclusions are of coarse-grained gabbro while an occasional hornfelsic type is clearly composed of indurated argillaceous sediments. This must show the proximity of both the gabbro body and the sedimentary rock into which it was intruded, although outcrops of these are here missing.

A pegmatitic facies was discovered by Prof. Scholtz who kindly gave the author a large sample of this coarse-grained pink rock. The rock is predominantly feldspathic, crystals of this mineral usually having dimensions of 2×1 cm. Much quartz occurs scattered interstitially and with it are associated blebs and spangles of pyritic ore. Patches of the rock are greatly enriched in epidote and around these green portions feldspar alteration has been extreme. A similar rock type is frequently found elsewhere but usually only in the form of narrow irregular stringers and veins. Those towards the north of the quarry do not usually show the pink colouration, while towards the south epidotisation becomes pronounced and colour is more strongly displayed. Also towards the south, injection has been accomplished by much shattering of the adjacent rock, fragments of which are included in the pegmatite veins.

LATE HYDROTHERMAL INJECTIONS.

One of the most striking features observed in the rocks to the south of the Point is the large number of veins which have been filled with late hydrothermal minerals. (Plate I, No. 3.) These veins are everywhere present and are found cutting all the various rock types. Along the coast between the Point and Die Eiland where these veins have been most prominently developed, the spacing between the individual veins is seldom more than a foot, while their thickness varies from a few millimetres to well over a foot. To the north the veins are generally more widely separated and the hydrothermal products are present as thin veneers along joint planes, seldom being visible without the aid of a lens. Towards the south from Die Eiland a similar decline in their development is apparent.

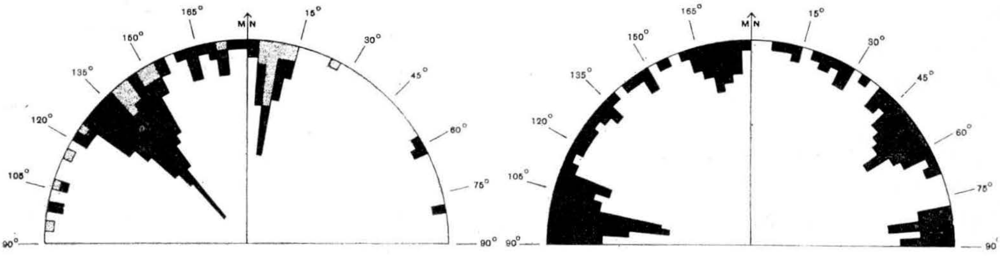
The minerals occurring in these veins include tourmaline, pyrite, jasperoid, quartz, muscovite, calcite and epidote. With the exception of quartz, these minerals are never found to occur singly in the veins. Thus calcite is usually accompanied by epidote, muscovite by quartz, pyrite by tourmaline, quartz or jasperoid. In the larger veins these associations take on the form of rhythmic crustification banding, while in the thinner veins a random distribution of the minerals is observed. An indication of the relative ages of the minerals is given by this banding and by the occasional intersection of the veins, which shows that the tourmaline and pyrite were introduced before the jasperoid and that the epidote and calcite marked the final hydrothermal stage.

The introduction of this late hydrothermal material was by means of aqueous solutions and this has invariably resulted in the alteration of the adjacent rock. In the field this is manifest either by the chalky white appearance of the feldspars or by the pink staining of this mineral, while under the microscope the cloudy, saussuritised feldspars may show the presence of fine, dusty hematite and are frequently in the process of being replaced by tourmaline, epidote and calcite. Extensive chloritisation of the dark minerals is also a feature of this alteration. Perhaps the difficulty experienced in finding suitable, unaltered specimens of diorite south of the Point may be attributed to the extensive alteration of these rocks by the closely spaced veins in this region. Either the presence of the hydrothermal material in the veins or the alteration of the adjacent rock seems to have lowered the resistance of these directions to the attack of the elements, for the numerous steep-sided gullies on the western coast are found to parallel the general directions of these veins and invariably such veins of greater than average thickness are found at the heads of such inlets. (Plate I, No. 2.) The broad tidal channel separating Die Eiland from the mainland is also developed along two exceptionally thick pyrite-tourmaline-jasperoid veins.

There is little doubt that the material filling these veins is connected with the late hydrothermal mineralisation along the zone extending from Helderberg through Koeberg to Yzerfontein and which Scholtz (1946, p. lxxviii) suggests is related to the intrusion of the Cape granites and represents the products of a single metallogenic epoch. In this connection, Scholtz records the presence of 4 penny-weight of gold and subordinate chalcopyrite in some of the massive pyritic quartz-tourmaline veins. A study of polished sections of these veins from the quarry, however, failed to reveal the presence of these ores, but frequent green malachite staining of some of the veins towards the south indicates the existence of copper compounds. It is interesting to note that chalcopyrite and blende have been observed in the granites of the Schaapenberg quarry. (Scholtz—personal communication.) Tin mineralisation evidently did not occur as far north as Yzerfontein and panned concentrates revealed no cassiterite.

STRUCTURE.

The directions over 350 joints and veins have been measured and their orientations are shown by Figs. 1 (*a*) and (*b*).



(*a*) (*b*)

FIG. 1.

Plot of the strike directions of 350 joints.
(*a*) Stippled—aplite dykes, solid black—veins bearing hydrothermal minerals.
(*b*) Barren joints.

From Fig. 1 (*a*), which shows the directions of those joints that have been filled with vein-material, either aplitic or hydrothermal, two systems are clearly defined. The older with a strike varying between 3° and 15° is the most important aplite direction, while the younger which is best developed between 138° and 141° is the most prominent direction south of the Point. Although aplites do sometimes follow them, these latter joints have been chiefly exploited by the later hydrothermal veins, and, without exception, all the larger veins follow this set.

Fig. 1 (*b*) represents the orientation of the younger joints along which no late, hydrothermal minerals were observed in the field. Here four definite sets are apparent, the oldest striking at approximately 170°. It is quite possible that the joints of this set are also filled with thin films of the hydrothermal material which may easily have been overlooked in the field. The 170°-set could then be introduced into Fig. 1 (*a*) where it would be intermediate between the 140° and the 9° systems. The orientation of interesting crush-breccias parallel to this direction is noteworthy. These breccias assume the form of broad veins filled with angular fragments of diorite and fine, black mylonite, and have been extensively tourmalinised. (Plate II, No. 6.) Both in appearance and alignment they parallel similar features observed at many localities in the Western Province granites, particularly near Cape Columbine.

The younger joints of the remaining sets, striking at approximately 56°, 82° and 97° are less persistent in length than the earlier joints, which they have often displaced. Finally, a further, nearly horizontal joint-direction, younger than all other sets, is ubiquitous. (Plate I, No. 3.)

Unfortunately, no flow structures in the diorites could be detected either in the field or in orientated thin sections, and it is therefore impossible to determine whether the alignment of the joints corresponds to q-, s-, or d-directions. That the 9°, 140° and possibly 170° sets are of early formation and that they were due to tensional forces is shown by their universal exploitation by the aplitic and hydrothermal fluids, and this, according to Balk (1937), indicates the q-direction rather than the s-direction. However, the alignment of these older joints roughly along the N.W.-S.E. direction indicates their concordance with those so prominently developed in the pre-Cape Granite plutons. In these the dominant N.W.-S.E. direction parallels both the linear flow structure and the direction of elongation of the plutons and, although they are occasionaly mineralised, apparently represent s-directions (Scholtz, 1946).

The older aplite-bearing veins may follow true q- or cross joints, while the hydrothermal minerals appear to have been emplaced along slightly younger s- or longitudinal joints, these structures probably originating under the regional stresses that were operative on the granites during their intrusion and consolidation. The younger sets, displaying a tendency for preferred orientation in the N.E.-S.W. direction, also have counterparts in the granites, and being barren, succeeded the introduction of the hydrothermal fluids.

IV. THE PETROLOGY OF THE BASIC ROCKS

The essential minerals present are: plagioclase, hypersthene, diopsidic augite, hornblende, biotite, orthoclase and quartz, while magnetite, ilmenite and apatite are the most abundant accessory minerals. Unaltered olivine is not found in any thin section but its presence in the darker varieties of gabbro is suspected and confirmed by chemical analysis. Chlorite, epidote, calcite, saussurite, uralite, talc and serpentine are present as alteration products. The modal proportions of these minerals are tabulated in Table II.

The texture of the rocks is very variable. In the gabbros it ranges from subophitic to monzonitic and poikilitic, and the preferred orientation of the plagioclase and pyroxene crystals in the banded varieties has already been described. The less basic rock-types, the diorites, develop a more uneven, eugranitic texture.

Except in the immediate vicinity of the crush-breccias there is no evidence that these rocks have been regionally deformed by either crushing or shearing. While the extensive alteration of the gabbros may be attributed mainly to weathering processes, to which they display a marked susceptibility, a certain amount of late, hydrothermal alteration has affected the diorites. Thus, although the freshest possible samples were collected during quarrying operations at the harbour, these rocks all showed varying degrees of alteration.

Plagioclase is one of the most abundant minerals in all the rock types and two generations of this mineral are present. The earlier generation varies in composition from an acid labradorite to a basic andesine, while the younger generation, confined to the transitional and dioritic suites, is usually oligoclase.

In the gabbros the individual crystals are distinctly lath-shaped with an average length of 2·5 mm. and a width of 0·5 mm. in the most basic varieties, but slightly less in the poikilitic types. Often the laths show euhedral borders and occasionally develop subophitic intergrowths with the pyroxene crystals, but usually a certain amount of mutual interference of growth between individual plagioclase crystals has resulted in more irregular boundaries. In the presence of large amounts of interstitial orthoclase, slight resorbtion has occurred, the sharp crystal corners having been rounded off and the faces scalloped by the orthoclase groundmass. This feature is most noticeable in the poikilitic varieties, but even here the lath shapes are retained and resorbtion is apparently less than that found in the other rock suites.

The plagioclase feldspars of the gabbroic suite are wholly of the first generation. Their anorthite content ranges from 57% in the most basic banded varieties, to 43% in the poikilitic type, while the average variation in any particular section was never found to exceed 4% An. The anorthite content is further found not to fluctuate appreciably across any particular band. Zonal structures are generally absent, although a slight normal zoning of less than 2% An. is observed in some of the larger, more basic crystals.

Far greater diversity is displayed by the plagioclase of the rocks of the transitional and gabbroic suites. Seldom do they reach the same dimensions as those of the gabbros, their length ranging from less than 0·1 mm. to about 1·0 mm., while the occasional crystal may exceed 1·5 mm. The largest crystals, with a core composition of from 40% to 49% An., are always the more basic and may present euhedral boundaries to pyroxene or other plagioclase crystals, but their edges against orthoclase or micropegmatite are always highly resorbed and completely anhedral. Except along their euhedral boundaries these crystals always possess a thin, zoned outer layer of more sodic composition. This mantle is so thin that the determined average composition of 28% An. is uncertain.

The smaller plagioclase crystals are universally associated with micropegmatite in which they occur as small rounded grains averaging less than 0·2 mm. in diameter. These show a normal zoning from core to mantle and their composition corresponds to the outer zone of the larger crystals. Their core composition may fluctuate between 38% and 28% An., while their mantles contain between 20% and 28% An.

The two generations of plagioclase feldspar in the rocks of the transitional and dioritic suites are thus clearly apparent. The first generation, represented by the more calcic cores of the larger crystals, corresponds in composition to the feldspars of the gabbros, while the thin outer layers of these and the smaller granular crystals, characterised by a more sodic composition, belong to the second generation. The role of the micropegmatitic fluid as both a resorber of the plagioclase crystals of the first generation and the medium from which the second generation crystallised is indicated.

On the whole the plagioclase is remarkably free from alteration. Only in the vicinity of the aplite and hydrothermal veins has it been much altered, while in some of the "inclusion-bearing diorites" the first generation cores have been rendered almost opaque by minute flakes of secondary material although the second generation mantles and granules remain perfectly transparent.

The relative frequency of the twinning laws exhibited by the plagioclases of the first generation (composition range 43% to 57% An.) in 50 crystals selected at random and determined on the Universal Stage is as follows:—

Albite	52%
Carlsbad	18%
Roc Tourné ...	18%
Albite-Ala	8%
Acline	4%

The twin lamellae of the second generation were found too narrow to determine the feldspar by the usual Universal Stage methods. Albite twins were therefore selected as far as possible and the compositions were deduced from the extinction angles against (010) in the [100]-zone.

Olivine was not found in an unaltered form, but in one section of a particularly dark gabbro abundant rounded grains of highly altered material are believed to be the decomposition products of olivine in view of their frequent inclusion within large host crystals of pyroxene. The average size of these decomposed patches is 1 mm., but those which are not surrounded by pyroxene may have an average major diameter of 3·5 mm. Three separate alteration products are recognised in these particles:—

(*a*) The central patch is composed of fine colourless flakes of talc which has replaced the olivine in such a way that all the flakes possess an approximately common optical orientation.

(*b*) Fine, dusty particles of opaque iron ore mark the approximate boundaries of the original crystals which sometimes show the typical six-sided form of a prismatic section of olivine. This secondary iron ore is also concentrated along lines which appear to be the traces of the irregular fracture surfaces in the original olivine crystals.

(*c*) Radiating out from the particles are pale green antigorite flakes. This product never occurs within the boundary marked by the outer iron ore layers, but completely surrounds the particles with layers from 0·1 to 0·3 mm. thick and from these it pervades along cracks and cleavages in the other minerals of the rock. It seems probable then that these decomposed patches represent altered crystals of an olivine with a fairly high tenor of iron. The pyroxenes were not found to show similar alteration.

Orthopyroxene is limited to the rocks of the gabbroic and transitional suites where it occurs as small subhedral grains often surrounded by clinopyroxene. The crystals range in size from 0·5 to 2·5 mm. and frequently show alteration to a pale green to colourless chlorite, decomposition commencing along the margins and cleavage traces of the mineral. When fresh, their negative optic axial angle varies between 49° and 52°. According to Winchell (1951) the composition of the orthopyroxene probably ranges from $En_{45}Fs_{55}$ to $En_{39}Fs_{61}$. The pleochroism: α = pale pinkish brown, β = colourless to pale yellow brown, γ = colourless to pale green; and absorbtion: $\alpha > \beta = \gamma$.

Clinopyroxene is the most widely distributed mafic material occurring in all the rock suites. The individual crystals are largest in the gabbros where basal sections often measure up to 4 mm. and prismatic sections up to 6 mm. Their crystal boundaries against the alkali feldspars are complete and euhedral, but a slight rounding of the sharp crystal corners may be detected in the poikilitic monzo-gabbro. Most of the clinopyroxene crystals are riddled with small poikilitic inclusions which may form up to 7% of the volume of the crystal and include orthopyroxene grains, rounded blebs of plagioclase, apatite and iron ore. The many biotite flakes occurring in the pyroxenes are regarded as "advance islands" in view of their exploitation of the cleavage directions and the fact that all the grains in a single pyroxene crystal show a common optical orientation. Similarly, adjacent interstitial orthoclase frequently veins the pyroxenes along the open basal parting or as irregular stringers aligned parallel to the prominent prismatic cleavages, and isolated blebs of this feldspar, showing optical continuity with the surrounding orthoclase ground, are taken to be transverse sections of such veins rather than poikilitic inclusions.

The same mineral is also abundant in the dioritic and transitional suites but, in the former, comparable dimensions are never obtained and the grain size is almost always less than 1 mm. In the dioritic suite too, the crystals are often resorbed and surrounded by reaction rims of hornblende and in some hornblende crystals only small skeletal remnants of pyroxene remain. This reaction is not common in rocks of the transitional zone.

The mineral appears to be a colourless to pale green diopsidic augite or endiopside, characterised by the following optical constants:—

$2V\alpha = 51^\circ\text{-}52^\circ$; $\gamma/c = 38^\circ\text{-}39^\circ$
$\beta = 1{\cdot}673 \pm 0{\cdot}002$; $\gamma - \alpha = 0{\cdot}0235$
Dispersion weak, $\rho > v$

According to Deer and Wager (1938) this represents an augite with composition $Wo_{38}En_{55}Fs_7$. It is interesting to note that a pyroxene with similar optical constants is found in the quartz-hyperites of Insizwa (Scholtz, 1936) and has been described in the rocks of the Basal Zone of the Bushveld Complex. These pyroxenes, however, usually display diallage parting parallel to (100), but this feature is not observed in the augites from Yzerfontein, although twinning, both simple and polysynthetic, always has this direction as composition face.

Zoning of the clinopyroxenes is rare. In two crystals, however, a slight zoning was observed whereby the cores have slightly lower axial and extinction angles ($2V\alpha = 49^\circ$; $\gamma/c = 37^\circ$) than the mantles which possess optical constants corresponding to those given above.

Like the orthopyroxene, the augite may alter to a pale green chlorite, but alteration to flaky uralite is also common.

Primary Hornblende is limited to the rocks of the dioritic suite, of which it may constitute up to 17%. The mineral almost always occurs as reaction rims surrounding pyroxene granules and the boundary between these two minerals is irregular and intergrown. The hornblende is usually confined to an outer reaction envelope but may penetrate far into the pyroxene crystal along cleavage and parting directions, and isolated patches of hornblende in common orientation with the material forming the reaction rim may riddle the larger pyroxene crystals. The reaction rims are further seldom homogeneous but contain many poikilitic inclusions of similar shape, size and mineral constitution as those found in the pyroxenes. Rarely are hornblende crystals found which do not contain pyroxene cores, and they may themselves be surrounded by reaction rims of biotite.

All the hornblende is of a green variety the optical constants of which are as follows:—

Optic axial angle: $2V\alpha = 76^\circ\text{-}82^\circ$
Extinction angle: $\gamma/c = 12^\circ\text{-}16^\circ$
Pleochroism: α = pale straw
β = pale green to olive-green
γ = brownish green, rarely bluish green
Absorption: $\alpha < \beta < \gamma$

Biotite is a component of all the Yzerfontein rock types constituting from 1·5% to 10% by volume.

The mineral is most commonly a golden brown type but may show slight variation of optic properties. It is probably a siderophyllite as shown by the following optical constants:—

Pleochroism: α = pale brownish yellow
$\left.\begin{matrix}\beta \\ \gamma\end{matrix}\right\}$ = golden reddish brown to blackish brown
Absorption: $\alpha < \beta = \gamma$
Refractive indices: $\gamma = 1{\cdot}641 \pm 0{\cdot}002$
$\alpha = 1{\cdot}600 \pm 0{\cdot}002$

The biotite occurs abundantly as a reaction product of pyroxene and hornblende. In the quartz-free rocks it forms directly by reaction with pyroxene, but in the presence of micropegmatite or quartz the pyroxene is first replaced by hornblende which is in turn converted to biotite. The mineral is also often associated with the accessory minerals, apatite and ilmenite, or it may occur as a primary mineral in the form of large equidimensional flakes. Further, in the poikilitic gabbros, nodules composed of small, radiating and bent flakes of biotite are common in the large orthoclase individuals.

The mineral commonly alters to a pale green to colourless chlorite, usually with the segregation of fine ore particles along the cleavages.

Alkali Feldspar and Quartz occur both as micropegmatitic intergrowths and as individual minerals.

In the gabbros, alkali feldspar is typically interstitial and forms the groundmass in which the other earlier crystals, with idomorphic outlines, are embedded. Its appearance is that of a late liquid filling the spaces between the components of a relatively porous crystal mush, and for large stretches this feldspar ground mass shows optical continuity. The mineral constitutes varying proportions of the gabbro and Table II shows that it is most abundant in the poikilitic varieties. The figure here given is, however, considered misleadingly high as the cut sections usually covered only the large poikilitic orthoclase insets and seldom included the orthoclase-free gabbro between these portions.

The alkali feldspar of the gabbro is always perfectly fresh and either untwinned or simply twinned according to the Carlsbad law. The optical axial angle, $2V\alpha$, varies from 61° to 66° indicating soda-orthoclase. The optical constants of the alkali feldspar in the micropegmatite are more variable but also indicate a soda-orthoclase.

Micropegmatitic intergrowths of alkali feldspar with quartz are limited to the rocks of the dioritic and transitional suites. Here too the mineral has the appearance of having been introduced as a late fluid which bore a reaction relation to the minerals of earlier crystallisation. The components of this intergrowth may show optical continuity over large areas or they may form smaller shapeless grains with diameters ranging down to about 0·2 mm. The intergrowth has by no means been evenly developed, most of the grains showing portions entirely free of quartz. Where it does exhibit homogeneous development the ratio of quartz to feldspar was measured and found to remain practically constant at 27·2% : 72·8%. The quartz stringers of the micropegmatite are seldom wider than 0·02 mm. and under normal magnification they give the micropegmatite a dusty appearance. This is also due to the presence of many fine inclusions, most notably long slender needles of apatite with average dimensions of 0·04 by 0·005 mm. Among the larger inclusions apatite and iron ore are prominent.

Just as orthoclase free from quartz may be found in the transitional and dioritic suites, so also are patches of free quartz found in these rocks. The mineral is, however, usually subordinate and fills interstitial voids between the minerals of earlier crystallisation.

The Accessory Minerals are apatite, magnetite, ilmenite and sphene. The apatite of the gabbro occurs as fairly large euhedral crystals and is present as inclusions in practically all the minerals of this suite. Apatite crystals of a similar size and appearance are also found in the transitional and dioritic suites. In these latter suites there are also developed smaller acicular apatites chiefly associated with the micropegmatite.

Much magnetite has been released by the alteration of the mafic minerals but the primary mineral is more abundant. Together with ilmenite it is prominently included in the biotite and pyroxene grains. Small amounts of sphene are found in the less basic rocks, while zircons are absent. Pyrite, tourmaline, epidote, calcite and hematite may be developed in accessory amounts by hydrothermal alteration.

V. REACTION RELATIONS IN THE DIORITES

Reaction rims are commonly observed amongst the dark minerals of all the Yzerfontein igneous rocks, their best development being attained in the dioritic rock (augite-biotite-diorite) collected at the Vlaekop beacon where resorbed cores of augite are completely surrounded by hornblende, which may in turn have rims of biotite. A further example of a discontinuous reaction relation is shown between the hyperthene and the surrounding augite in the gabbroic rocks, and an example of a continuous reaction series, by the normal zoning of the plagioclase crystals in the diorites.

During the petrological examination of the rocks it was observed that, when a twinned crystal of augite was surrounded by a reaction rim of hornblende, the replacing hornblende was also twinned and in such a manner that the twinning laws were identical and that one and the same plane formed the composition face of the twin in both minerals. This could only be explained by a preferential orientation of the reacting material towards the orientation of the core mineral being replaced. It also indicates, incidentally, that the (100) twinning of hornblende is paragenetic rather than metagenetic. After the measurement of the relative orientations of a number of pyroxene cores and amphibole mantles, constant relation between the two parts became apparent.

An attempt was therefore made to determine whether such constant orientation relations are common between the rim and core material in the discontinuous reaction series of N. L. Bowen (1928, p. 61):—

olivine—Mg pyroxene—Ca-Mg pyroxene—amphibole—biotite.

The determinations were made primarily on the Yzerfontein rocks, but they were supplemented by and checked against observations made on rock-sections from the Malmesbury diorite, the picrites and hyperites of Insizwa, the Bushveld gabbros and norites and rocks from the basal zone of the Stillwater Complex, Montana. The investigation showed that such relations undoubtedly exist, and in Fig. 2 stereographic projections of the principal morphological and optical directions of these minerals have been arranged in such a way as to reflect their mutual orientations in reaction rims.

Olivine-pyroxene reaction.

No observations of this nature could be made on the Yzerfontein rocks, but determinations on other olivine-bearing rocks show that a complex relation may obtain between the two minerals. This becomes apparent when the crystallographic b-directions of a number of pyroxenes are plotted stereographically relative to the b-axes of an olivine crystal. The tendency for the pyroxene b-axes to concentrate around the poles of $\{101\}$, $\{160\}$, $\{1\bar{3}1\}$, etc., is then observed. These directions appear to be related to the face-normals of the isolated Si-O tetrahedra forming the fundamental structure of the olivine.

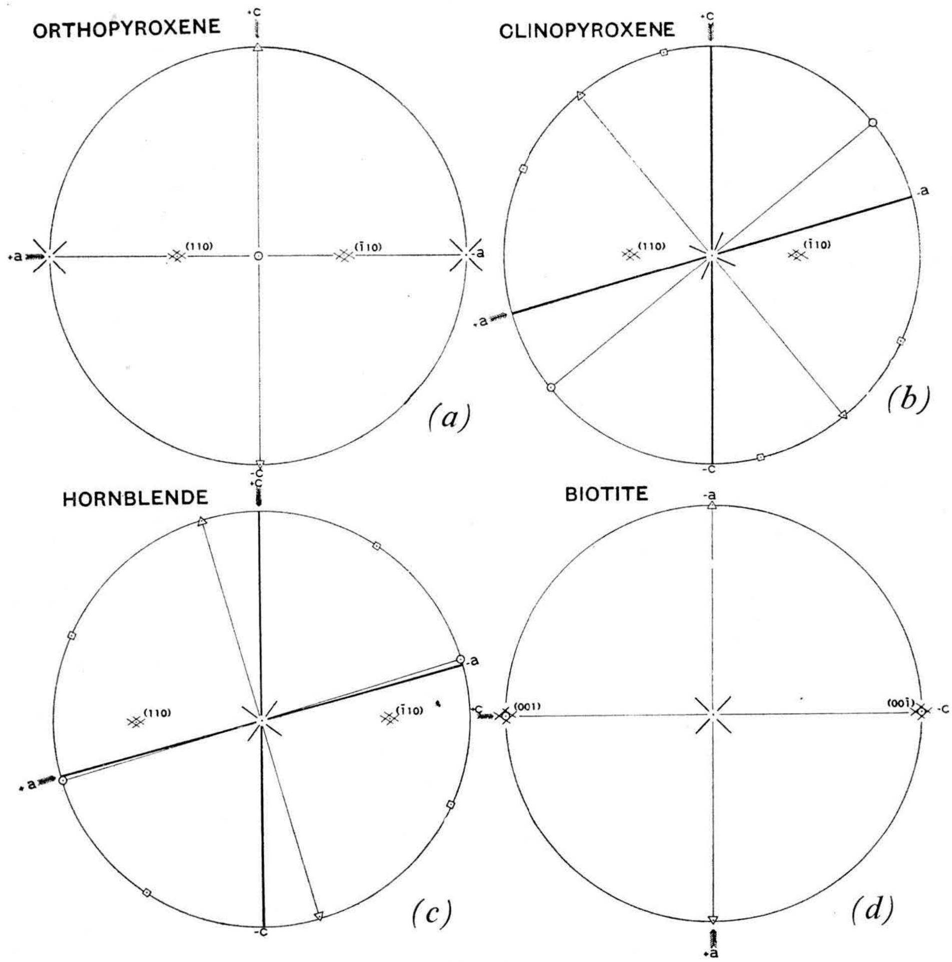


FIG. 2.

Illustrating the relation obtaining between the aether axes (α = ⊙, β = -|-, γ = △) and the a-and c-crystallographic axes in the (010) plane of the principal dark minerals of the reaction series.

Orthopyroxene-clinopyroxene reaction. (Figs. 2 (*a*) and 2 (*b*)).

Hypersthene is often surrounded by or in contact with augite in the gabbroic rocks of Yzerfontein, but true reaction or replacement structures are comparatively rare. Their inter-relationship suggests rather that the two minerals separated from the liquid more or less simultaneously and the greater part of their crystallisation periods overlapped. Under such circumstances true reaction rims of clinopyroxene about orthopyroxene are not expected to be abundant. Where they are developed, however, the two minerals of the reaction pair show common cleavage traces, while the α-axis of the ortho-pyroxene coincides with the β-axis of the clinopyroxene. Adopting Groth's orientation of the orthopyroxene, such that the axial ratio a : b is greater than unity, these observations show that the b- and c-crystallographic axes of the replacing clinopyroxene are arranged parallel to the corresponding axes of the orthopyroxene.

A similar relationship was observed by H. J. Nel (1940, p. 48) in the diabases of the Basal Zone of the Bushveld Complex where "monoclinic pyroxene is sometimes found as a mantle round the hypersthene, the latter in this instance always exhibiting embayed outlines". J. C. Boshoff (1942) reports a like feature in the diallage-gabbros of the Upper Zone of the same intrusion, and he shows further that, where the orthopyroxenes of the olivine-diorites exhibit sets of fine, clinopyroxene exsolution lamellae, the same orientation is common but not exclusive. G. S. J. Kuschke (1939, p. 62) and H. J. Nel (1940, p. 54) confirm this for rocks of the Basal and Critical Zones of the Complex.

Clinopyroxene-Amphibole reaction. (Figs. 2 (*b*) and 2 (*c*)).

In every case of the development of hornblende reaction rims about clinopyroxenes at Yzerfontein, the following mutual relations are found:—

(*a*) the optic axial planes of the two minerals are parallel,
(*b*) the prismatic cleavages of the two minerals are tautozonal.

Since the β-axis of each mineral is coincident with the b-crystallographic axis of that mineral, and since the cleavages in each case lie in the (100) zone, it follows that the amphibole replaces the pyroxene in such a way that their b- and c-crystallographic directions coincide. The a-axes, however, differ slightly, this being due to the slight difference of monoclinic angle of the two minerals.

In the investigation it was also observed that the direction of one of the optic axes of the augite always coincides with one of the hornblende, while the direction of the other augite optic axis very nearly parallels the γ-direction of the hornblende. This relation is, however, probably purely coincidental, resulting from the particular optic constants of these two mineral varieties, and is not expected to be general.

An attempt to trace literature on this point revealed that, as far back as 1896, A. Harker (1896, p. 324) described similar relations where augitic xenocrysts derived from gabbro are surrounded by reaction rims of green hornblende in the granophyres of Strath (Skye), replacement occurring in such a way that the b- and c-axes are common to both portions. It is perhaps interesting to note that these two minerals have identical extinction angles to those found at Yzerfontein.

In his description of the diorites of Klein Paardeberg, Malmesbury district (Oranjefontein stock), A. W. Rogers (1905, p. 48) mentions that "the pyroxene sometimes forms complicated intergrowths with the hornblende and also occurs in the centre of large hornblende crystals; in such cases one set of prism cleavages is common to both minerals". Microscopic examination of the rocks from this area, however, failed to disclose such relations, but fully confirmed the replacement noted at Yzerfontein.

Amphibole-biotite reaction. (Figs. 2 (*c*) and 2 (*d*)).

The examination of the orientation of biotite reaction rims relative to that of hornblende cores shows that:—

(*a*) the optic planes of the two minerals are parallel,
(*b*) the biotite cleavage (001) is parallel to the (100) direction of hornblende,
(*c*) α of biotite falls in the [001]-zone of hornblende,
(*d*) the γ-axis of biotite parallels the c-axis of hornblende.

Resolving these to the morphological directions of the two minerals, biotite replaces hornblende in such a way that their b-crystallographic axes remain common, while the a-direction of biotite coincides with the c-direction of hornblende. In addition, this arrangement preserves the tautozonal disposition of the prominent cleavages of the two minerals, a feature already noted in the pyroxene-amphibole reaction.

Occasionally, biotite may appear as a direct reaction product with pyroxene and here the relative alignment of the two minerals is the same as it would have been had an intermediate reaction layer of hornblende been present. D. L. Scholtz (1936, p. 116) noted this tendency towards parallel alignment of the aether axes of biotite flakes replacing pyroxene in the hyperites of Insizwa.

To summarise, it appears then that when an earlier mineral of the discontinuous reaction series:—

olivine-orthopyroxene-clinopyroxene-amphibole-biotite

is surrounded by a later one of the same series, *a definite crystallographic relation* obtains between the two individuals. When olivine forms the core, the relations may be complex, but in all the other cases the b-crystallographic axes coincide, while the most prominent cleavages tend to be tautozonal.

The above associations may relate to the conversion of the fundamental silicon-oxygen tetrahedral structure of the mesosilicates, first to that of the inosilicates and then to the phyllosilicates with decreasing temperature. The relations are such as to require the least possible rearrangement of this fundamental structure, while the diffusion of the ions not forming part of the silicon-oxygen framework would accompany such conversion. Such features demand equal freedom of growth in all directions and would therefore be expected to obtain only under the influence of hydrostatic pressure, such as would exist in a fluid, magmatic environment, but not in the restricted, solid state.

VI. THE ANALYSIS OF THE PRIMARY BANDING OF THE GABBROS

The poverty of exposures of rocks of the gabbroic suite renders impossible the task of determining the probable form and size of the gabbro body on the distribution of these outcrops alone. The development in these rocks of primary rhythmic banding was, however, believed to have some genetic significance, and in an attempt to obtain additional information this feature was investigated in greater detail.

The field appearance of the banding has already been described and in this connection it simulates both the "rhythmic layering" of the Layered Series of the Skaergaard Intrusion as described by L. R. Wager and W. A. Deer (1939), and the "primary banding" observed by H. H. Hess (1938) in the norites of the Stillwater Complex.

Mineralogically the banded rock is essentially composed of varying proportions of labradorite, augite, hypersthene, biotite and orthoclase. The plagioclase and pyroxene usually occur as large, individual, well developed crystals, although rounded grains of orthopyroxene may often be included in more perfect clinopyroxene crystals. Their appearance may suggest their accumulation as discrete crystals and, solely for descriptive purposes, they may be called the early precipitate, while the interstitial orthoclase and biotite appear to have crystallised subsequently from a liquid which surrounded the early crystals and may be termed the rest magma or inter-precipitate material. Thin sections cut across the plane of banding exhibit a directed texture as the crystals of the primary precipitate appear to be preferably orientated with their largest dimensions parallel.

This feature is described as igneous lamination and in order to ascertain its genetic connection with the primary banding, these rocks were subjected to a series of petrofabric analyses. The direction followed by this investigation was an examination of the frequency of the orientation of the primary crystals in thin sections cut both parallel to and at right angles to the banding. Following custom, the three mutually perpendicular fabric axes have been chosen so that the c″-axis is normal to the banding and the a″- and b″-axes lie within this plane. The b″-axis is horizontal and corresponds to the strike of the banding at 72° M.N. while the a″-axis dips towards the south-east at an angle of 68°. The density gradation indicates that the base of the body lies towards the north.

The results of the investigation of clinopyroxene and plagioclase are, for convenience, discussed separately.

(1) *Clinopyroxene.*

Most of the crystals of this mineral show a distinct elongation in the direction of the c-crystallographic axis and, in addition, show flattening parallel to the clinopinacoid crystal face. Contoured petrofabric diagrams showing the concentration of these features in various orientated sections were therefore prepared after the method described by Fairbairn (1942).

Diagrams showing the distribution of the c-crystallographic axes all display a pronounced concentration of points along a belt seldom more than 20° broad and coincident with the a″b″-fabric plane. This is clearly illustrated by Fig. 3 (*a*), a collective diagram of information obtained from three sections cut perpendicularly to the c″-fabric axis. The complete girdle concentration along the periphery of the projection circle indicates that the c-crystallographic axes of the clinopyroxene crystals either lie in the plane of banding or are inclined thereto at a slight angle. The slight grouping of poles at two points on opposite sides of the circle, constituting a maximum in this plane, may indicate minor directional control over the alignment of the grains.

Closely related to this pattern is the pronounced axial symmetry of diagrams showing the distribution of β-aether axes of this mineral. Fig. 3 (*b*), prepared in a similar way to Fig. 3 (*a*), clearly illustrates this concentration of β-axes approximately parallel to the c″-fabric direction. Since the direction of β coincides with [010] or the normal to the (010) crystal-face, the arrangement of the clinopinacoidal faces of clinopyroxene parallel to the plane of banding is indicated by this pattern.

Single crystals of different orientation from those described above were occasionally encountered but, through limiting the lowest contour value to 2%, they do not appear in Figs. 3 (*a*) and (*b*).

(2) *Plagioclase Feldspars.*

The plagioclase crystals of the banded gabbro generally possess a tabular habit, "a habit which is usual for bytownite and labradorite in basic igneous rocks" (Wager and Deer, 1939). Cross-sections of these crystals, however, are nearly always rectangular and flattening is commonly parallel to the clinopinacoid, but larger faces may occasionally be developed in the case of (001), (021), ($0\bar{2}1$), etc. Because of this, it was considered inadvisable to express the orientation of the plagioclase crystals in terms of their crystallographic directions. Instead, only the orientations of the longest axes of all feldspar laths showing a fairly pronounced elongation were measured in sections cut in the three principal fabric directions. The results so obtained were

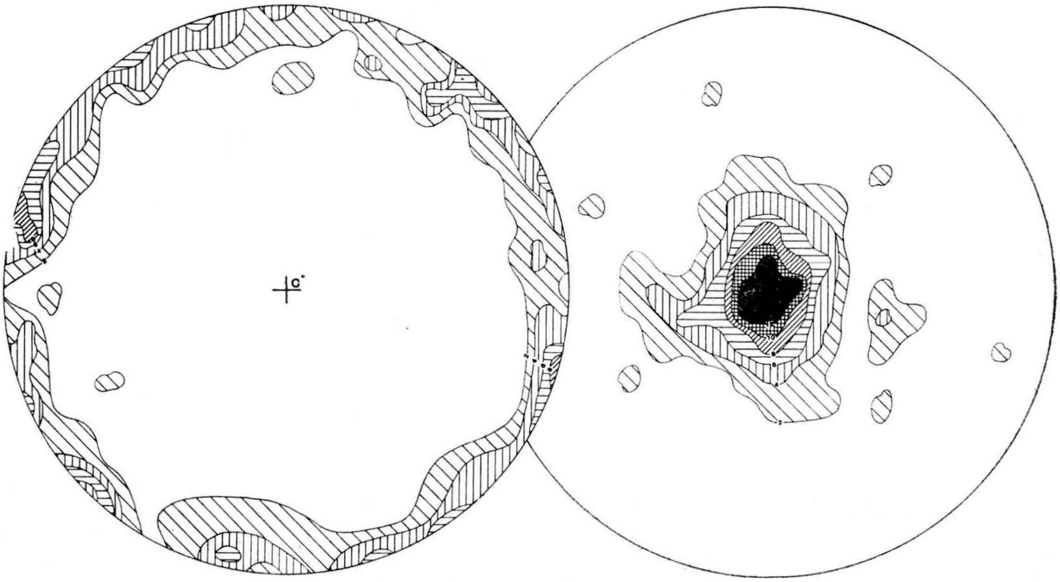


FIG. 3.

(*a*) (*b*)

Petrofabric diagrams of sections cut perpendicular to the c″-fabric axis, showing the distribution of (*a*) 100 c-crystallographic axes, and (*b*) 100 β-axes of clinopyroxenes. Distribution contours at 2-4-6-8-10-12%.

utilised in preparing azimuth diagrams as described by Fairbairn (1942). On the one hand, diagrams of sections cut perpendicular to the c″-fabric axis show a random orientation of the elongation of these crystals in the plane of banding, while on the other hand, Fig. 4, which is of sections cut parallel to the c″-axis, indicates a pronounced common orientation of the elongated feldspares in such a way that their longest axes lie parallel to the plane of banding.

To summarise, the principal features of the igneous lamination of the banded gabbros at Yzerfontein are such that the somewhat flattened early crystals all have their greatest dimensions parallel to the plane of banding. In petrofabric diagrams this is apparent as a complete belteroporic girdle concentration of the elongation elements perpendicular to the c″-fabric axis, and a pronounced axial symmetry of the normals of the best-developed crystal faces parallel to this direction.

According to E. B. Knopf (1938, pp. 70 and 123), axial symmetry is characteristic of the depositional fabric of non-tectonites, but may also be developed in *B*-tectonites. Similarly, a girdle fabric may be displayed by both tectonites and non-tectonites, but, whereas the non-tectonite depositional girdle is normal to the c″-axis, tectonite girdles usually parallel this direction. The preferred orientation of the crystals of the Yzerfontein banded gabbros therefore indicates a depositional fabric, which results from "the deposition of particles in a stagnant medium by a settling movement under the influence of gravity." (Knopf and Ingerson, 1938.)

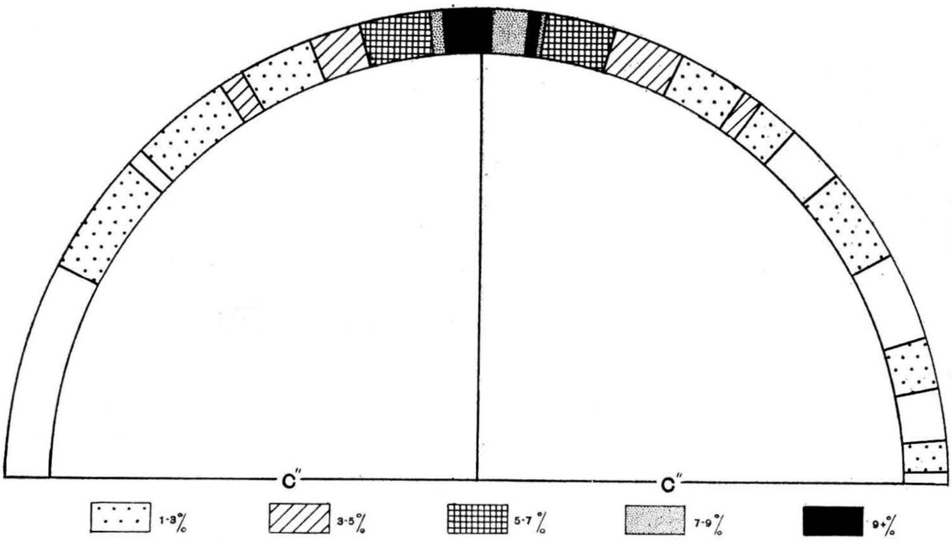


FIG. 4.

Azimuth diagram of the orientation of the elongation of 200 feldspar laths, in sections cut parallel to the c″fabric axis.

Various theories to explain the formation of primary rhythmic banding have been advanced and have been ably reviewed by R. A. Daly (1933), R. R. Coats (1936), H. H. Hess (1938), and L. R. Wager and W. A. Deer (1939). These theories may now be briefly referred to especially on the basis of the fabric of igneous lamination, in order to ascertain which would best explain the rhythmic banding as observed at Yzerfontein. Obviously, in view of the clear depositional fabric, any process operative in the solid state could not have obtained.

The magmatic theories may be broadly divided into the following:—

(*a*) theories which require the intrusion of two different magmas,
(*b*) theories relying on strong convection currents in the magma during crystallisation, and
(*c*) theories of gravitative settling from a quiet magma.

(*a*)

Although the proportions of the minerals vary across the individual bands, they show no variation in either composition or size. This is suggestive of a consanguineous relationship between even the most extreme rock types in the banded gabbros, and the banding could therefore hardly have resulted from the intrusion into the same chamber of two different magmas, either simultaneously as proposed by A. Harker (1904), or successively as suggested by N. L. Bowen (1928). The regular rhythmic nature of the layering and the well-defined density gradation across the bands would also be difficult to explain by such a process.

(*b*)

F. F. Grout (1918) has suggested that convection currents in the magma were responsible for the banding of the Duluth gabbros, while Wager and Deer (1939) conclude that a similar process, coupled with crystal fractionation, resulted in the primary layering of the Skaergaard Intrusion. In the latter instance, crystals of early precipitation which formed at the roof and margins were transported to the floor of the intrusive body where they were graded according to their densities and evenly distributed by these strong magmatic currents. The rhythmic nature of the banding is attributed to the periodic nature of these currents. Much evidence from the field shows the existence of the powerful convection currents, the most important being the distinct linear arrangement of the rectangular plagioclase laths in the plane of igneous lamination. The absence of any pronounced lineation at Yzerfontein emphasises rather the quiescence of the gabbro magma during the formation of the bands, and crystal settling, without the aid of convection currents, seems a more likely explanation of this feature.

(*c*)

The earlier theories of crystal settling of P. A. Wagner (1924), A. L. Hall (1932) and R. A. Daly (1933) were more in the nature of preliminary suggestions and were conceived to explain the large-scale, regional banding observed in the Bushveld Complex rather than the type of local, rhythmic banding under consideration. R. R. Coats (1936) first advanced the theory that rhythmic banding could result from a process involving the simultaneous crystallisation and settling under the influence of gravity of two or more minerals in a magmatic medium of lower density. This mechanism of "rhythmic differential settling" was, moreover, supported by laboratory experiments.

An essentially similar theory has been advanced by H. H. Hess (1938) to account for the banded norites of the Stillwater Complex. The rhythmic nature of the banding, as well as the occurrence of "zones of disturbed banding", was explained by "disturbance of the normal state of quiescence in the magma by short epochs of mild, but irregular turbulence". In both hypotheses the actual deposition of the crystals takes place from a practically motionless magma and igneous lamination, with a distinct non-tectonite depositional fabric, may therefore be expected to be developed by either process. On the texture alone then, neither mechanism can be favoured, but the presence of possible zones of disturbed banding at Yzerfontein may indicate that the process outlined by Hess has here been operative.

A recent petrofabric study by J. J. van den Berg (1946) of the igneous laminated gabbros of the Bushveld at Bon Accord has revealed a fabric so similar to that of the Yzerfontein banded gabbros that a comparison of the two is instructive. Orthopyroxene and plagioclase crystals form the early precipitate of the Bon Accord gabbros, and the preferred orientation of these crystals gives the rock a fairly distinct non-tectonite depositional texture. The formation of these rocks by fractional crystallisation and crystal settling, as first proposed by P. A. Wagner (1924), is thus fully substantiated. In an important respect, however, the fabric of these rocks differs slightly from both the ideal depositional fabric, as described by E. B. Knopf (1938), and that of the Yzerfontein gabbros. This is apparent in petrofabric diagrams of the elongated elements which show a fairly definite preferred alignment parallel to the strike direction of the igneous lamination. Van den Berg interprets this feature as the effect of "the force of intrusion" of the magma on the settling crystals. J. Ellis (1946) suggests that the lineation is due to glide and recrystallisation in the solid phase.

Neither of these explanations appears to be satisfactory, the former because the "force of intrusion" during crystallisation was the isotropic hydrostatic pressure of the fluid magma, and the latter in view of the non-tectonic nature of the fabric.

The typical girdle as postulated by E. B. Knopf is, however, such as would be formed only by deposition on a flat floor, and the lineation observed by van den Berg could more suitably be explained by a slight variation of the normal crystal settling process.

The non-tectonic depositional fabric may be attributed to two factors: the planar control of the floor of deposition, and the linear gravitational force of settling; and for perfect development it must be assumed that the latter acted perpendicularly to the former so as not to destroy its planarity. If, however, the floor of deposition slopes, then a component of gravity would act in the direction of the dip of the floor and the linear elements would show some degree of preferred orientation within the plane of foliation and at right angles to this component. This lineation would disturb the perfection of the even girdle fabric pattern by displaying a maximum concentration of elongation at right angles to the slope of the floor, while not appreciably affecting the axial symmetry of the tabular elements.

Unfortunately, literature pertaining to the petrofabrics of undoubted igneous non-tectonites is surprisingly limited and no mention of the variation of the attitude of the floor of deposition could be found.

If, however, the above argument is correct, then the fabric of the Bushveld gabbro at Bon Accord is exactly that which would be expected from the settling of crystals under the influence of gravity on a *moderately inclined* floor. Although the floor of the Bushveld is generally believed to be basined, and around the periphery both the planes of pseudostratification of the basal rock and the contact with the underlying sediments dip regularly towards the centre, often at high angles, practically all writers on the Complex apparently consider that the attitude of the floor and the pseudostratification was horizontal or nearly so, not only at the time of the intrusion of the basic magma, but also during its consolidation. The crustal collapse which caused the central subsidence is generally regarded as having been initiated by the intrusion of the later Red Granite magma into a position above the solid norite body. No positive evidence has, however, been submitted which would justify this insistence on an initial horizontal, rather than a slightly basined attitude of the norite body.

Thus, P. A. Wagner (1924, p. 77 and 1929, p. 41), on the presumptive evidence that the rocks of the Transvaal System, forming the floor of the body, were horizontal or nearly so at the time of the basic intrusion, accepts unreservedly G. A. F. Molengraaf's original suggestion (1904, p. 57) and assumes that the present basin-like disposition of the Complex originated subsequent to the consolidation of the igneous rocks composing it. A. L. Hall (1929, p. 12 and 1932, p. 201 *et seq.*) relies on the horizontal attitude of the norite body during its consolidation to account for the remarkable conformity of the plane of pseudostratification displayed by the basic rocks, and concludes that the original norite body had the form of "a gigantic sub-horizontal sill". A. L. du Toit (1939, p. 174), also impressed by the regularity of the mineral banding, contends that the pseudostratification "was produced in an approximately horizontal position" and that the basining was presumably subsequent to the consolidation of the norite.

A notably different view is, however, expressed by R. A. Daly (1928), who indicates the significance of simultaneous crustal subsidence and magmatic intrusion, as by this means the depression of salic material to a hotter region may have been responsible for the generation of the younger granite magma. Daly therefore questions the majority opinion that the banding was initially horizontal and, by analysing the mechanics of the intrusion, believes that "the magmatic extrusions meant the transfer of material from beneath the crust, which was therefore, inadequately supported", and demonstrates that the central subsidence and basining of the Transvaal beds was closely connected with the emplacement of the Complex. While the weight of igneous material on the sedimentary floor must necessarily have functioned in an analogous manner, Daly apparently regards its effect as being far less important.

The close relationship between the attitude of the Bushveld Complex and the rocks of the Transvaal System cannot be overemphasised and there can be little doubt that the intrusion of the Bushveld magmas was an integral phase of the geosynclinal cycle of the deposition of the Transvaal sediments. Unfortunately, the sedimentational aspects of these rocks have not yet been fully investigated, but the primary structures indicate that deposition frequently occurred under shallow water. In order to accommodate the considerable thickness of sediments (varying between 9,000 and 16,000 feet) and yet retain a shallowly submerged upper surface of deposition, continual gradual subsidence of the sediment-collecting basin must have kept pace with the deposition.

On the one hand then, there is no reason to believe that this sagging ceased during or immediately following the intrusion of the magma, especially as the emplacement of the Complex accompanied the foundering of the crust, while on the other hand, justification could not be found for the argument that the regular banding could only have been formed by differential crystal settling on a horizontal floor, and the development of equally distinct banding with an original, moderate inclination is believed to be possible. Under the circumstances, it may reasonably be deduced that the floor of deposition of the basal rocks of the Bushveld Complex possessed an initial shallow, though somewhat elongated, basin-like form and that the present high centripetal dips recorded along the margin of the Complex must not be attributed entirely to conditions closely following the intrusion of this magma, as considerable central subsidence followed the consolidation of these rocks. This must naturally be attributed to the adjustment of isostatic equilibrium, necessitated by the tremendous load carried by this portion of the crust. Du Toit (1933, p. 11) shows that the latest movement in this direction dates to as recent a time as the mid-Tertiary and amounted to a sinking of the surface of the basin of perhaps 1,000 feet. The evidence for this warping has been deduced largely from the behaviour of the diamondiferous gravels of the Lichtenburg and Ventersdorp district when traced up to the margins of the depression (du Toit, 1933), and the nature of the antecedent rivers which cross the Bushveld Basin of the Central Transvaal (Maske, 1956).

From the above discussion we may conclude that the sedimentary floor of the Bon Accord gabbros, at the time of their intrusion, was moderately inclined, although the present centripetal dip of 30° must be attributed in part to considerable post-consolidation tilt. The fabric of the rock indeed seems to substantiate this conclusion and it is reasonable to assume that the development of the lineation observed in such a fabric is a function of both the degree of inclination of the floor and the elongation index of the crystals. In this respect it is interesting to note that in a preliminary investigation (based on measurements of only two thin sections) of the fabric of pyroxenites from the Eastern Transvaal, van den Berg (1946) observes that there is no evidence of linear orientation owing to the equidimensional habit of the pyroxene crystals. The elongation index of the orthopyroxenes of the Bon Accord gabbro has an average value of 3, while that of the clinopyroxenes of the Yzerfontein gabbro is but slightly less. The preferred orientation of these elements in the plane of foliation is, however, decidedly inferior in the latter when compared to that displayed by the former, and it is believed that the inclination of the floor of the Yzerfontein gabbro body could not have exceeded the order of a few degrees during the consolidation of the banded rocks.

The small extent of these rocks, however, renders a deduction of either the shape or the size of the body speculative. The regularity of the banding and the coarseness of grain suggests a fairly large body, probably a thick sill or laccolith, in which, according to Wager and Deer (1939), powerful, regular convection currents are less likely to develop than in a funnel-shaped body. Further, as the process of rhythmic differential crystal settling requires the presence of a "head" of magma above the consolidating rock, the banded gabbro presumably occupied a position in the lower portion of the body. The attitude of the banding is no longer horizontal but dips steeply towards the south-east. This tilting, necessarily subsequent to the consolidation of the layered rock, indicates that the greater portion of the gabbro body should lie beneath the surface on the south-eastern side of the foliation plane of these banded rocks.

In conclusion, it would seem as if the fabric displayed by gravitational accumulations of early minerals of bladed habit enables the petrographer to deduce the initial attitude of the depositional surface of intrusions characterised by fractional crystallisation along a gravity gradient.

VII. THE PHASE PETROLOGY OF THE BASIC ROCKS

Owing to the gradation between the various rock types, the lack of sharp intrusive contacts between them and the poverty of primary flow structures in the less basic varieties, it was considered advisable to map the Yzerfontein Complex according to the distribution of "critical mineral phases" rather than by the traditional practice of mapping arbitrary "rock species". The former method of mapping is attributed to Shand (1942), and the terms "phase" and "critical phase" are here used not in the strict thermodynamic sense but in the sense implied by Shand. Applying this method in a modified form, van Zyl (1950) was able to ascertain the stock-like form of the Malmesbury diorite bodies by mapping the distribution of the dark minerals.

At Yzerfontein, it was found that olivine, hypersthene, hornblende and quartz are critical phases, their distribution being restricted to particular parts of the complex and also to particular periods in the cooling history of the magmas. Although plagioclase is widely distributed in all the rocks, the recognition of two generations of this feldspar, namely, an earlier and widely distributed variety, and a later type characterised by a more restricted occurrence, permits the distinction of a critical oligioclase phase. Quartz is usually microscopically intergrown with orthoclase in the form of micropegmatite, and, since the occurrence of this intergrowth is limited, it is also critical. As the distribution of the micropegmatite is identical to that of quartz, it was found convenient to map the distribution of micropegmatite.

To a certain extent the distribution of these critical phases is interrelated and the mapping of this distribution discloses the existence of three distinct zones (see accompanying geological map, Plate III):—

Z 1. An olivine-hypersthene zone.
Z 2. A hypersthene-micropegmatite-oligioclase zone.
Z 3. A micropegmatite-oligoclase-hornblende zone.

The apparent parallelism between the location of the zones and the distribution of the various rock suites follows, of course, from the method whereby the rocks of the complex were subdivided into their different suites. The ultimate basis for this classification has been mineralogical. Thus Z1 covers the distribution of the gabbroic suite;

Z 2 comprises what has been referred to as the "transitional zone"; while the rocks in Z 3 correspond to the dioritic suite.

Although augite and basic plagioclase feldspar do not represent critical minerals, their ubiquitous distribution is important as it offers a clue to the relative ages of formation of the zones. During their petrological examination, it was noted that in Z 1 these minerals show their most perfect crystalline development and largest dimensions, while resorption, replacement and a decrease of grain size is observed in Z 2 and Z 3. In other words, the formation and growth of these minerals in Z 1 was followed by their corrosion, resorption and replacement in Z 2 and Z 3, thereby implying that the rocks of Z 1 are older than those of Z 2 and Z 3.

The original form and extent of the gabbro intrusion (Z 1) has been discussed and the positions of Z 2 and Z 3 indicate the discordant intrusion of a later magma cutting across the strike of the primary banding of the gabbro. Field and microscopic evidence suggests the incorporation in this magma of much disintegrated gabbroic material, probably derived from both crystalline and partly crystalline xenoliths and xenocrysts. The micropegmatite appears to be genetically related to the later magma which reacted with the augite and basic plagioclase xenocrysts of the gabbro, precipitating the critical hornblende and oligoclase phases, and the resultant, highly contaminated magma appears to have finally crystallised as the diorites of Z 3. Apart from the discordant attitude of the diorite body and its possible downward and eastward extension, phase petrology could offer no further evidence as to the form of this body.

Both the intermediate position of Z 2 and the field characteristics of this zone suggest that it is a marginal phase of the diorite in which further mixing between the gabbro and the contaminated dioritic liquid occurred.

VIII. THE CHEMISTRY OF THE IGNEOUS ROCKS

As no analyses of the igneous rocks of Yzerfontein were available and since chemical data were considered necessary for the interpretation of the relations between the rock types, 14 representative samples were submitted to the Division of Chemical Services for analysis. Five of the samples were of rocks belonging to the gabbroic suite, one to the transitional suite, four to the dioritic suite and four were of the aplitic and pegmatitic injections. These analyses, listed on Table I (*a*), show an increase in the silica content from the gabbroic type to the aplitic and pegmatitic varieties, and it will be seen that the silica ranges of the different types do not overlap. The Niggli molecular values and the basic molecular norms, as calculated from the analyses, appear in Tables I (*b*) and I (*c*) respectively.

In order to deduce the possible origin and to ascertain the course of crystallisation of the Yzerfontein rocks, several variation curves, based on the norms, the Niggli-values and the relative proportions of the various oxides, were prepared. These were compared with standard curves.

Early in the mineralogical investigation it was felt that, owing to the prominent development of orthoclase, the series may show potassic rather than calc-alkaline affinities. A diagram of the *k'*-type (Fig. 5), which represents the relative amounts of normative feldspar, shows, however, that except for the aplite and pegmatite analyses (Nos. 11, 13 and 14) the entire series belongs to the calc-alkali suite.

TABLE I (*a*).

CHEMICAL ANALYSES.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	D.	R.
SiO_2 ...	43·23	49·02	49·84	51·28	51·56	54·28	55·78	55·90	57·26	56·31	61·04	66·60	63·92	71·48	56·31	63·98
Al_2O_3 ...	9·71	13·13	14·92	17·05	15·42	16·06	15·40	15·66	16·00	16·40	18·00	15·60	19·93	12·60	15·87	16·45
Fe_2O_3 ...	6·72	5·60	4·34	4·00	5·11	3·20	4·16	3·04	2·72	3·04	0·80	1·45	0·96	3·19	3·24	1·06
FeO ...	8·33	6·61	6·03	5·03	5·75	4·60	4·02	4·60	4·45	4·02	0·14	2·29	—	tr	4·27	6·05
MgO ...	15·15	7·65	7·66	5·21	5·79	4·89	4·62	4·58	4·04	4·16	0·59	2·12	1·07	0·07	4·35	3·06
CaO ...	9·20	9·62	9·30	8·62	7·80	7·38	5·96	6·22	5·82	6·00	5·32	1·08	2·18	1·62	6·00	1·80
Na_2O ...	1·04	2·50	3·03	2·54	2·81	2·71	2·93	2·84	2·90	3·32	6·47	2·14	8·38	2·14	3·00	3·72
K_2O ...	1·39	1·97	1·67	2·69	1·88	3·88	3·90	3·82	4·46	3·60	3·15	4·25	1·33	6·85	3·95	3·07
$+H_2O$...	2·70	1·37	1·38	1·34	1·63	1·12	1·36	1·47	0·79	1·31	0·64	1·87	0·90	0·44	1·23	—
$-H_2O$...	0·08	0·09	0·06	0·08	0·04	0·03	0·06	0·11	0·08	0·07	0·07	0·11	0·13	0·55	0·08	—
CO_2 ...	—	—	—	—	—	—	—	—	—	—	2·99	—	—	—	—	—
TiO_2 ...	1·08	1·10	0·90	0·93	1·13	0·79	0·80	0·76	0·81	0·79	0·33	0·58	0·76	0·31	0·79	0·55
S ...	—	—	—	0·02	—	tr	tr	tr	tr	tr	tr	tr	tr	1·02	—	—
MnO ...	0·26	0·24	0·18	0·19	0·17	0·19	0·17	0·15	0·15	0·16	0·02	0·09	0·03	0·02	0·16	—
P_2O_5 ...	0·74	0·71	0·48	0·38	0·42	0·43	0·45	0·44	0·43	0·43	0·07	0·21	0·08	0·08	0·43	0·26
Total ...	99·63	99·61	99·79	99·54	99·51	99·52	99·61	99·59	99·91	99·61	99·63	99·55	99·67	99·87	99·68	100·00

TABLE I (*b*).

MOLECULAR VALUES.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	D.	R.
si ...	82·3	114·1	116·7	132·8	133·1	150·1	162·9	164·1	166·8	168·0	233·3	295·2	247·7	394·4	165·5	231·0
al ...	10·8	17·9	20·5	25·9	23·4	26·0	26·4	27·1	27·4	28·8	40·4	40·7	45·3	41·1	27·4	35·2
fm ...	66·8	49·7	46·9	39·3	45·0	38·1	39·6	38·6	37·8	35·8	6·2	27·7	9·1	13·9	37·9	37·8
c ...	18·7	23·9	23·3	23·9	21·5	21·8	18·6	19·2	18·2	19·1	21·8	5·3	9·1	9·6	18·9	6·9
alk ...	3·7	8·5	9·3	10·9	10·1	14·1	15·4	15·1	16·6	16·3	31·7	26·3	36·5	35·4	15·4	20·2
k ...	0·47	0·34	0·27	0·41	0·31	0·48	0·47	0·47	0·51	0·42	0·25	0·46	0·14	0·68	0·47	0·35
mg ...	0·65	0·54	0·57	0·51	0·50	0·53	0·51	0·53	0·47	0·52	0·56	0·51	0·69	0·05	0·51	0·44
c/fm...	0·28	0·48	0·50	0·61	0·48	0·58	0·47	0·50	0·48	0·54	3·52	0·19	1·00	0·69	0·50	0·18
qz ...	−32·5	−19·9	−20·5	−10·8	−7·3	−6·3	+1·3	+3·7	+0·4	+2·8	+6·5	+85·4	+101·7	+152·8	+2·3	+50·0

TABLE I (*c*).

BASIC MOLECULAR NORMS.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	D.	R.
Kp ...	5·1	7·2	6·1	9·9	6·4	13·9	14·0	13·7	16·2	12·9	11·5	15·8	7·1	25·3	14·7	11·0
Ne ...	5·8	13·7	16·2	14·0	14·4	14·9	16·1	15·7	15·9	18·0	35·2	18·2	43·5	11·8	16·4	20·1
Cal ...	10·8	11·5	13·5	16·6	13·7	12·2	10·8	11·6	10·5	11·9	6·4	2·9	5·8	2·9	11·2	4·3
Cp ...	1·4	1·4	1·1	0·9	0·8	0·9	0·8	0·9	0·8	0·9	0·3	0·3	0·3	0·3	0·9	0·6
Sp ...	—	—	—	—	—	—	—	—	—	—	—	6·2	0·3	—	—	7·2
Cs ...	7·4	7·6	6·3	4·1	14·6	4·3	2·9	2·7	4·5	2·4	4·6	—	—	0·8	3·4	—
Fs ...	7·0	6·0	4·7	4·3	5·1	3·4	4·4	3·2	2·8	3·2	0·8	1·5	1·0	3·5	3·4	1·2
Fa ...	10·7	8·2	7·4	6·2	6·5	5·7	5·0	5·6	5·4	4·9	0·2	2·8	—	—	5·2	7·0
Fo ...	32·5	16·4	16·2	11·1	11·6	10·4	9·9	9·8	8·5	8·8	1·3	1·8	3·3	0·2	9·3	2·8
Ru ...	0·8	0·8	0·6	0·7	0·7	0·6	0·6	0·6	0·6	0·6	0·2	0·5	0·5	0·3	0·6	0·4
Q ...	18·4	27·1	27·9	32·2	26·2	33·7	35·5	36·1	36·0	36·4	39·5	50·1	39·3	55·0	36·0	45·4
L ...	21·7	32·4	35·8	40·5	34·5	41·0	40·9	41·0	42·6	42·8	53·1	36·9	56·4	40·0	41·8	35·4
M ...	57·6	38·2	34·6	25·7	37·8	23·8	22·2	21·3	21·3	19·3	6·9	6·1	3·2	4·5	21·0	11·0
	+2·2	+2·2	+1·7	+1·6	+1·5	+1·5	+1·4	+1·5	+1·4	+1·5	+0·5	+7·0	+1·1	+0·6	+1·5	+7·8
	0·50	0·36	0·38	0·41	0·40	0·30	0·26	0·28	0·25	0·28	0·12	0·08	0·10	0·07	0·27	0·12

1. Coarse-grained olivine(?)-gabbro, North Beach, Yzerfontein.
2. Medium-grained hypersthene-gabbro, "Promontory", Yzerfontein.
3. Coarse-grained leuco-gabbro, North Beach, Yzerfontein.
4. Coarse-grained, poikilitic monzo-gabbro, "Promontory", Yzerfontein.
5. Fine-grained gabbro inclusion in diorite, quarry at harbour, Yzerfontein.
6. Medium-grained, transitional, gabbro-diorite, the Eiland, Yzerfontein.
7. Medium-grained augite-bictite-diorite, south of "Promontory", Yzerfontein.
8. Medium-grained augite-biotite-diorite, bathing beach, Yzerfontein.
9. Medium-grained augite-biotite-diorite, Vlaekop beacon, Yzerfontein.
10. Medium-grained augite-biotite-diorite, quarry at harbour, Yzerfontein.
11. Fine-grained soda-aplite, the Eiland, Yzerfontein.
12. Fine-grained potash-soda-aplite, Gladdeklip, Yzerfontein.
13. Coarse-grained soda-pegmatite, quarry at harbour, Yzerfontein.
14. Coarse-grained potash-soda-pegmatite, Yzerfontein.

D. Average analysis of four Yzerfontein diorite analyses.
R. Composite analysis of two highly contaminated, marginal granites, Darling pluton.

Analyst: C. J. Liebenberg, except analysis R, which is quoted from Scholtz (1946).

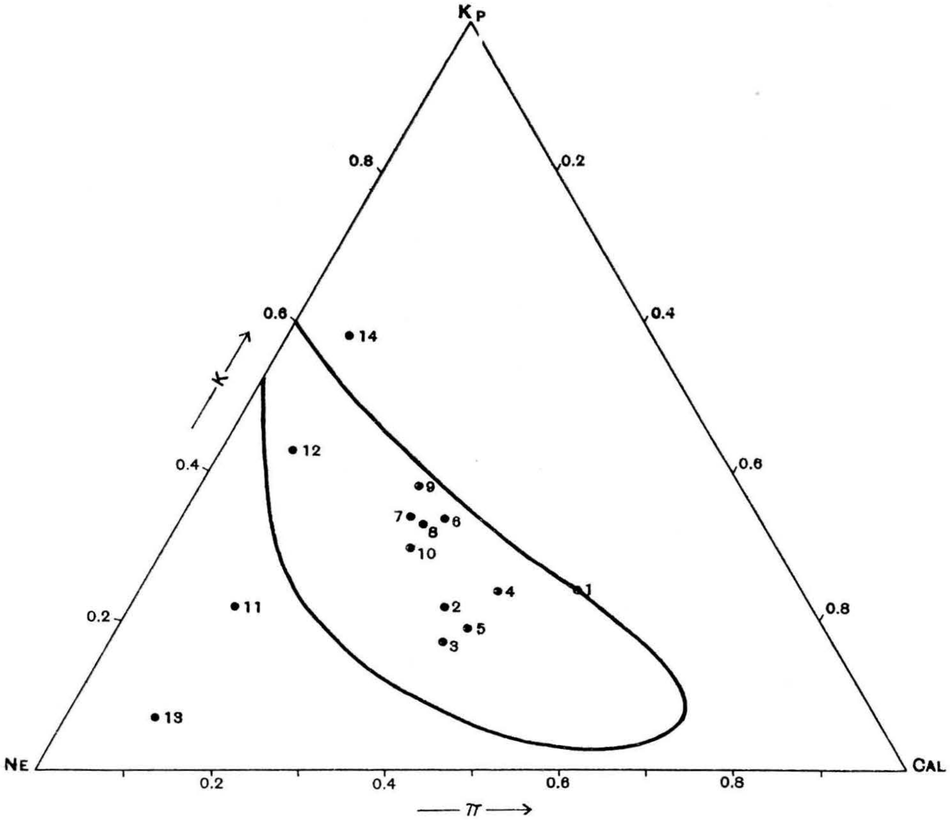


FIG. 5.

In Fig. 6, the various Niggli values have been plotted against the *si*-values as abscissa. The analyses of the aplitic suite have been excluded from this diagram as their abnormal composition is indicated by Fig. 5, and the crystallisation of these rocks will be discussed later, while, because of their similarity, the molecular values of the rocks of the dioritic suite (analysis No. 7, 8, 9 and 10) have been averaged to yield the type D, with an *si*-value of 165·5.

Examination of Fig. 6 discloses that the analyses of the different rock suites are limited to definite *si* ranges, the analyses of the gabbros being spread between *si* = 82 and 133 and the transitional rock having an *si*-value of 150, while the analyses of the diorites are grouped between *si* = 163 and 168. Further, the molecular values of the gabbros and diorites are seen to vary regularly and continuously within their respective suites, but a distinct break in the trends of these curves is apparent between *si* = 140 and *si* = 163, and it is therefore possible to distinguish separate courses of chemical variation in these two suites. It is interesting to note that the molecular values of the transitional rock (analysis No. 6) illustrate the intermediate character of this type by being located within this gap, while its values do not differ markedly from those of a theoretical calc-alkali differentiate of analogous silica content.

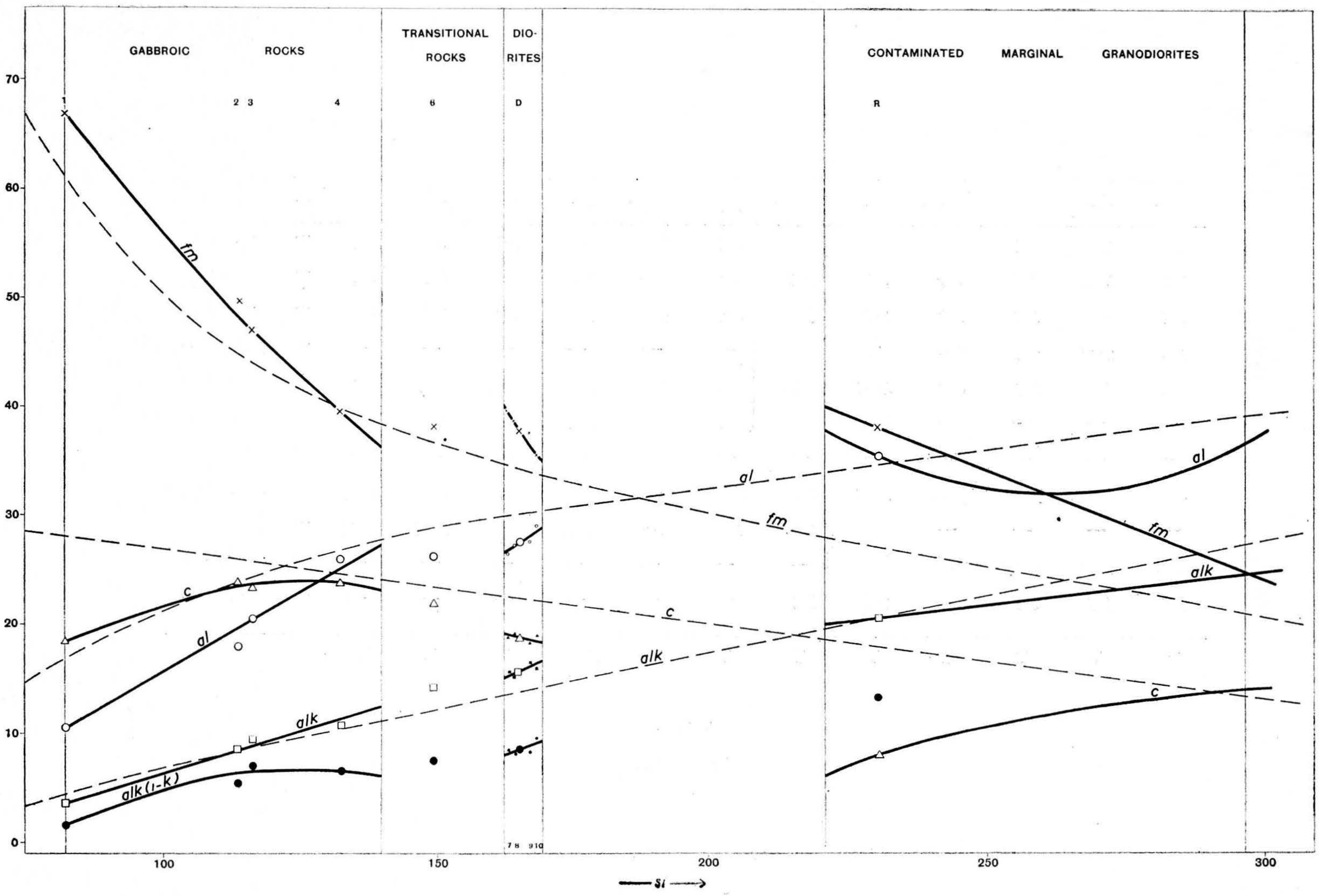

GABBROIC ROCKS
TRANSITIONAL ROCKS
DIO-RITES
CONTAMINATED MARGINAL GRANODIORITES
1
2 3
4
6
D
R
7 8 9 10
fm
al
c
alk
alk (1-k)
0
10
20
30
40
50
60
70
100
150
200
250
300
si →

FIG. 6.

TABLE II.

Modes.

	1A.	2.	3.	3A.	3B.	4.	5.	6.	7.	8.	9.	10.
Quartz	—	—	—	—	—	—	1·8	1·9	4·5	5·0	5·3	3·0
Micropegmatite	—	—	—	—	—	—	—	35·0	33·3	33·0	25·4	42·3
Orthoclase ...	17·3	16·5	11·3	15·8	14·2	34·7	13·7		—	—	—	—
Plagioclase ...	41·8	37·7	44·3	43·9	34·6	28·9	49·5	31·8	32·3	34·7	37·0	27·8
Olivine... ...	—	—	—	—	—	—	—	—	—	—	—	—
Hypersthene ...	12·6	10·0	9·3	8·8	10·0	4·7	28·3	6·1	—	—	—	—
Augite	20·0	21·9	20·3	19·1	26·0	19·2		14·7	8·9	7·5	10·2	8·3
Hornblende ...	—	—	—	—	—	—		tr.	9·5	9·9	11·9	8·8
Biotite	3·6	6·5	8·9	7·4	9·0	6·9	8·3	5·1	6·3	5·7	6·9	5·0
Iron ore ...	3·8	5·9	4·8	4·1	4·9	4·5	7·6	4·4	4·3	3·0	2·4	4·0
Apatite... ...	0·9	1·5	1·1	0·9	1·3	1·1	0·8	1·0	1·0	1·2	0·9	0·8
Total ...	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0

A trend in common with the variation in all the suites is the rising of the *alk*-value with increasing acidity and this may be expected to reflect the increase of the proportion of alkali feldspar as crystallisation proceeded. In the gabbros this augmentation is not equally shared by sodic and potassic feldspar as may be shown by the *alk*(l-*k*) curve, which indicates the proportional development of normative albite. Here the initial increase of albite changes gradually to a slight reduction, while normative orthoclase shows continual enrichment.

The *al*-curve also exhibits a continuous upward trend in the gabbros, but with a slope steeper than that of the *alk*-curve, indicating by the difference (*al*-*alk*) an increasing normative anorthite. Mineralogically, however, a slight decrease in the amount of this mineral is observed and the explanation of this phenomenon probably lies in the fact that both the biotite and the augite contain aluminium. It is significant that the modal proportions of the two last named minerals are low in the most basic gabbros and increase with increasing acidity. Biotite retains this trend throughout the series while a decrease in the proportion of augite becomes apparent in the most acid gabbros.

When the behaviour of augite is considered in conjunction with the *c*-curve, the decreasing anorthite content of the plagioclase may be further demonstrated. If

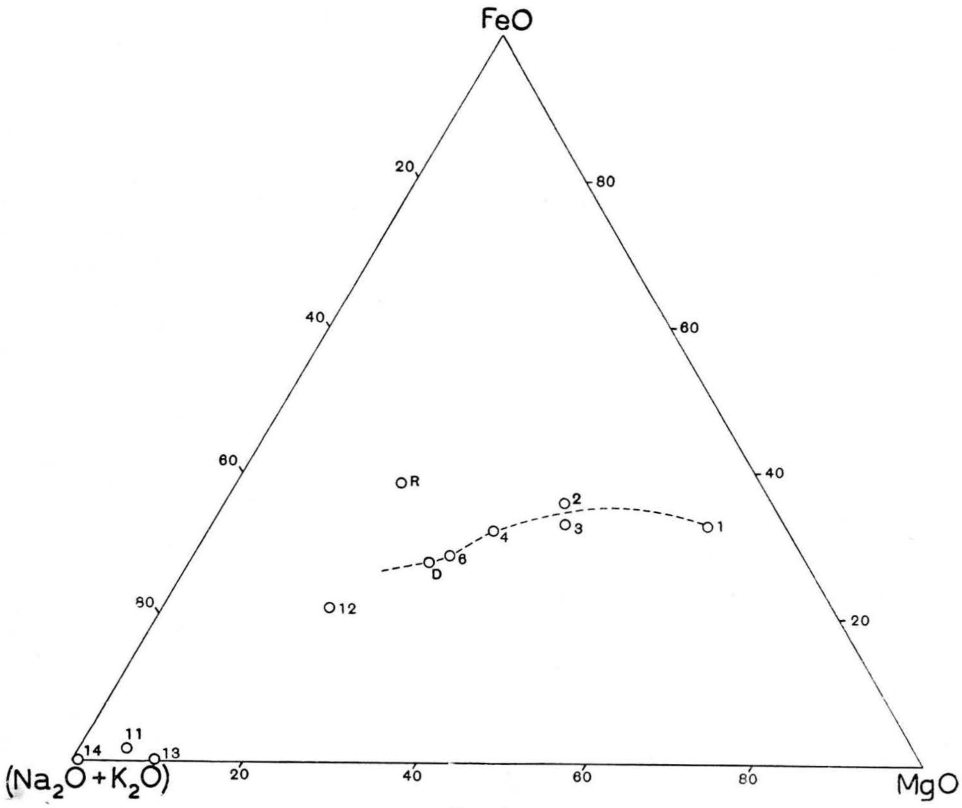


FIG. 7.

augite is disregarded, then the value of *c-alk*(l-*k*) will represent the anorthite content of the plagioclase, and since the *c*- and *alk*(l-*k*)-curves are essentially parallel, this anorthite content would remain constant throughout the suite. The addition of augite would now decrease this value proportionally. Thus, increasing augite with increasing acidity must result in a decrease of the anorthite content of the plagioclase.

The behaviour of the other dark minerals may be demonstrated by the *fm*-, *mg*- and *c*/*fm*-values. The steep downward trend of the *fm*-curve designates a pronounced decrease of the mafic minerals with decreasing basicity, while the distinct increase of the ratio *c*/*fm* from 0·28 to 0·61 shows that this decrease is probably entirely due to the rapid diminution in the amount of olivine and orthopyroxene. This trend is further accompanied by a decrease of the *mg*-value from 0·65 to 0·51 which may reflect the early crystallisation and separation of olivine.

Many of these features may be verified by the trends of variation illustrated in Figs. 7 and 8.

In Fig. 7 the relative proportions of the alkalis, ferrous iron and magnesia have been plotted on a ternary diagram. In the gabbroic suite, it is seen that the initial increase of iron and the alkali content and the decrease of magnesia is followed by pronounced alkali enrichment with little variation of the FeO/MgO-ratio.

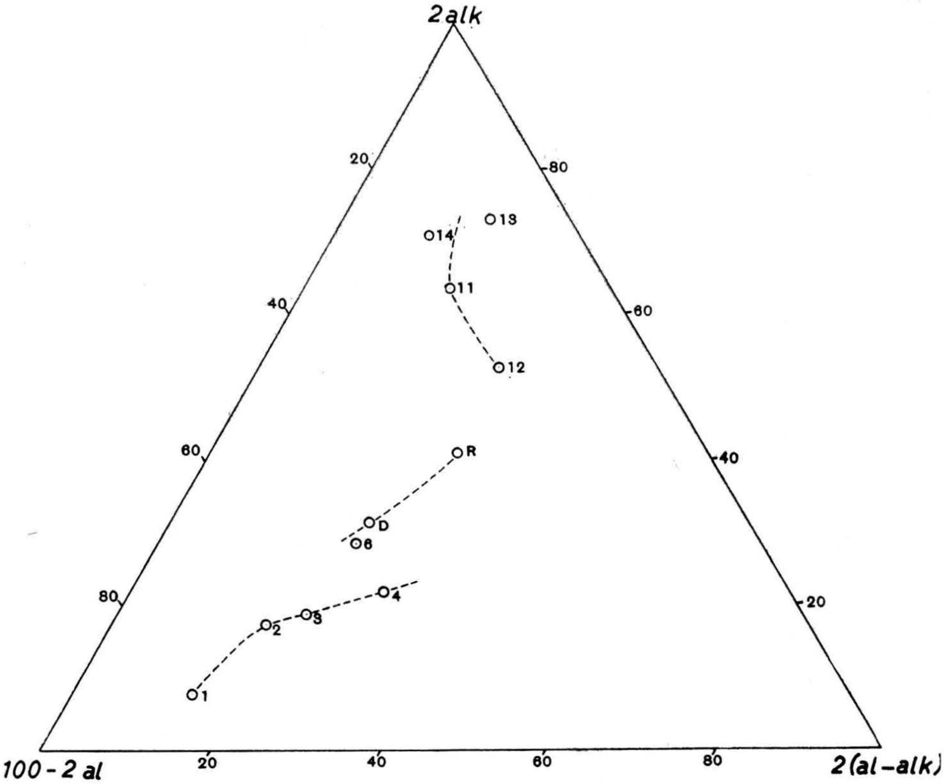


FIG. 8.

Fig. 8 is a ternary plot of (100-2*al*), 2*alk* and 2(*al*-*alk*), which represent respectively the normative proportions of the dark minerals, alkali feldspar and anorthite. Here the pronounced decrease of dark minerals coincides with a general increase of feldspar, initially alkali- and subsequently lime-enrichment. Van Zyl (1950) shows that both these trends characterise the course of crystallisation of the Newry suite of igneous rocks.

The passage from the gabbro to the diorite across the transitional zone involves an *si*-increase of approximately 20 units, the change being demonstrated across the relevant gap in Fig. 6. The alkali enrichment which accompanies this transition is due almost entirely to an increase in soda feldspar, potash remaining essentially constant as shown by the sympathetic relationship between *alk* and *alk*(l-*k*). A pronounced reduction of anorthite is indicated by the decrease of the *al*-value and is corroborated by the similar behaviour of the *c*-value. On the other hand, increasing *fm* shows an addition of mafic minerals. These changes also appear in Figs. 7 and 8, the latter showing clearly that the transition from the gabbro to the diorite is accompanied by pronounced alkali enrichment, a slight increase of the mafic constituents and a notable reduction in the anorthite content.

In the dioritic suite, the trend of variation apparently parallels that of the gabbroic suite, and here too the increase of normative anorthite may be explained by the presence of such aluminium-bearing minerals as amphibole, biotite and augite. The further downward trend of the *c*-curve indicates an actual reduction of both anorthite and diopsidic augite.

For comparative purposes the standard curves of Niggli's calc-alkaline suite of rocks have been incorporated in Fig. 6. While the molecular values of the most basic gabbros and diorites differ markedly from the standard values, the trend of the variation in these suites results in the approaching and coincidence of their variation curves with the corresponding standard curves. This is particularly well displayed by the *fm*- and *al*-curves. The convergence is probably due to the fact that the minerals of early crystallisation were composed of those constituents which, in the original magma, exceeded their normal proportions, and this resulted in a concentration of the remaining constituents in the rest magma. Such a trend of variation is believed to be due to a process of normal and undisturbed differentiation.

Among the analyses of Yzerfontein rocks which were not used in the preparation of the variation diagrams, analysis No. 5 (Table I) is of a representative sample of the dark, fine-grained, rounded inclusions collected at the quarry. In hand specimen this rock has the appearance of an even-grained hornstone, but in thin section it possesses a texture which may be described as microporphyritic, occasional phenocrysts of pyroxene and plagioclase being scattered in an aphanitic groundmass. The freshest samples, such as are found at the cores of the largest inclusions, are mineralogically similar to the gabbros, the phenocrysts being composed of unresorbed crystals of augite and labradorite, while the groundmass contains the same minerals and is moreover usually free from quartz, micropegmatite and hornblende. Towards the margins of the inclusions, however, quartz becomes more prominent and the augite grains have frequently been altered to green hornblende. The texture and mineralogy suggest that this rock was originally the chilled phase of the gabbro magma, and the alteration which it often displays may be attributed to its envelopment by the diorite, a position in which the selective transfer of material between the solid xenolith and the liquid diorite must have proceeded. Chemically, the analysis (No. 5, Table I) also shows an affinity to the gabbroic suite, while its very slight departure from the normal gabbro variation curves is possibly the effect of soaking in the composite dioritic liquid.

The various aplitic and pegmatitic injections, on the other hand, show affinity to a granitic suite and probably represent the pegmatitic and aplitic phases of the adjacent Darling granite pluton. Analysis No. 11 and 12 show that two distinct types of aplite occur at Yzerfontein:—

(i) a soda-aplite with $k = 0 \cdot 25$ and
(ii) a potash-soda-aplite with $k = 0 \cdot 46$.

Both have comparable fine grain and pink colour and are impossible to distinguish in the field. Although they both invade and are younger than all the other igneous rocks at Yzerfontein, it was not found possible to determine their relative ages. The soda-aplite seems to occur mainly in the form of more regular veins and extends further into the gabbro, while the more abundant potash-soda-aplite, though usually comprising the irregular pocket-like bodies in the diorite, may also occur as more regular vein fillings.

The soda-aplite is composed almost entirely of a fine-grained groundmass of albite and subordinate quartz with occasional microcline or albite phenocrysts. Much calcite, epidote and some pyrite represent later additions, while fine hematite dust gives the rock its pink colour. The potash-soda-aplite has a more varied mineralogical composition, microcline, albite, quartz, chlorite, amphibole and accessory blue tourmaline occurring as well as the later minerals.

Pegmatite dykes are not well developed at Yzerfontein, but the frequent occurrence of irregular, lenticular and stringer-like patches of coarse-grained, leucocratic material was taken to represent pegmatite injections. Here too, soda-pegmatites and soda-potash-pegmatites, corresponding to the two aplite types, may be distinguished on both mineralogical and chemical grounds (Table I, Nos. 13 and 14).

In his investigation of the pre-Cape Granite plutons of the George district, C. T. Potgieter (1950, pp. 378-383) also records the presence of two different pegmatites; a quartz-microcline-plagioclase pegmatite, and a quartz-plagioclase pegmatite. He discusses in detail the two main theories accounting for the formation of mineralogically distinct but consanguineous pegmatites, independently emplaced and derived from immiscible potash- and soda-rich residual magmatic products, as theoretically envisaged by S. J. Shand (1948). This hypothesis appears to account most satisfactorily for the presence of both soda- and potash-soda-aplites and pegmatites at Yzerfontein.

IX. AGE RELATIONS

The basic rocks of Yzerfontein appear to be situated along the western margin of the Darling pre-Cape granite pluton, but owing to the absence of any granite outcrops in the immediate vicinity of these rocks, their mutual relationships could not be determined in the field. The sequence could, however, be deduced by the evidence supplied by the aplite, pegmatite and hydrothermal veins. It seems likely that these injections comprise material related to the late magmatic period of the adjacent granites, and that the fissures and joint planes which they have exploited in the diorites all follow directions parallel to those characteristically developed in the granites during their final stages of consolidation. The fact that these aplite, pegmatite and hydrothermal mineral-bearing veins and dykes traverse and include xenoliths of both the diorites and the gabbros suggests that the rocks were emplaced contemporaneously with, or more probably earlier than, the intrusion of the granite. This is further borne out by the shearing and mylonitisation of the diorites by forces which produced analogous and parallel cataclastic structures in the older pre-Cape granites.

It has already been demonstrated that, within the basic complex itself, intrusions of two different ages are present, namely, an earlier gabbroic and a later dioritic intrusion holding xenoliths of the gabbro. Assigning to the diorite its youngest possible age, that is, synchronous with the intrusion of the granite magma, the pre-granite age of the gabbro magma is definitely indicated.

X. PETROGENESIS

(i) **The Gabbro.**

It is believed that the form of the early intrusion of basaltic magma was either a laccolith or a sheet-like body characterised by a sub-horizontal floor. Evidently chilling of the magma occurred where it came into contact with the colder rocks forming the roof and floor of the intrusion, but, although rounded xenoliths of the fine-grained chill phase are frequently encountered in the later diorites, the actual contacts are nowhere exposed.

During the period of quiescene following on the intrusion of the magma, fractional crystallisation proceeded apace and the early precipitated crystals of olivine, pyroxene and basic plagioclase settled to the base of the intrusion under the influence of gravity. Owing to the differential crystal settling, a well-defined primary banding and igneous lamination developed parallel to the floor of the intrusion. The removal of these early crystals left a magma enriched in potash and alumina, some of which was trapped in the interstices between the settling crystals of the banded gabbro, where it finally crystallised as biotite and orthoclase. However, the greater part of the rest-magma concentrated towards the top of the body and here, as has been demonstrated by J. H. L. Vogt (1923, pp. 233-239), the progressive enrichment in potash and alumina as crystal fractionation proceeded must have greatly reduced its fluidity. Under conditions of increasing viscosity, the settling of the early-formed crystals was arrested and orthoclase, which crystallised from the potash-enriched residual liquid, enveloped them in a poikilitic fashion to form the mottled monzonitic facies of the gabbro.

The course of crystallisation of the gabbro suite, as reflected by the variation diagrams, follows that displayed by the Newry suite of igneous rocks, a trend which P. J. van Zyl (1950) erroneously generalises as characterising the contamination of an acid magma by basic material, and the presence in this region of material more basic than the gabbro could not be entertained. When compared with the variation of the molecular values of Niggli's standard calc-alkali suite, however, the variation of the Yzerfontein gabbros may be explained as a product of normal differentiation by crystal fractionation along a gravity gradient.

The existence in the south-western Cape Province of a pre-granite basaltic magma was first suggested by P. J. van Zyl (1950) who found that this magma had been emplaced into a dome-structure in the pre-Cape sediments along the south-western margin of the Malmesbury-Paardeberg granite pluton after it had undergone slight modification by differentiation in depth. It is interesting to note that both the Malmesbury and Yzerfontein gabbro suites possess relatively high *fm*-values and rather low *c*-values, but appear to have followed individual, dissimilar differentiation trends, due no doubt to the different physical conditions under which the magma was emplaced. At Malmesbury differentiation occurred in depth and the variation observed is due to successive intrusions with little differentiation *in situ*, while at Yzerfontein all differentiation may be ascribed to processes succeeding the emplacement of the magma.

The Malmesbury diorite intrusions produced intense contact metamorphic alteration of the country rock and the secondary structures of these metamorphosed sediments appear to be wrapped around the diorite stocks. Owing to the absence of outcrops of pre-Cape sediments in the vicinity of Yzerfontein, it was unfortunately impossible to deduce either the relationship which might exist between the attitude of the gabbro body and the structure of the surrounding, invaded sediments, or to observe the metamorphic effect the former had had on the latter. It is, however, noteworthy that the basic intrusions under consideration are located along the south-western flanks of the Malmesbury and Darling pre-Cape granite batholiths, that is, on the side from which the pressure, which caused the elongation of these last-mentioned bodies, operated during their emplacement. No other gabbroic or dioritic bodies of analogous form or equivalent size are known to occur on the north-eastern flanks of the granite plutons.

(ii) **The Diorite.**

Any discussion bearing on the probable genesis of the Yzerfontein diorites must take into account the four main hypotheses which have been advanced for the origin of this rock clan in general. Thus, diorite may be the product of:—

(*a*) the normal differentiation of a basic magma,
(*b*) the reaction between a basic magma and acid country rock,
(*c*) the reaction between acid magma and limestone,
(*d*) the reaction between acid magma and basic igneous rock.

The applicability of each of the above-mentioned hypotheses in the case of the Yzerfontein diorites may be critically reviewed.

(*a*)

The discordant attitude of the dioritic suite towards the primary structure of the gabbro intrusion precludes the possibility that these rocks have resulted from the *in situ* differentiation of the earlier gabbro magma. However, by a process similar to that which led to the intrusion of diorite at Malmesbury, the Yzerfontein diorite may be the product of a subsequent heave of the basaltic magma which had undergone differentiation in depth. It has, however, already been pointed out that the trends of the variation curves of the Malmesbury and Yzerfontein rocks are markedly dissimilar. Moreover, petrographic studies disclose the presence of a considerable amount of gabbroic material in the Yzerfontein diorites and this necessarily implies that the composition of the second intrusion must have been decidedly more acid than that of the resultant dioritic rock. Additional evidence of the more acid nature of this magma is afforded by the extensive reaction which had apparently taken place between it and the gabbroic xenocrysts, but there is no field evidence to justify the former existence of a large body of basaltic magma capable of yielding adequate quantities of an acid differentiate.

(*b*)

Any theory of the origin of the diorites which involves the contamination of the gabbroic magma by acid country rock would also be unable to explain the discordant transgression of the gabbro by the diorite. That the latter was derived from a later fluid intrusion is further indicated by the transitional zone where a plastic mixing of the two types is clearly visible. The total absence of peraluminous minerals or sedimentary xenoliths in the diorite also militates against any such hypothesis.

(*c*)

Further to the east, occasional thin and rather impure limestone beds are known to be present in the pre-Cape formations which have been invaded by granite. Small outcrops of metamorphosed calcareous rocks occur near the southern extremity of the Darling pluton, while the Robertson boss cuts across thin limestone beds, typical metamorphic lime silicates being developed along the contacts. No diorites are, however, known in these areas. (Scholtz, 1946, pp. liv.)

The pre-Cape rocks in the Yzerfontein-Saldanha region are apparently devoid of primary limestone beds and, since the diorites under consideration provide no positive mineralogical or chemical evidence of the addition of lime, any hypothesis postulating the contamination of granite by calcareous rock may be dismissed without further comment.

(*d*)

It has been previously suggested that the diorite could have resulted from the incorporation of gabbroic material in a later magma considerably more siliceous than the resultant diorite (i.e. si $>$ 165·5). The existence of such a magma in this vicinity is demonstrated by the granitic rocks of the Darling pluton, and the fact that Yzerfontein is situated close to the margin of this batholith may be deduced from the profusion of aplites, pegmatites and other marginal veins and dykes related to the final stages of the consolidation of the granite. D. L. Scholtz has shown that this pluton has developed a highly contaminated marginal facies by the incorporation and assimilation of shaly country rock, and it is believed that this contaminated magma, rather than the more normal granite magma, reacted with the gabbro to produce the diorite. This is verified by the almost perfect linear relation between the compositions of the marginal granite (analysis R, Table I), the average diorite (analysis D) and the gabbro (analysis No. 4), which permits a quantitative synthesis of the diorite. To quote a particular example, we may select the most acid gabbro analysis (Table I, No. 4) and add to this such a proportion of the marginal granodiorite (analysis R) that on recalculation on the basic molecular values to 100, the *si*-value of this mixture will correspond to that of the average Yzerfontein diorite (analysis D). Thus, if two parts of gabbro analysis No. 4 are added to the average marginal granodiorite analysis R, a hybrid with *si*-value of 165·7, corresponding to *si* = 165·5 of the average diorite analysis D, is produced. A remarkable agreement between the molecular values of the calculated and the average Yzerfontein diorite can be demonstrated:—

	si	*al*	*fm*	*c*	*alk*
R	231	35·1	37·8	6·9	20·2
2 × no. 4	266	51·8	78·6	47·8	21·8
Sum	497	86·9	116·4	54·7	43·0
∴ Calculated diorite	165·7	29·0	38·8	18·2	14·3
Average diorite (D)	165·5	27·4	37·9	18·9	15·4

Considering the variable composition of both the gabbro and the contaminated granodiorite, the correspondence of the basic molecular values of the calculated and actual diorite is exceptional, but still better agreement is shown when 63·7% of gabbro analysis No. 4 is added to 36·2% of a slightly more basic granodiorite from the Darling pluton (analysis No. 42 of Scholtz (1946)).

	si	*al*	*fm*	*c*	*alk*
No. 42	223	33·5	37·7	6·4	22·3
36·2% of no. 42 + 63·7% of no. 4	165·5	28·7	38·7	17·7	15·0
Average diorite (D)	165·5	27·4	37·9	18·9	15·4

Like results may be obtained from similar calculations in which various contaminated granodiorite analyses are added to interpolated gabbro analyses read off from the more acid portion of the gabbro differentiation curves in Fig. 6.

The calculations all demand, however, that a given mass of granodiorite should incorporate approximately twice as much gabbro, and the source of the heat necessary becomes problematic. Volumetric comparisons show that the amount of diorite formed is but a fraction of the volume of the granite intruded, and it is possible that a considerable supply of heat was available from the centre of this mass. According to D. L. Scholtz, the upward transfer of heat by convection currents during the emplacement of the Darling pluton appears to have been more effective in this batholith than in most of the other younger pre-Cambrian granite plutons of the Cape Province. Moreover the available petrographic evidence suggests that the granite magma invaded the gabbro body prior to its complete consolidation. In this connection, it may be recalled that, instead of a sharp, intrusive contact displaying evidence of chilling of the granite against the gabbro, a broad transitional zone exists in which the plastic mixing of the two types is apparent—a relation which implies that the heated gabbro was, in all probability, in a semi-plastic or crystal-mush state when the later acid magma was discordantly emplaced from the east. This conclusion is also substantiated by the rarity of gabbroic inclusions in the diorite, other than that of the fine-grained chilled marginal variety, which seems to indicate that the chill phase of the gabbro had already congealed and was sufficiently cold and compact to effectively resist complete digestion by the younger, intrusive, contaminated pre-Cambrian granite.

The attitude of the primary banding of the gabbro suggests that originally the greatest portion of this body was probably situated some distance below the present diorite outcrops. Although some of the gabbro had undoubtedly consolidated before the intrusion of the granite, most of the body was presumably still at a relatively high temperature and the more acid differentiate was probably mobile although fairly viscous. The granite magma, its composition already modified by the assimilation of argillaceous country rock, apparently invaded the gabbro body from below and was further altered by the addition of the gabbroic rest magma and by the incorporation of already crystalline gabbroic material in the form of both single crystals and semi-plastic crystal aggregates. Although considerably more basic than the original granite magma, this contaminated liquid was still sufficiently acid to react with the foreign solid phases, earlier in the reaction series, with the production of coronas about discrete crystals. Disruption of the larger mushy inclusions could have been effected by active mechanical disintegration, by passive chemical reaction, or by a combination of these processes. The hybrid magma so formed rose to a higher level where, by further mixing with gabbro in the act of crystallisation, it gave rise to the rocks of intermediate composition characterising the transitional zone.

In most examples of the hybridisation of an acid magma by the assimilation of basic material the final product is almost invariably heterogeneous in character. Both W. A. Deer (1935) and G. D. Nicholls (1951) have, however, observed that under favourable conditions, the product of hybridisation may be completely uniform rock having the appearance of a normal igneous type which reveals little or no evidence of its hybrid origin. On the one hand, in the Cairnsmore of Carsphairn Igneous Complex such conditions apparently obtained and here the hybridisation of granitic magma by partly solidified gabbro took place in depth before the intrusion attained its present position. The resultant tonalitic hybrid is completely uniform (Deer, 1935, p. 66). On the other hand the petrological uniformity of the Eastern Adamellites of the Glenelg-Ratagain Igneous Complex is ascribed to the fact that the assimilated material had a composition similar to the phase in equilibrium with the intruded magma (Nicholls, 1951, p. 338). The gabbroic minerals in the Yzerfontein diorites, however, show evidence of extensive reaction with the later magma and it is unlikely that the last named mechanism of hybridisation could account for the homogeneity of these rocks. On the contrary, the history of formation of the Yzerfontein diorites and the Carsphairn tonalites is remarkably similar, and the comparative uniformity of the diorites may be ascribed to hybridisation and homogenisation at depth prior to intrusion. It is interesting to note that S. R. Nockolds (1933, p. 589) suggests that the movement of a magma is a potential aid to the mechanical disintegration of included xenoliths, and the products of such activity are either small, rounded clots of foreign material or individual xenocrysts. Moreover, the motion tends to distribute the solid phases set free from the xenoliths in an even manner throughout the contaminated magma, thus obscuring its hybrid nature. Whereas the homogeneity of the Yzerfontein diorites, therefore, suggests movement after hybridisation of the granodiorite magma, the heterogeneity of the transitional hybrid is suggestive of origin *in situ*.

Another common feature of diorites which have been formed by the reaction between an acid magma and basic rocks is the prominence of the role of reciprocal reaction. By this process, which involves the selective transfer of certain constituents from the magma to the basic rocks and vice versa, the reaction products, whether contaminated magma or reconstitued country rock, are rarely simple addition products of the pure magma and basic rock. As the Yzerfontein diorite does show such linear relationship between the gabbro and granodiorite, the role of reciprocal reaction appears to have been negligible. In general, linear variation has been explained by:

(i) the mixing in all proportions of two different liquid magmas (Wilcox, 1944);
(ii) the completion of the reciprocal reaction process under exceptionally favourable conditions (Thomas and Smith, 1932);
(iii) the mechanical incorporation in the magma of assimilated material *en masse* (Deer, 1935; Nicholls, 1951).

At Yzerfontein all three processes have probably been active in varying degrees, but only the unselective incorporation of gabbroic material has occurred on a sufficiently large scale to produce the linear variation observed. This essentially mechanical process which, as we have already seen, was also responsible for the uniformity of the diorites, was probably greatly assisted by the pre-heated and semi-plastic nature of much of the gabbro.

From the foregoing petrological investigation, the writer is of the opinion that the following sequence of events probably occurred in the igneous history of the Yzerfontein Complex:—

(i) The intrusion of a sub-horizontal sill-like or laccolithic body of a basaltic magma, which underwent differentiation *in situ* by crystal fractionation along a gravity gradient. The gabbroic rocks so formed are evidently co-magmatic with the Malmesbury gabbro-diorite suite.

(ii) The emplacement of the younger pre-Cambrian granite of the Darling batholith and the assimilation of argillaceous country rock giving rise to the marginal granodioritic phase of this intrusion.

(iii) Contamination of the granodiorite magma by gabbroic material at Yzerfontein led to the development of a hybrid dioritic liquid. Upward movement of this hybrid liquid induced greater uniformity, while further mixing with uncongealed gabbro resulted in the production of the heterogeneous hybrids of the transitional zone.

(iv) Shortly after their consolidation, these rocks were invaded by late aplitic and pegmatitic differentiates of the Darling granite batholith, primarily along N.W.-S.E. directions of jointing and shearing.

(v) The infilling of some of these joints by later, hydrous, magmatic fluids from which crystallised the various assemblages of hydrothermal minerals was probably connected with the final stages of magmatic activity of the granites.

(vi) The development of S.W.-N.E. orientated joints.

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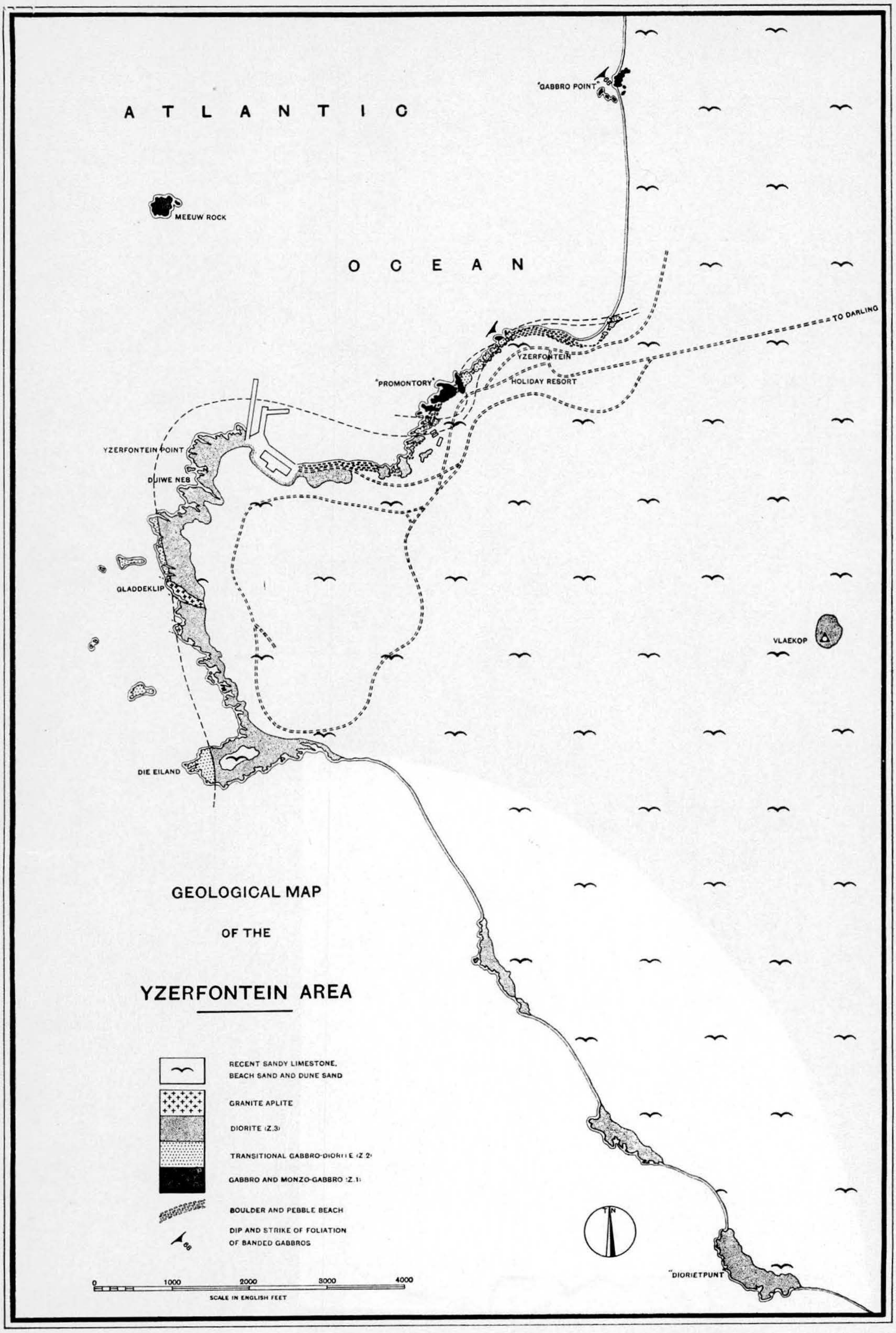
ATLANTIC
OCEAN
GABBRO POINT
MEEUW ROCK
TO DARLING
YZERFONTEIN
HOLIDAY RESORT
"PROMONTORY"
YZERFONTEIN POINT
DUIWE NES
GLADDEKLIP
VLAEKOP
DIE EILAND
DIORIETPUNT
GEOLOGICAL MAP
OF THE
YZERFONTEIN AREA
RECENT SANDY LIMESTONE, BEACH SAND AND DUNE SAND
GRANITE APLITE
DIORITE (Z.3)
TRANSITIONAL GABBRO-DIORITE (Z.2)
GABBRO AND MONZO-GABBRO (Z.1)
BOULDER AND PEBBLE BEACH
DIP AND STRIKE OF FOLIATION OF BANDED GABBROS
68
0
1000
2000
3000
4000
SCALE IN ENGLISH FEET
T.N.

PLATE III