

THE PETROLOGY OF THE ELEPHANT'S HEAD DIKE

AND

THE NEW AMALFI SHEET.



THIS IS PRESENTED FOR THE DEGREE OF PH.D.

by

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University of Cape Town.

1942.

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### Abstract.

The following is a detailed study of two allied intrusions of Karroo dolerite, situated in the Matatiele district of East Griqualand (South Africa).

The one intrusion is a multiple dike of exceptional form and great length. It served as the main feeder of the second intrusion, a thick transgressive sheet.

Two magmas contributed to the formation of the dike. A first intrusion of tholeiite magma was followed by the injection of a large volume of olivine-dolerite magma. The tholeiitic phase is absent in the sheet, which only contains the cooled representatives of the olivine-dolerite magma.

A considerable degree of magmatic differentiation in the latter magma has led to the production of a great variety of rock types. In the dike such types are represented by picrites and olivine-dolerites, whereas the dolerites of the sheet range from olivine-bearing types to rocks, rich in soda and iron. Such variability is found to be consistent with processes of differentiation, involving gravitational settling of olivine and marked crystal-fractionation.

The dike is roofed, and its behaviour recalls the characters of the Cleveland dike in northern England. Evidence is forwarded, suggesting that the dike possesses a floor as well as a roof.

Both the tholeiite- and the olivine-dolerite magma were very active in their behaviour towards the associated sediments. The tholeiite magma mobilised and reacted with the Molteno sediments of the dike-walls. In the sheet a block of Burghersdorp sandstone was

metasomatised/...

metasomatized by emanations derived from the olivine-dolerite magma. As a result a well-defined band of pale granophyric rocks was produced. Chemical and mineralogical data are given and the inferences drawn are applied to the general problem of the mode of intrusion and the differentiation of the Karroo magma.

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## I. INTRODUCTION

### Previous Work.

The New Amalfi sheet and the Cape portion of the Elephant's Head dike were mapped and described by du Toit (1929, p.24-25), who also gave a brief account of some of the rock types encountered. The maps contained in this study are largely based on du Toit's work, the excellence of which did not allow for much improvement. The author is indebted to Mr. G.M. Stockley (\*) for a map of the dike's continuation in Basutoland, which added a further 37 miles to the known length of this curious intrusion.

The present study was chosen as an illustration of the behavior<sup>u</sup>, mode of intrusion, and trend of crystallisation of the Karroo magma. Of late a great many new data on the Karroo igneous province have become available. Such data all stress certain characters peculiar to the hypabyssal phase of the Karroo magma. These may be summarised as follows:-

- (1) A great many intrusions of peculiar and irregular shape are found among the Karroo intrusives (du Toit, 1920, p. 5-15).
- (2) The Karroo magma was unusually active in its behaviour towards the associated sediments (Mountain, 1936; Walker and Poldervaart, 1940, 1941b).
- (3) The Karroo dolerites are by no means as uniform in chemical and mineralogical composition as was previously asserted (Daly and Barth, 1930; as against Walker and Poldervaart, 1941a, 1942a).

(4)/....

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(\*) personal communication.

- (4) Differentiated sheets and sills are rare in the Karroo, though some highly differentiated bodies are found in its eastern parts (Scholtz, 1936).

The above characteristics are reproduced in the two intrusions which form the subject of the present study, and the rock types encountered are in many ways typical representatives of the Karroo magma. Phenomena of rheomorphism and metasomatism are also clearly exhibited and lend themselves to detailed study.

Collecting in the dike was confined to the Cape portion of its course, as present conditions make work in Basutoland rather difficult. Though the work is thus incomplete as regards the total length of the dike, there is reason to believe that the study is representative, and that its results are also applicable to those portions which were not visited.

#### Acknowledgements.

The writer wishes to express his gratitude to Professor F. Walker, of the University of Cape Town, for his guidance and help in the present research; to Dr. A.L. du Toit for his useful advice, to Mr. J.A. Purchase, of Ashton, for his much appreciated hospitality, which extended over so long a period, and to Mr. H. Goldstone, of Cape Town, for the photographic reproduction of the maps and diagrams. The cost of 12 chemical analyses was met by a liberal grant of the National Research Board, which is here gratefully acknowledged. I am also indebted to Professor F. Walker and to Professor D.L. Scholtz, of Stellenbosch University, for allowing me to use several of their unpublished analyses for the diagrams.

While/.....

While engaged in the research, the author was fortunate in holding the Union Post Graduate Scholarship.

#### Laboratory Methods.

The modal compositions were assessed by means of the Leitz-Scheumann Integrating Stage, the traverses varying from 300-600 m.m., according to the grain-size of the rocks. Some rocks show a considerable amount of alteration. Their modal compositions are given without the decimal figure.

The refractive indices were determined in crushes by the immersion method, in sodium light. The liquids used were checked after each determination by the Leitz-Jelley Refractometer.

The crushes for the determinations were sieved on a 120-150 sieve standard and washed. Subsequently a first separation of the light and heavy minerals was carried out with bromoform.

The accuracy of most of the determinations is well within  $\pm 0.003$ . For the clinopyroxenes attempts were made to insure the greatest possible accuracy by handpicking of measured crystals from thin sections. The values of  $\chi$  were calculated by adding 0.004 to the observed value of  $\delta'$  (Tomita, 1934, p.47).

Measurements of  $2V$  and  $\delta:c$  were made with a 4-circle Universal Stage. The accuracy of direct measurements on the Universal Stage is usually given as  $\pm 2^\circ$ . The data for  $2V$  and  $\delta:c$  given in this work are representations of a large number of measurements.

Optical/....

Optical data and their correlation  
with chemical composition.

Plagioclase was determined on the average  $\beta$  only. The olivines were determined on  $\gamma$  and 2V, except the most fayalitic olivines for which  $\alpha$  only was measured. Clinopyroxenes were assessed on  $\gamma$ ,  $\delta:c$ , and 2V, whereas the orthopyroxenes were measured on 2V and  $\gamma$ . Those orthopyroxenes which show a "graphic intergrowth" were measured on  $\gamma$  only, as no uniform extinction could be obtained in any position on the Universal Stage.

In this paper the compositions of the plagioclase series were determined from the diagrams of Rogers and Kerr (1933,p.213). The olivines were deduced from Deer and Wager's diagram (1939a, p.21), whereas the magnesian orthopyroxenes were determined from the diagram of Hess and Phillips (1940,p.280). The more ferriferous orthopyroxenes were plotted from Henry's diagram (1935, p.223). The composition of the clinopyroxenes was deduced from the values for 2V and  $\gamma$  according to the diagrams given by Deer and Wager (1938, p.20-21).

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## II. GENERAL GEOLOGY.

### Physiography.

The area under consideration is dominated on the one hand by the imposing Drakensberg range with the numerous high spurs extending from it, and on the other by the unique feature of the even stretch of country represented by the Cedarville Flats. In between the country is extremely variable, with hills, ridges and narrow V-shaped valleys, basins and wide flood plains. Geologically the following sequence is present in the regions:-

1. Recent deposits and soil of the Cedarville Flats.
2. Karroo dolerite dikes and sheets.
3. Drakensberg volcanic series.
4. Cave sandstone.
5. Red beds.
6. Molteno beds.
7. Upper Beaufort or Burghersdorp beds.

The area forms a striking example of the influence of geological formations upon the topography of the country. The numerous plateaux, terraces and magnificent amphitheatres are produced by the alternations of thick bands of coarse, pebbly sandstones and softer strata of mudstones and shales belonging to the Molteno beds. The long, evenly topped spurs with their deep and narrow gorges, extending from the Drakensberg range, are likewise crowned by horizontal Molteno beds. The unstratified and unjointed nature of the desert-formed Cave sandstone produced the precipitous and often fantastically shaped sandstone ramparts along the Drakensberg. The crest of the range with its alternating bare cliffs and gentler slopes,

is/....

is attributable to the pseudo-stratification of the lava flows belonging to the Drakensberg volcanic series.

Amidst such an area of high relief and continuous undulation, it is rather unusual to find a stretch of plane marsh-land as represented by the Cedarville Flats. du Toit (1929, p.8) considers this feature to have been produced by - "an old drainage system -, which was dismembered by quite recent crustal warpings".

The rainfall of the district varies from 30 to 40 inches per annum; the rainiest months being January, February and March. In winter the rainfall is approximately 1 inch per month, but prolonged periods of drought are not unusual. The country is nearly all grassland and used mainly for cattle and sheep farming. The quality of the grass varies considerably with the nature of the soil derived from the geological strata. The poor soils of the Molteno beds and the Cave sandstone only allow of a scanty vegetation of hard, sour grass and Proteas.

Large areas have recently been bought by the Native Trust, for farming by natives on the same principles as applied to the native Locations. As a result, some of the minor side-roads have been greatly neglected and certain portions of the district have become difficult of access.

#### Field Characters.

The bulk of the New Amalfi sheet occupies the greater part of Makoba's Location and the farms Katfontein, Zwartfontein, Uitkyk, Wanstead, Riversdale and Confluence. The sheet is transgressive and has a general, though varying dip to the North-West. It intruded the Burghersdorp beds, which, like all other sedimentary formations of the area, show a gentle dip of 2-5° towards the Drakensberg range/.

The New Amalfi Sheet.

The New Amalfi Sheet.



The New Amalfi Sheet.

Taken from the granophyre band in the West of the sheet; along the main road from Matatiele to Zwartberg. Note the typical form of the dolerite exposures; low hummocks of jumbled joint-blocks.

range.

The sheet has a rather irregular outcrop and is surrounded by numerous side-intrusions. Most of these are allied to the New Amalfi sheet and the dolerites show identical petrographical characters. Generally such side-intrusions show an inclination towards the main intrusion.

Within the New Amalfi exposure, numerous sedimentary xenoliths were encountered. Some of these were mapped, but many others proved too small for mapping purposes. Invariably the xenoliths consist of argillaceous material, which was baked to a hard, black hornstone. No reaction phenomena between dolerite magma and argillaceous sediment were observed, but examples of rheomorphic veining of dolerite by mobilised sediment are exceedingly common.

All along the western boundary of the sheet, from the top of Confluence peak up to a point on the Hanover-Ditkyk boundary, there occurs a well-defined, broad band of pale-coloured granophyric rocks. The granophyre differs considerably in grain-size from point to point, but everywhere preserves its essential features; long, feathery augite crystals set in a dirty grey, quartzo-feldspathic base. Within the granophyre band sedimentary xenoliths were encountered. In all cases the sediment proved to be identical with the normal Burghersdorp sandstone.

The igneous rock of the sheet is a coarse-grained, bluish black dolerite, generally enveloped in a thick, reddish brown weathering crust. Exposures consist of isolated heaps of sub-angular joint blocks, surrounded by the characteristic red dolerite soil. Blasting for road material has been carried out in several places and

much/....

**The Elephant's Head peak.**

The Elephant's Head peak.

The peak consists of a large block of coarse-grained  
trachyte of typical character. The dike here in-  
trudes Moliseo sediments and is highly transgressive.



The Elephant's Head peak.

The peak consists of a large block of coarse-grained tholeiite of typical characters. The dike here intrudes Molteno sediments and is highly transgressive.

much simplified the task of obtaining fresh specimens.

The Elephant's Head dike emerges from the sheet on the farm Hanover, near the entrance of the Umzimvubu River into the New Amalfi intrusion. On the boundary line of Mooi Plaats and Mzongwani's Location, the dike seemingly merges into a thin sill, only to reappear again further West. Thence it continues to Calamity Hill, its outcrop being marked by a low, rugged ridge. At Calamity Hill it meets a long spur of Molteno sandstone, extending from the Drakensberg range, in which the dike disappears. Further West the dike outcrops at several quite unexpected points along the spur, between which the strata run unbroken and undisturbed.

A good illustration of its curious behaviour is afforded by the imposing dolerite block of the Elephant's Head peak, which forms part of the large spur of Molteno sandstone. A small stream has cut a deep gorge in front and behind the exposure, so that the peak is detached on three sides from the main plateau. Towards the West the dike dips under the horizontal Molteno beds at  $10^{\circ}$ . Towards the East, however, it descends at a high angle, and thus no trace of the dike can be found at the other side of the river gorge, which here separates the dike from the main plateau. The Molteno beds show columnar jointing at the bottom of the gorge, indicative of the dike's continuation at yet lower levels. The walls of the dike are here perfectly vertical and the incision of deep clefts into the frontal side of this enormous dolerite block has given it the close resemblance to an elephant's head.

In this undulatory manner the dike climbs up the Drakensberg range, to enter Basutoland at Montai. Thence it continues into Basutoland, crossing the Orange River/.....

River and the Sinqungane River, to disappear into the great mountainous tract of Mount Robinson, through which it was not followed. It cannot be doubted that the dike is continuous underground, even although its exposures are discontinuous. Its irregular behaviour is exceptional and can only be compared with a few instances, of which the great Cleveland dike of northern England is probably the best known. On the Cape side, the 250-400 yards wide intrusion ascends, within a distance of some 18 miles, a surface elevation of roughly 3000 feet. The 37 miles of its known course in Basutoland is in yet more mountainous country, but here its outcrop is apparently continuous.

Within the Cape-portion of the dike a great variety of rock-types were met with, including brown coloured, coarse-grained tholeiites, black picrites and lighter coloured olivine-dolerites. In addition many instances of mobilisation and reaction between sediment and dolerite magma were encountered.

The tholeiites generally show sharp contacts against the picrites and olivine-dolerites, and occur near the sides or the top of the intrusion. Picrites were found in only two localities; at Calamity Hill and Mount Fred. In both these places they occur at, or near the bottom of major undulations in the dike. The passage from picrite to olivine-dolerite is gradational and no sharp contacts were observed. The latter rock in both instances overlies the picrite exposures.

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### III. THOLEIITES OF THE ELEPHANT'S HEAD TYPE.

#### General Statement.

Tholeiites of this type show chemical and petrological characters which class them in a group of their own. They are regarded as representing the first magma to intrude the dike and have no direct connection with the later olivine-dolerite magma. No tholeiites of the Elephant's Head type were found in the New Amalfi sheet.

#### Field Occurrences.

Tholeiites of the Elephant's Head type were found in several places along the dike, and their occurrences are generally associated with exposures of the walls or the roof of the dike.

At Calamity Hill fine-grained veins of tholeiitic material are observed to be intrusive in coarse picrite, near the southern wall of the dike. The contact itself proved to belong to the later olivine-dolerite magma. The 2-3 inches wide tholeiite veins resemble rheomorphic veins in character.

Exposures of igneous rock at the Elephant's Head peak consist mainly of brown-weathering, coarse tholeiite. In addition many irregularly-shaped patches of dark, basaltic rocks were found embedded in the normal tholeiite. Such patches occur in particular near the side-walls of the dike. The basalts proved to be chilled modifications of the tholeiite magma.

On the flat spur behind the Elephant's Head peak, the dike outcrops at several places. Only the roof is exposed and the exposure invariably consists of tholeiite.

Further/....

MICROPHOTOGRAPH.

Elephant's Head Tholeiite.

(Index No. 70).

The Elephant's Head Tholeiite.

(Index No. 70).

Broad latite of plagioclase, epidiorite-  
phic clinopyroxene, granular or skeletal  
iron ore and an interstitial mesostase  
tows the principal constituents.

Ordinary light x 10.5 diameters.



The Elephant's Head Tholeiite.

(Index No. 70).

Broad laths of plagioclase, hypidiomorphic clinopyroxene, granular or skeletal iron ore and an interstitial mesostasis form the principal constituents.  
Ordinary light x 10.5 diameters.

Further along, in the river-valley of Mount Fred, a single isolated outcrop of coarse-grained tholeiite is surrounded on all sides by picrite. Finally, an exposure of this rock occurs just under the Berg, near the northern wall of the dike.

### Petrography.

#### Normal Tholeiite.

The rock consists mainly of plagioclase, clinopyroxene, and mesostasis, whereas olivine and iron ore occur in minor quantities. Plagioclase builds thick laths, showing medium zoning. Its aver.  $\beta$  is 1.564 and its composition An.61. Clinopyroxene is sub-ophitic to idiomorphic and has a brown colour. The optical properties are:  $2V_{\gamma} : 41^{\circ}$ ,  $\gamma:c : 45^{\circ}$ , and  $\delta : 1.725$ . Apparently it borders onto the group of the ferroaugites (Hess. 1941, p.518). Zoning is negligible. Olivine occurs as a few, medium-sized crystals. The mineral is always altered to a yellow serpentine. Iron ore builds skeletal crystals, moulded on plagioclase or pyroxene. The interstitial mesostasis contains small skeletal laths of a medium plagioclase, elongated prisms of clinopyroxene, quartz, and abundant iron ore.

The rocks have a highly altered appearance in the field and are generally of a rusty-brown colour. This is due mainly to the oxidation of iron ore and the alteration of the mesostasis, both plagioclase and pyroxene remaining perfectly fresh. The alteration of olivine is believed to belong to a late stage of magmatic consolidation. The mineral is obviously not in equilibrium with the quartzose, iron-rich mesostasis crystallising later.

Chilled/....

Chilled Modifications.

The chilled basalts are characterised by phenocrysts of plagioclase, clinopyroxene and altered olivine, the last being exceedingly scarce. The groundmass is a fine-grained copy of the normal tholeiite, except that olivine is absent. The pyroxene of the groundmass shows identical properties to that of the normal rock.

The fine-grained material of the veins at Calamity Hill shows certain departures from the average chilled basalt. It contains the same porphyritic elements, but the groundmass shows a great prevalence of pyroxene over plagioclase. The pyroxene is also dominantly granular in habit. The mesostasis has been replaced by a white, intensely altered, feldspathic base.

The above features are best explained by assuming the partial melting of the chilled tholeiite by the later olivine-dolerite magma. Such mobilisation apparently only affected the plagioclase and the mesostasis, though the pyroxene crystals were corroded and modified in shape by the ensuing feldspathic liquid. The mobile mass evidently acquired rheomorphic properties and in turn invaded the partly solidified picrite nearby. The phenomenon is on a very small scale, and only visible on the S.W. side of the dike.

Discussion.

At Calamity Hill, rheomorphic veins of fine-grained tholeiite occur in coarse-grained picrite, a little distance from the southern contact of the dike. The contact itself is related to the olivine-dolerite magma and is basaltic. This second magma thus apparently worked its way through the tholeiite mantle and came locally in direct contact with the sediment. The fact that the  
contact/....

contact is chilled shows that the sediment had cooled down again. This is taken as partial evidence indicating that the olivine-dolerite magma invaded the dike wall after the complete solidification of the tholeiite magma.

At Elephant's Head, irregular patches of chilled, basaltic tholeiite were found in normal, coarse-grained tholeiite. Here apparently the chilled contact phase was negotiated by the magma shortly after its formation. The newly established contact is not chilled, as the sediment had been thoroughly heated and still maintained such heat. In sills it is customary to picture the basaltic contact modifications as distinct and uninterrupted zones along both boundaries. In dikes these zones are often interrupted and sometimes only remnants of the chilled phases remain as isolated blocks, surrounded by coarser grained rock. The basaltic contacts obviously possess a pronounced tendency to develop cracks, due to their sudden cooling and contraction. In a dike, where there is conspicuous flow of magma, often prolonged over a considerable period, conditions are favourable for the widening of such cracks, and the detachment of blocks of chilled basalt from the sedimentary walls. The newly exposed sediment is now thoroughly heated up and the impetus for the formation of chilled modifications has thus been lost. On the other hand, conditions are favourable for interaction between hot and semi-mobile sediment and magma. At Elephant's Head it is also found that a considerable amount of reaction between the tholeiite of the dike and the Molteno sediments of its walls has taken place.

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DIAGRAM 1.

Field Relations at Mount Fred.

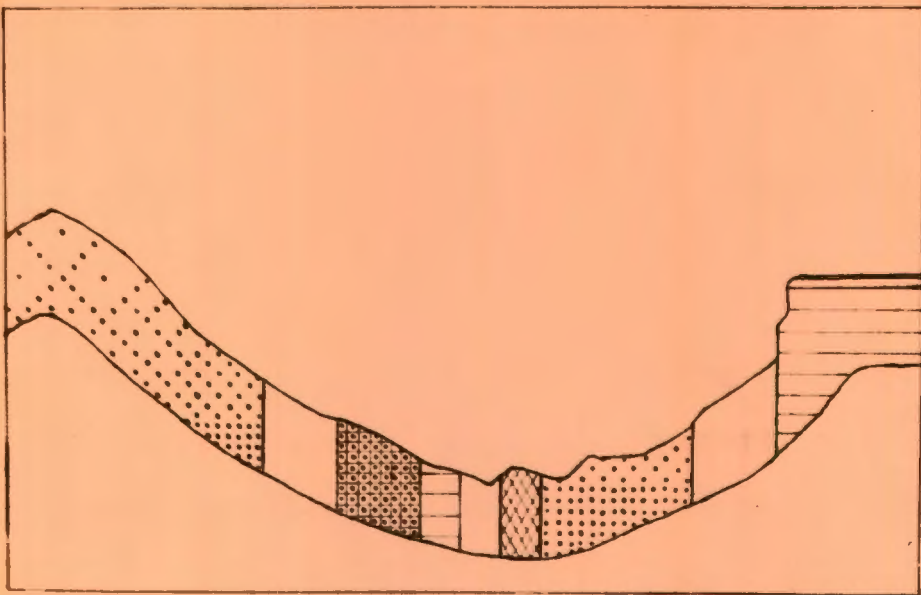
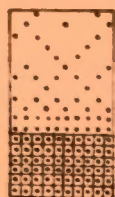


DIAGRAM 1.

The Field Relations at Mount Fred.

INDEX.



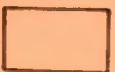
*Olivine-dolerite and  
Picrite.  
Variolitic Picrite.*



*Tholeiite of Elephant's Head Type.*



*Molteno Sediment.*



*No Exposures.*

#### IV. THE OLIVINE-DOLERITE MAGMA.

##### General Statement.

All the rocks to be discussed under this heading, are considered to be derived from one common magma. It followed the intrusion of the tholeiite magma and is responsible for the formation of the New Amalfi sheet. The olivine-dolerite magma commenced crystallisation with the precipitation of magnesian olivine, followed shortly afterwards by basic labradorite. The crystallisation proceeded towards an end-pole, rich in soda and iron.

##### A. Picrites and Associated Olivine-Dolerites.

###### Field Occurrences.

The rocks to be described here outcrop along the dike from Montai on the Basutoland border to near Taylorville in the Mzongwani's Location. The picrite exposures show a gradual decrease in olivine content with increasing elevation. They occur in close association with olivine-dolerites of typical characters. Such olivine-dolerites represent the normal dike-rock of the exposures both in Basutoland and the Cape Province. No corresponding acid phases were encountered in the dike.

Picrites occur at Mount Fred and Calamity Hill. At both these localities they lie at the bottom of steep undulations in the dike. The field relations of the Mount Fred exposure are given in diagram 1. Both at Mount Fred and at Calamity Hill the picrites are directly overlain by olivine-dolerites. Rocks of identical character were also found in Basutoland and in the poort of Mahainkwe. A peculiar type of olivine-dolerite forms a small, pipe-like exposure in Molteno sediment at the foot of the Elephant's Head peak.

MICROPHOTOGRAPH.

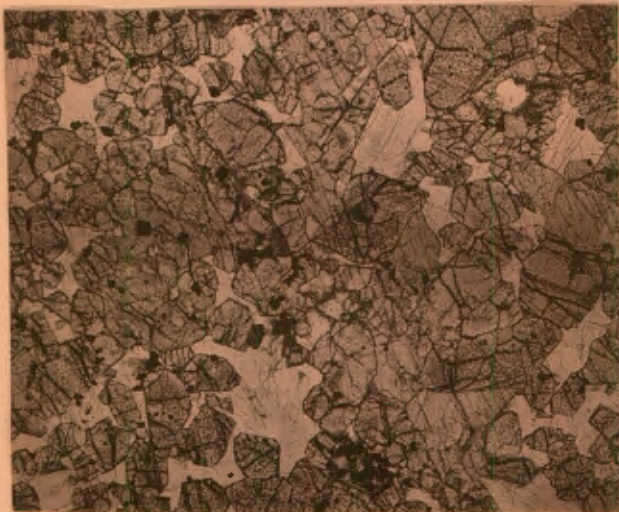
Normal Picrite.

(Index No. 39).

Normal Picrite.

(Index No. 39).

Idiomorphic olivine in two generations,  
paleolithic pyroxene and pyroxene  
occur together with octahedral chrom-  
magnetite and a little biotite. The  
olivine is charged with dendritic inclu-



Normal Picrite.

(Index No. 39).

Idiomorphic olivine in two generations, poikilitic plagioclase and pyroxene occur together with octahedral chrom-magnetite and a little biotite. The olivine is charged with dendritic inclusions of ore.

Ordinary light x 10.5 diameters.

Petrography.

Normal Picrites.

The normal picrites of Mount Fred and Calamity Hill show great similarity in their petrographical and mineralogical characters. The rocks resemble the basal phases of the Insizwa lopolith, described in detail by Scholz (1936, p. 102-117).

Olivine occurs as well-developed crystals, decreasing gradually in amount from 61-22%. Although all sizes may be encountered, it chiefly occurs in two generations of large and small crystals, without there being much difference in composition between the two generations. There is a tendency for the larger crystals to become rarer as the olivine percentage decreases. Crystals are non-zonal, though different grains may have different compositions, ranging from Fa. 17-23.

Plagioclase is poikilitic in habit in the picrites richer in olivine. Here it builds stout crystals showing but little zoning. With decreasing olivine percentage, a second generation of slender zonal laths appears and becomes increasingly more abundant. As the first generation is substituted by the second, the larger crystals assume a more complex character as regards twinning and zoning.

Both ortho- and clinopyroxene occur in the picrites. The former varies in amounts from 15-30% of the total pyroxene. Crystals are poikilitic in habit; the texture becoming best developed in rocks with 25-35% olivine. At 22% olivine, however, there is a sudden change, the pyroxene here being ophitic to sub-ophitic. Moreover, simple twinning on (010), absent in the other picrites, is here occasionally observed. All the

crystals/...

crystals show but little zoning.

Iron ore also changes its habit in the series. In the most basic rocks it occurs as small octahedra, enclosed in olivine, plagioclase and pyroxene alike. In the picrites with less olivine, the iron ore forms large skeletal masses, bounding plagioclase or pyroxene. The small octahedra were qualitatively examined and thus the presence of chromium was established in the early ore. This proved to be absent in the ore of later formation.

The usual deep reddish brown biotite forms a constant accessory. It is regarded a reaction-product of chromiferous iron ore. A few, yellow patches of sulphidic ore occur scattered through the rock.

Optical data.

Olivine.	$2V_{\alpha}$ .	$\delta$	Composition.
large	88°	1.705	Fa. 17
small	85°	1.717	Fa. 23
Plagioclase.		av. $\beta$	av. Composition.
large		1.569	An. 70
small		1.566	An. 66
Clinopyroxene.	$2V_{\gamma}$ .	$\delta : c$	$\delta$
	49-46°	38-36°	1.713-1.716
Orthopyroxene.	$2V_{\alpha}$ .	$\delta$	Composition.
	82-77°	1.684-1.689	Of. 15.-18.
Biotite.	$\delta$		Pleochroism.
	1.643	$\delta$ : deep reddish brown	$\alpha$ : cream-yellow

MICROPHOTOGRAPH.

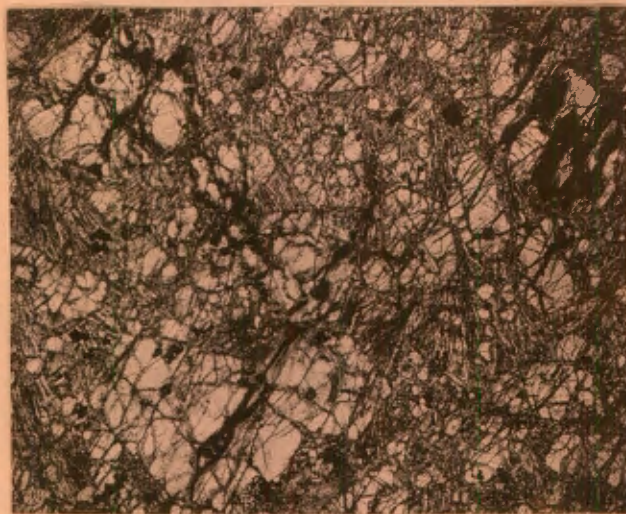
Variolitic Picrite.

(Index No. 11).

Variolitic Picrite.

(Index No. 11).

Large and small olivine crystals embedded  
in a groundmass of plagioclase and pyrox-  
ene with variolitic texture. A little



Variolitic Picrite.

(Index No. 11).

Large and small olivine crystals embedded in a groundmass of plagioclase and pyroxene with variolitic texture. A little chromiferous magnetite occurs as octahedral crystals.

Ordinary light x 10.5 diameters.

Variolitic Picrites.

These peculiar rocks contain large phenocrysts of olivine set in a fine-grained groundmass, in which olivine also occurs in a second generation. The groundmass consists chiefly of slender laths of feldspar and sub-ophitic, elongated augite, together with small granules of iron ore. Bundles of feldspar and pyroxene often have a fan-shaped arrangement, reproducing the structure of the variolitic basalts. Both the olivines of the phenocrysts and those of the groundmass are corroded and embayed. Except for olivine, all the constituents show the same optical properties as those of the normal picrites. Olivine is generally more magnesian, its range being Fa. 15 (phenocrysts) to Fa. 17 (groundmass).

In one of the rocks a small xenolith of black, compact hornfels was found. The material of the xenolith is not resolved by the microscope. Marginally two narrow, monomineralic zones occur. The first and inner one consists of a single layer of small iron ore granules. The second zone consists of numerous small olivine crystals, closely packed together. These proved to have the composition Fa. 17.

Olivine-Dolerites.

The olivine-dolerites range in grain-size from medium to coarse. Their texture is ophitic to sub-ophitic.

Olivine occurs as groups of small crystals or larger, individual grains. A wide range of composition is observed, the clusters of small grains generally being the most fayalitic.

Plagioclase builds small zonal laths. In addition a few stouter crystals were observed, which are similar to the first-generation plagioclase of the picrites. They show the same intricate pattern of zoning and twinning on

an even/....

an even more elaborate scale.

Clinopyroxene occurs as sub-ophitic plates, generally showing twinning of the butterfly type. Individuals may differ considerably in size. Occasionally aggregates of small crystals with different orientations are encountered. Zoning is very pronounced.

Orthopyroxene builds sub-ophitic to ophitic plates, and is generally of later formation than clinopyroxene. The crystals show the structure variously designated as "graphic intergrowth", "lamellar intergrowth" and "lamellar twinning" on a minute scale.

Black ore forms skeletal masses of late crystallisation. Chocolate-brown biotite and apatite are ubiquitous and likewise of late formation. Interstitial micropegmatite occurs in varying, but always small amounts.

Optical data.

Olivine.	$2V_{\alpha}$ .	$\gamma$	Composition.
	73-79°	1.766-1.744	Fa.47-36
Plagioclase.	av. $\beta$		av. Composition.
	1.566		An.66
Clinopyroxene.	$2V_{\gamma}$ .	$\delta : c$	$\delta$
	49-34°	38-35°	1.713-1.723
Orthopyroxene.	$\gamma$		Composition.
	1.705-1.711		Of.30-36
Biotite.	$\gamma$		pleochroism.
	1.646		$\gamma$ : Chocolate-brown $\alpha$ : Straw-yellow.

Olivine-/. ....

Olivine-dolerite of Elephant's Head.

The rock shows close alliances to the P.K. type of Karroo dolerite (Walker and Poldervaart, 1941a, p.137-140), but is unusually rich in olivine. The latter mineral occurs as abundant small crystals of Fa. 23. In addition a few larger individuals of composition Fa. 15 were recorded. The division of the two generations is perfectly sharp and no intermediate sizes were met with. Plagioclase (An. 70) occurs as narrow, zonal laths. Pyroxene ( $2V_{\gamma} : 47^{\circ}$ ) is of the monoclinic variety only, and builds zonal, ophitic plates. Octahedral black ore and red ish-brown biotite form the accessory minerals.

Micrometric Analyses. (volume percentages)

Picrites.

Index No.	37.	39.	41.	42.	11.	14.	10.	9.
Olivine	61.2	56.1	34.5	23.6	49.4	44.1	38.2	21.9
Plagioclase	16.7	21.2	36.1	44.6	24.6	30.2	44.7	52.9
Pyroxene	14.0	17.3	24.0	27.9	21.3	18.9	15.0	23.6
Iron ore	5.5	2.9	2.9	2.4	4.7	4.0	1.7	1.4
Biotite	2.6	2.5	2.5	1.5	tr.	2.8	0.4	0.2

- 37-42      picrites, Calamity Hill, taken from road towards top of hill (vertical distance 100 ft.)
- 11          variolitic picrite, Mount Fred, bottom of river valley.
- 14-9      picrites, Mount Fred, taken towards top of hill S.W. of road (vertical distance 250 ft.)

Olivine/.....

Olivine-dolerites.

Index No.	67.	43.	44.	8.	29.
Olivine	12.5	3.9	2.6	6.3	3.0
Plagioclase	42.4	46.3	53.2	54.6	58.2
Pyroxene	36.0	39.0	38.4	33.9	33.8
Iron ore	5.4	4.1	2.0	2.1	2.0
Biotite	3.7	0.8	1.1	1.2	1.2
Micropegmatite	-	5.9	2.7	1.9	1.8

- 67            olivine -dolerite, foot of Elephant's Head peak.
- 43-44        olivine-dolerites along the Dike, from Calamity Hill towards Taylorville.
- 8             olivine-dolerite, Mount Fred, top of hill S.W. of road.
29.          olivine-dolerite, centre of Dike, poort at Mahainkwe.

Discussion.

A comparison of the modal compositions of the picrites from Mount Fred and Calamity Hill shows that the rocks from the first-named locality are constantly richer in plagioclase and poorer in pyroxene. At Mount Fred, variolitic picrites were found and the field relations there are somewhat unusual.

Rocks with variolitic structures are commonly described as being the products of sudden cooling. The formation of a similar variolitic picrite from the Island of Skoay (Harker, 1904, p.470) was likewise referred to sudden chilling. Bowen (1938, p.146-147) is most pertinent in his comment on the rock:- "It is not reasonably to be supposed that the large olivine crystals of this rock were formed under the same conditions as a groundmass which/....

which is but a step removed from the spherulitic state of crystallisation. - Plainly the groundmass was the only portion of the rock that was liquid when it was finally chilled on intrusion", The implications of the mode of formation of the variolitic picrites were, however, found to be somewhat puzzling. Two alternatives offered themselves:-

(1) either the magma contained some 30% of crystalline, solid olivine upon intrusion (this being the approximate amount of olivine phenocrysts).

(2) or a portion of the crystallising magma was suddenly cooled, when olivine had already commenced crystallisation and had settled in considerable quantities. The remaining portion apparently continued to crystallise undisturbed.

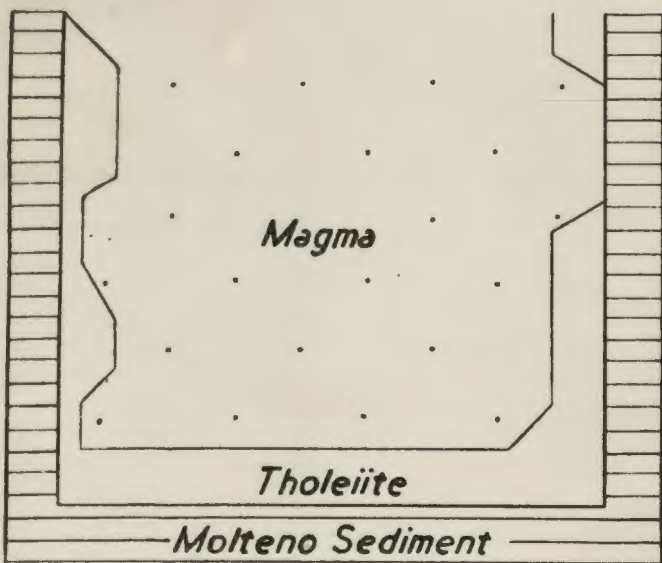
The author could not associate the first alternative with the observed facts and their full implications. The chilled modifications bounding the picrite exposures all proved to belong to the olivine-dolerite magma type. The overlying olivine-dolerites do not show sharp contacts against the picrites. The picrites themselves show a grading of olivine content which can only be associated with gravitational settling of that mineral in place. Their occurrences in the depressions of the undulatory dike also underlines the assumption of gravitation of olivine. Finally, the variolitic picrites form a solitary and isolated exposure, bounded by normal picrites.

Thus the second alternative had to be considered, however conjectural it appeared at first sight. The clue to its solution was found in a dolerite sill at Hangnest in the Calvinia district (Walker and Poldervaart, 1941b). The rock here is a coarse-grained bronzite-dolerite, containing an average of 6% micropegmatite. The

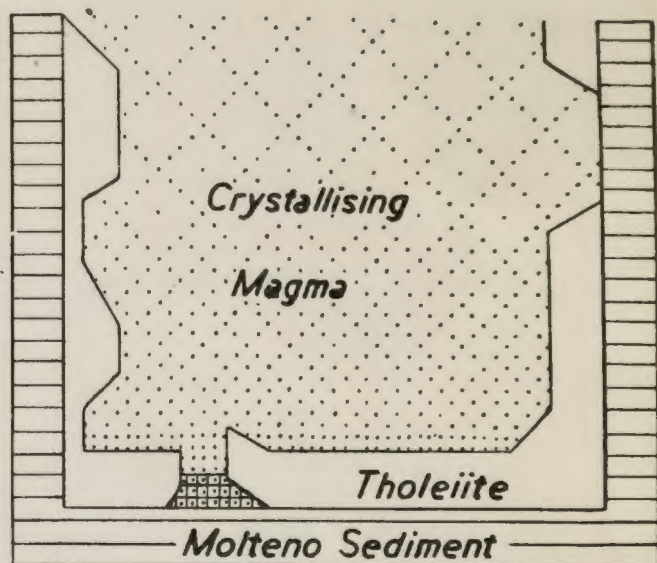
magma/....

DIAGRAM 2.

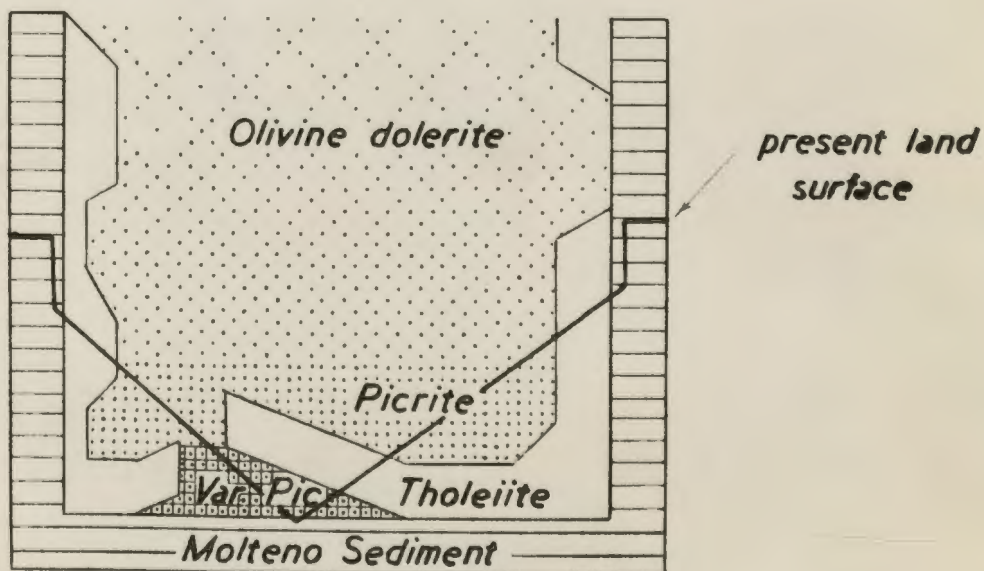
The Formation of the Variolitic Picrite  
at Mount Fred.



A.



B.



C.

### DIAGRAM 2 .

*Illustrating stages in the Stopping Process which resulted in the formation of the Variolitic Picrite .*

magma stopped down a block of sediment from the upper contact of the sill. The dolerite in the wedge above the stopped block is fine-grained and contains 12% mesostasis instead of micropegmatite. It shows no variolitic structures but possesses the essentials for the formation of such structures, i.e. great elongation of both plagioclase and pyroxene. Obviously the dolerite was formed by quick cooling.

Turning back to the Mount Fred exposure, the following sequence of events was visualised:-

- (i) intrusion of the first tholeiite magma;  
complete solidification of the tholeiite.
- (ii) intrusion of the olivine-dolerite magma;  
partial preservation of a mantle of tholeiite rock to protect the sediment.
- (iii) crystallisation of the olivine-dolerite magma, commencing with the separation of olivine. Gravitational settling of olivine and accumulation towards the bottom of the magma chamber.
- (iv) development of cracks in the tholeiite mantle, due to differential expansion on heating. Widening of these cracks. Stopping of a strip of tholeiite mantle from the floor of the magma chamber. Newly established contact between differentiated second magma and cold sediment, hitherto protected by the tholeiite mantle.
- (v) freezing of the differentiated magma in the gap thus produced; formation of the variolitic picrites (diagram 2a-c).

The above picture reasonably explains the occurrence of the variolitic picrite at Mount Fred, and also takes in account the field relations of the exposure. It has, however, two direct inferences:-

(a) the/....

DIAGRAM 3.

Modal Compositions of the Picrites.

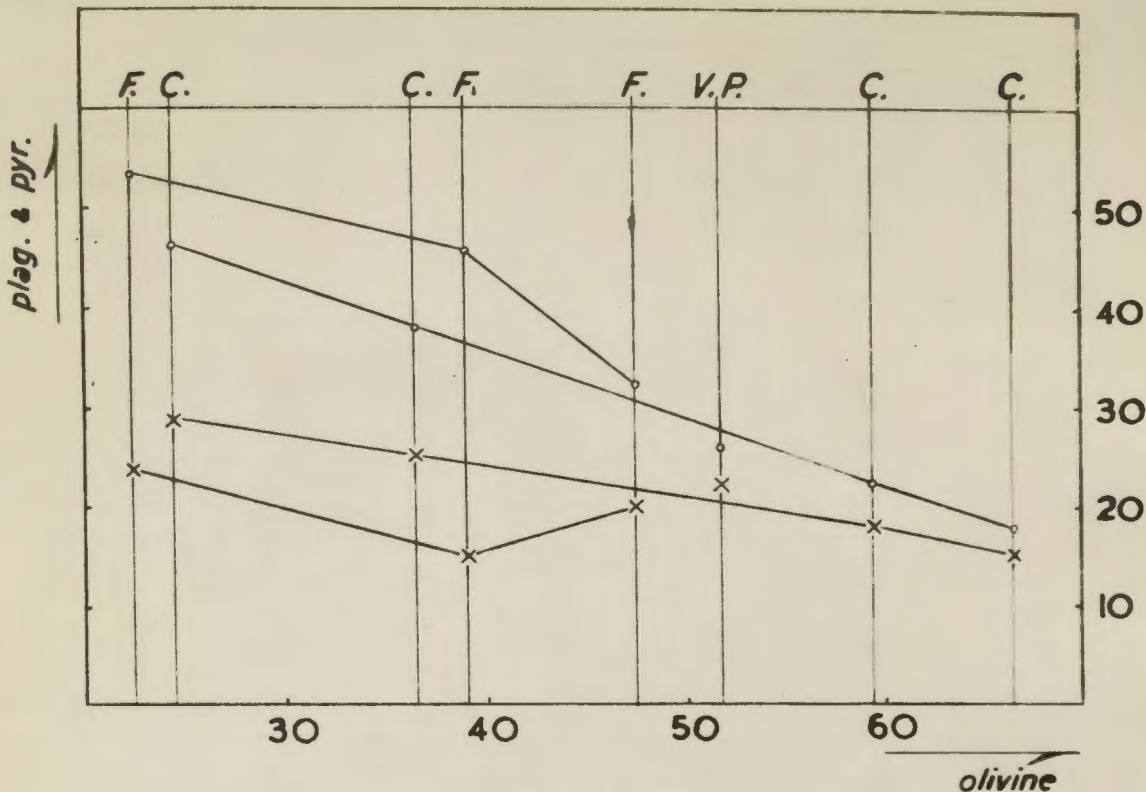
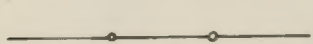


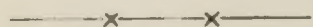
DIAGRAM 3.

Modal Compositions of the Picrites.

(minus accessories and recalculated to 100%).



Plagioclase.



Total Pyroxene.

C. : Calamity Hill Picrite.

V.P. : Variolitic Picrite.

F. : Mount Fred Picrite.

- (a) the picrites were formed by gravitational settling of olivine, crystallising in excess of the stoichiometric proportion from an olivine-dolerite magma.
- (b) the dike is floored as well as roofed.

Both these inferences will be fully discussed under later headings. For the moment the above picture, together with its necessary deductions, is taken as tentative, offering the most satisfactory explanation of the observed features.

Another character is also in keeping with the explanation given above. The Calamity Hill picrites are remarkably regular as regards the changes in mineral proportions with increasing olivine content. No such regularity is present in the Mount Fred series. It has already been observed that the Mount Fred picrites are constantly richer in plagioclase and poorer in pyroxene than the Calamity Hill series. To bring out these features the modes of all the picrites were recalculated to 100% in terms of olivine, plagioclase and pyroxene (diagram 3).

It is to be noted that the variolitic picrite shows less plagioclase and more pyroxene than corresponds with the Calamity Hill series. Subtraction of a portion of the magma by freezing to variolitic picrite would thus result in such differences as are produced in the Mount Fred series. Hence the results are in keeping with the theoretical deductions that, (1) the most basic rock of Mount Fred should contain less olivine than the corresponding most basic rock at Calamity Hill, and (2) the picrites of Mount Fred should contain markedly more plagioclase and consequently less pyroxene, than the Calamity Hill picrites.

It is interesting to note the occurrence of olivine-rich dolerite in a pipe-like offshoot of the dike at Elephant's Head. At the peak itself no olivine-dolerite is exposed, as only the roof and the two walls of the dike are visible. The occurrence of 67 proves, however, that there is olivine-dolerite at Elephant's Head, though the rock is concealed by the mantle of tholeiitic rocks.

B. Olivine-Dolerites and Iron-rich Dolerites  
of the New Amalfi Sheet.

Field Occurrences.

The dolerites of the dike from Hanover to the New Amalfi sheet are included under this heading. They resemble the dolerites of the sheet rather than those of the dike, though differences are physical rather than chemical. Thus the olivine-dolerites are generally coarser grained than the normal dolerites, which mark the dike in Basutoland and the Cape.

From the map of the New Amalfi intrusion the relative distribution of the rock types may be observed. The iron-rich dolerites form a narrow zone in between the olivine-dolerites and the band of metasomatic granophyre. The approximate distribution of the rocks was computed from a collection of over a hundred specimens from all over the area. The boundary lines were drawn for the sake of clarity and should not be interpreted as representing sharply defined contacts. The division between olivine-dolerites and iron-rich dolerites was drawn at the point of failure of olivine to crystallise. It is, however, noted that further differentiated rocks may again

show/...

show olivine, though then markedly more fayalitic.

Systematic collecting was hindered by the intermittent character of the exposures and the inevitable complications resulting from the inclination of the sheet and the relief of the area. Thus the orthodox method of recording heights of specimens above the lower contact was not applicable, and only rough orientations could be made.

### Petrography.

#### Olivine-dolerites.

These rocks consist of the usual association of olivine crystals, zonal plagioclase, sub-ophitic, zonal pyroxene, and interstitial micropegmatite in varying amounts. Iron ore, biotite and apatite form the accessories, and are all of late formation. The grain-size is that of a gabbro, but it is preferred here to apply the term "gabbro" only to plutonic rocks of basaltic composition. Near the contact, micropegmatite may be substituted by mesostasis. This is believed to be due solely to quicker cooling and the rocks preserve their chief characters.

The interrelations of the several pyroxenes are interesting and provide a means for a division of the rocks into three groups:-

- (1) Dolerites near contacts:- Orthopyroxene gives way to both early and late pigeonite (Walker and Poldervaart 1941a, p.132-134) as the contact is approached. Late pigeonite generally predominates over early. Olivine is always altered near the contacts; the alteration product being bluish-green, pleochroic bowlingite. Micropegmatite may be substituted by mesostasis. Clinopyroxene is moderately zonal and develops a tendency for an ophitic habit.

MICROPHOTOGRAPH.

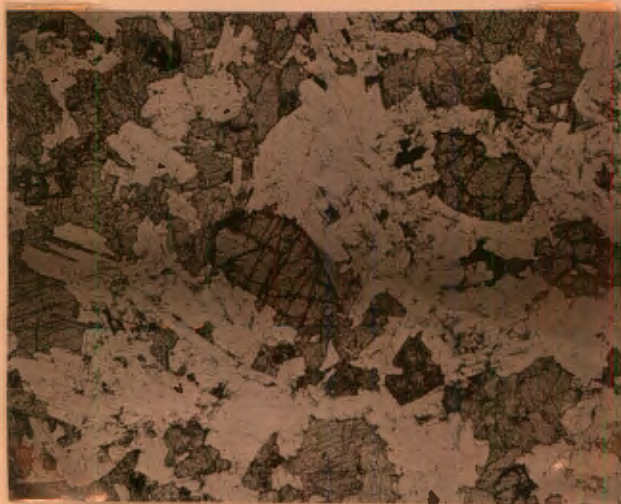
Olivine-dolerite.

(Index No. 58).

Olivine-dolerite.

(Index No. 58).

Large olivines, felds of plagioclase,  
ophitic orthopyroxene and enstatite



Olivine-dolerite.

(Index No. 58).

Large olivines, laths of plagioclase, ophitic orthopyroxene and sub-ophitic clinopyroxene occur together with a little iron ore, biotite, and micro-pegmatite.

Ordinary light x 10.5 diameters.

- (2) Dolerites away from contacts:- Pigeonite is always absent. Orthopyroxene is both earlier and later than clinopyroxene; the bulk being later. Olivine is always fresh. Clinopyroxene is strongly zonal and sub-ophitic.
- (3) Dolerites near the iron-rich zone (centre of sheet):- Rare, columnar crystals of early pigeonite form cores to mantles of orthopyroxene or augite. Late pigeonite is absent. All other minerals occur in the same fashion as in the dolerites of group 2.

The orthopyroxenes show a considerable range in composition in individual rocks. For example, in 58 the orthopyroxene commonly occurs as sub-ophitic crystals showing the "graphic intergrowth" on a minute scale. The majority of these grains is of later formation than clinopyroxene (av. composition Of. 26), but a few are of earlier crystallisation and then of composition Of. 20. In addition a third generation of orthopyroxene occurs as rare, ophitic plates of composition Of. 42. The latter crystals do not show the "graphic intergrowth" and are pleochroic, in tints of pale green to pale reddish-brown.

Optical data/....

Optical data.

Group 1.

Olivine	altered to pleochroic bowlingite.		
Flagioclase.	av. $\beta$	av. Composition.	
	1.568	An. 69	
	$2V_{\gamma}$ .	$\gamma : c$	$\gamma$
Early pigeonite.	5-10°	36-38°	1.702-1.705
Augite.	46-44°	38-36°	1.716-1.714
Late pigeonite.	13-6°	30-34°	1.733-1.735

Group 2.

Olivine.	$2V_{\alpha}$ .	$\gamma$	Composition.
	83-76°	1.728-1.757	Fa. 28-42
Flagioclase.	av. $\beta$	av. Composition.	
	1.568	An. 69	
Augite.	$2V_{\gamma}$ .	$\gamma : c$	$\gamma$
	47-31°	38-33°	1.715-1.721
Orthopyroxene.	av. $\gamma$ .	av. Composition.	
	1.698	Or. 26	

Group 3/.....

MICROPHOTOGRAPH.

Iron-rich Quartz-dolerite.

(Index No. 20).



Iron-rich Quartz-dolerite.

(Index No. 20).

Olivine is absent. Iron-rich clinopyroxene, plagioclase and micropegmatite are the chief constituents. Iron ore builds large skeletal masses.

Note the striated appearance of many of the clinopyroxene crystals.

Ordinary light x 10.5 diameters.

Group 3.

Olivine.	$2V_{\alpha}$ .	$\delta$	Composition.
	$74^{\circ}$	1.765	Fa.46
Plagioclase.	av. $\beta$		av. Composition.
	1.566		An. 66
Early pigeonite.	$2V_{\gamma}$ .	$\delta : c$	$\delta$
	$13^{\circ}$	$34^{\circ}$	1.700
Augite.	49-46 $^{\circ}$	38-34 $^{\circ}$	1.713-1.716
Orthopyroxene.	av. $\delta$ .	$\delta : c$	av. Composition.
	1.705	$0^{\circ}$	Of. 30

Iron-rich Dolerites.

The rocks again consist chiefly of plagioclase and clinopyroxene together with varying amounts of interstitial quartz and micropegmatite. Iron-rich olivine and orthopyroxene occur in small amounts as products of late crystallisation. Iron ore, biotite, hornblende and apatite are the accessory minerals.

The rocks show abundant evidence of continuous readjustment to a constantly changing environment. The somewhat unusual mineral associations encountered are therefore not wholly unexpected. Relations of individual groups of minerals are also complicated and often obscured by the fact that complete equilibrium between solid and liquid was rarely attained.

The series 20, 52 and 18 is here selected as representative for the whole group. The rocks show three stages of the differentiation process and intermediate rocks exhibit corresponding transitions.

Specimen 20 is essentially a quartz-dolerite. It consists/.....

MICROPHOTOGRAPH.

Iron-rich Fayalite-quartz

Dolerite.

(Index No. 52).

Iron-rich fayalite-quartz dolerite.

(Index No. 52).

Fayalite and iron-rich orthopyroxene occur  
rounded on titaniferous iron ore. The  
chief constituents are acid Labradorite,  
Ferroaugite and microperthite.  
Ordinary light x 10.5 diameters.

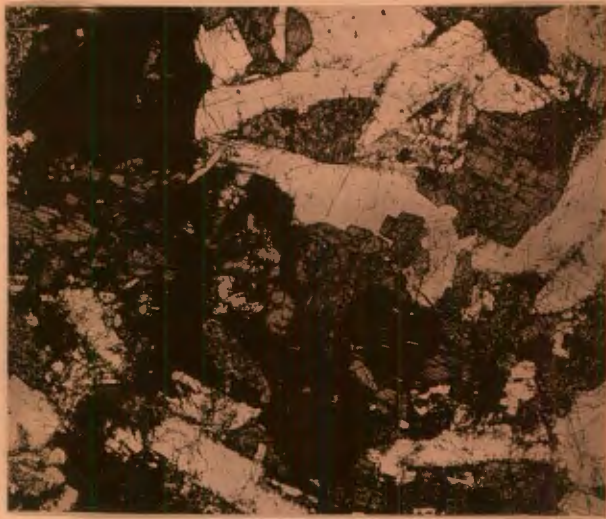
MICROPHOTOGRAPH.

Hedenbergite Granophyre.

(Index No. 18).

Hedenbergite Granophyre.

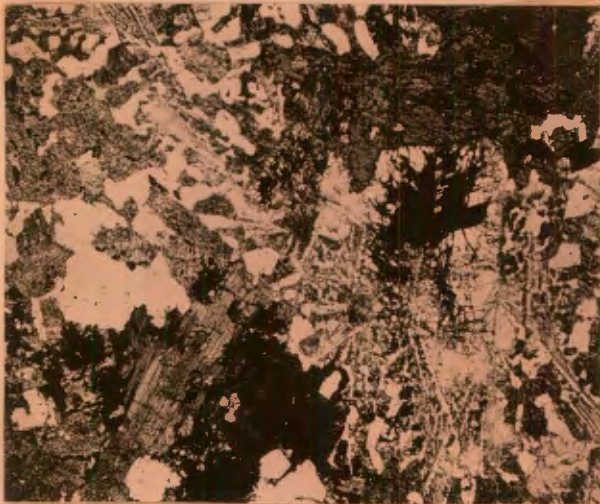
(Index No. 18).



Iron-rich Fayalite-quartz dolerite.

(Index No. 52).

Fayalite and iron-rich orthopyroxene occur moulded on titaniferous iron ore. The chief constituents are acid Labradorite, Ferroaugite and micropegmatite. Ordinary light x 10.5 diameters.



Hedenbergite Granophyre.

(Index No. 18).

Consists essentially of plagioclase, hedenbergite, micropegmatite and quartz. Iron ore, brown serpentine, hastingsite and fayalite occur in addition. Ordinary light x 10.5 diameters.

consists of the usual framework of broad plagioclase laths and sub-ophitic or insertal clinopyroxene, while micropegmatite and quartz occupy the interstices. Olivine is absent. Clinopyroxene shows the fine striations and the platy alteration to biotite, so commonly observed in teschenites. It occurs in two modifications; (1) a very pale greenish-brown augite, similar to the normal augite of the olivine-dolerites, and (2) a pale purplish-brown ferroaugite. The latter often forms borders to the pale augite crystals. Orthopyroxene occurs as small, stumpy crystals, moulded on clinopyroxene. A marginal alteration to green, pleochroic bastite is often observed. Iron ore occurs as large skeletal masses. Hornblende is absent.

Specimen 52 exhibits the same texture as 20. The normal pale-coloured augite is wholly wanting in this rock. Instead the clinopyroxene consists of pale purple-brown or pale green crystals. Both modifications are ferroaugites; the green variety being even richer in the  $\text{FeSiO}_3$  molecule. Here again the clinopyroxenes resemble those of the analcite-bearing rocks in appearance. Olivine occurs in addition to orthopyroxene. It forms small, fayalitic crystals moulded on clinopyroxene or iron ore. Among the accessories, biotite is largely replaced by a pale-brown, pleochroic hornblende.

Specimen 18 consists chiefly of plagioclase, micropegmatite, quartz, and pyroxene. The latter occurs as purple-brown or green crystals; the green variety occasionally forming borders to purple-brown crystals. The purple-brown colour is probably due to  $\text{TiO}_2$ , but the two varieties show little difference in their optical data. Orthopyroxene is absent. Fayalite occurs as scattered grains in association with iron ore. Greenish-blue, pleochroic hastingsite builds slender needles in

quartz/....

quartz, or occurs moulded on green pyroxene. In addition large masses of serpentine occur in the rock, varying in colour from reddish-brown to olive-brown. Iron ore is always associated with such masses. Some of the serpentine is demonstrably derived from fayalite or pyroxene, but a certain proportion may have crystallised during the final stages of magmatic consolidation. Zircon also appears for the first time among the accessories.

Optical data.

Specimen 20.

Plagioclase	av. $\beta$	av. Composition.	
	1.563	An. 60	
Clinopyroxene.  pale greenish brown pale purple-brown	$2V_{\gamma}$	$\gamma : c$	$\gamma$
	$40^{\circ}$	$44^{\circ}$	1.721
	$50^{\circ}$	$45^{\circ}$	1.734
Orthopyroxene.	$2V_{\alpha}$	$\gamma$	Composition.
	$57^{\circ}$	1.746	Of. 67
Biotite.	$\gamma$	pleochroism	
	1.673	$\gamma$ : dark brown $\alpha$ : pale brownish-yellow	

Specimen 52.

Olivine.	$2V_{\alpha}$	$\gamma$	Composition.
	$58^{\circ}$	1.835	Fa. 80
Plagioclase.	av. $\beta$	av. Composition.	

Plagioclase.	av. $\beta$ .	av. Composition	
	1.560	An. 57	
Clinopyroxene. pale purple-brown pale green	$2V_{\gamma}$ .	$\gamma : c$	$\gamma$
	$50^{\circ}$	$45^{\circ}$	1.734
	$52^{\circ}$	$43^{\circ}$	1.740
Orthopyroxene.	$2V_{\alpha}$ .	$\gamma$	Composition.
	$71^{\circ}$	1.762	Of. 79
Hornblende	$\gamma$	pleochroism.	
	1.693	$\gamma$ : dark chestnut-brown $\alpha$ : pale yellow-brown	

Specimen 18.

Olivine.	$\alpha$	Composition.	
	1.828	Fa. 100	
Plagioclase.	av. $\beta$ .	av. Composition.	
	1.547	An. 31	
Clinopyroxene. purple-brown green	$2V_{\gamma}$ .	$\gamma : c$	$\gamma$
	$56^{\circ}$	$45^{\circ}$	1.759
	$56^{\circ}$	$45^{\circ}$	1.758
Hastingsite.	$\gamma$	$\gamma : c$	pleochroism.
	1.709	$12-15^{\circ}$	$\gamma$ : dark greenish blue $\alpha$ : brownish green

Micrometric Analyses.

Index No.	58.	25.	79.	20.	56.	52.	18.
Olivine.	10.3	6.6	4.7	-	-	0.5	1
Plagioclase.	50.7	51.3	51.7	44.8	39.0	36.2	26
Pyroxene.	33.9	34.8	31.1	35.4	26.5	23.3	7
Iron ore.	1.8	1.9	2.2	1.8	5.8	6.2	5
Biot. & Amph.	0.4	1.1	1.3	4.3	7.6	10.2	2
Microp. & Qu.	2.9	4.3	9.0	13.7	21.1	19.7	51
Serpentine.	-	-	-	-	-	3.9	8

58. dolerite Dike, behind Hanover farmhouse.
25. dolerite 1 ml. E.N.E. of Umzimvubu bridge,  
Makoba's Location.
79. dolerite near W. margin of sheet, on Katfontein.
20. dolerite along road,  $\frac{1}{2}$  ml. W. of Umzimvubu bridge,  
Riversdale.
56. dolerite 200 ft. below granophyre band, kopje 2 mls.  
north of New Amalfi post office, Makoba's  
Location.
52. dolerite 100 ft. below granophyre band, same locality
18. dolerite immediately below granophyre band, along  
main road to Zwartberg.

Discussion.

The rocks described above show a gradual change towards an end-pole rich in soda and iron. This is evidenced by the change of the plagioclase from An. 69-31, the change of the olivine from Fa. 28-46, and again from Fa. 80-100, the change of orthopyroxene from Of. 26-79, and finally the change in the clinopyroxene from augite to ferroaugite, bordering on hedenbergite. In the beginning the processes were very gradual, but later on  
differentiation

differentiation appears to have proceeded at an accelerated pace. Thus the iron-rich dolerites really represent several phases of the differentiating magma; the first phase being completely out of equilibrium with subsequent phases. The preservation of remnants of earlier phases of crystallisation urges for the incompleteness of the equilibria, which the constantly changing restmagmas attempted to establish with the solid products of previous crystallisation. The pale coloured augite of 20 represents one such a remnant, opposed to the purple-brown ferroaugite separating later. Particularly during the later stages of differentiation, the processes involved become very complicated. The great weight carried by such later stages is emphasised here. The plagioclase laths of the iron-rich dolerites invariably show a thin outer margin of oligoclase, even where the central parts are as moderately zonal as in 20. The striation of the clinopyroxene, the late formation of ferriferous olivine and orthopyroxene, the substitution of biotite for hornblende, all indicate the increasingly more prominent part played by the later rest-magmas. Deuteric alteration, as testified by processes of albitisation, amphibolitisation and serpentinisation, likewise becomes more pronounced as higher levels in the sheet are reached.

On the whole it appears that, during the later stages of crystallisation, there was an upward migration of highly differentiated rest-magmas. In their ascent the fluids attacked the crystal framework through which they passed. Their transit is evidenced by the occurrence of minerals, rich in iron and soda, and of late formation, in the iron-rich dolerites of the sheet.

Specimen/....

Specimen 18 was here treated as a pure differentiation product, but it is probable that the rock is not solely the result of magmatic differentiation. It directly underlies the band of granophyric rocks, believed to originate in the metasomatic conversion of Burghersdorp sandstone. 18 Shows interstitially a great deal of quartz, and in addition irregular grains of oligoclase, which interlock with the quartz crystals. The oligoclase is non-zonal and twinning is absent. In appearance it resembles the feldspar, which occurs in some of the metamorphosed grits of the Molteno sediment. Thus the possibility, that 18 is contaminated by a certain amount of sedimentary material is not overlooked. Its genesis and chemistry are fully discussed at a later stage.

C. Dolerites of Side-Intrusions of the  
New Amalfi Sheet.

Field Occurrences.

Numerous transgressive sheets and dikes surround the main body of the New Amalfi sheet in all directions. In the South the outcrop on the farm Paradise forms a direct continuation of the sheet. Other intrusions, such as the Sydenham and Driefontein sheets in the West, and the Springfontein outcrop in the East, are inclined towards the New Amalfi sheet, and undoubtedly connected with it underground. In addition to the above, many smaller intrusions cluster around the northern extremity of the sheet. Amongst these the sill at Mooi Plaats and Hanover, and the thin sheets of Uitkyk are mentioned. Finally there occurs a strip of dolerite above the granophyre band in the sheet itself. This dolerite differs in its petrographical characters from the rocks of the main exposure and is thus dealt/.....

dealt with separately. It is noteworthy that the granophyre band dips at a low angle towards the North. Thus the overlying dolerite outcrops on a wider front when traced northwards.

#### Petrography.

The dolerites of the side-intrusions lend themselves to a division into two main groups; i.e. those in which olivine occurs as large crystals, and those in which olivine builds small individuals.

#### Dolerites with large olivines.

To this group belong the dolerites of the Paradise, Springfontein and Sydenham-Driefontein sheets. The rocks closely resemble the contact-dolerites of the New Amalfi sheet. Olivine is always altered, usually to bowlingite. Plagioclase (An.69) forms stout, zonal laths. Orthopyroxene is absent. The clinopyroxene consists of early pigeonite, augite ( $2V_{\gamma} : 46^{\circ}$ ), and late pigeonite. Interstitial mesostasis commonly replaces micropegmatite.

#### Dolerites with small olivines.

This group includes the numerous northern side-intrusions, as well as the dolerite overlying the granophyre band in the New Amalfi sheet. The rocks are all fine- to medium-grained, but may show great differences in texture and constituency. In the thicker bodies the texture is sub-ophitic, but thinner intrusions show ophitic textures, producing typical P.K. types (Walker and Poldervaart, 1941a, p. 137-140). The highest sheets contain no olivine and show interstitial micropegmatite. Lower intrusions show small, altered olivines and an  
interstitial/....

interstitial mesostasis. In the lowest sheets a few larger olivines are developed in addition to the small grains and thus the rocks may grade over in the first group.

Both the sill at Mooi Plaats-Hanover and the dolerite overlying the granophyre band of the New Amalfi sheet show the same mineralogical characters. Olivine occurs in minor quantities as small, altered grains. Plagioclase (An. 66) builds the usual zonal laths. Orthopyroxene is absent, but early - and late pigeonite occur instead. Augite ( $2V_{\gamma} : 46^{\circ}$ ;  $\delta : 1.713$ ) forms the bulk of the clinopyroxene, and occurs as ophitic or sub-ophitic plates. A dark mesostasis fills the interstices.

Micrometric Analyses.

Index No.	Ol.	Plag.	Pyx.	l.O	Biot. & Amph.	Mesost.
78.	1.7	46.3	38.9	2.3	1.9	8.9
46.	1.3	51.1	35.5	1.8	0.7	9.6

78. dolerite with large olivines, along road to Afzondering and Basutoland, Sydenham.
46. dolerite with small olivines, along Dike,  $\frac{1}{2}$  ml. S.E. of Taylorville.

Discussion.

There can be little doubt that the dolerites of the Springfontein, Paradise and Sydenham-Driefontein sheets are identical to the rocks occurring near the contacts of the New Amalfi intrusion. The inclination of the intrusions towards the main sheet, also shows their close alliance to this body.

The northern/....

The northern side-intrusions and the dolerite overlying the granophyre band show some differences, which are difficult to account for. The zone of granophyric rocks running along the western margin of the New Amalfi intrusion, is believed to represent a metasomatised block of Burghersdorp sandstone, stoped down from the upper contact of the sheet. The time of the stoping process, relative to the crystallisation history of the magma, is obviously of interest. It may account for the differences existing in the igneous rocks above and below the granophyric belt. Unfortunately the exact relationship is difficult to determine, but apparently the magma had already precipitated the bulk of its olivine when the stoping of the sediment was effected. Alternatively, earlier formed olivine was actively being resorbed, and nuclei of more fayalitic olivine were formed when the above process took place. The mineralogical resemblance of the other minerals, except for olivine, between the rocks above and below the granophyre belt is evident. Such differences in texture and grain-size as do exist are well accounted for by the relatively quicker cooling of the dolerite above the band of granophyric rocks.

The northern side-intrusions may be interpreted in the same manner. They cluster around the northern end of the granophyre band and may represent side-intrusions, effected during the stoping process. It is noted that they intruded around the northern, downward end of the stoped block. Finally, they show a grading of olivine-size with depth which also seems in accord with the views expressed above. It is equally possible that such intrusions are of a later period, derived from a different source. The author prefers to consider both possibilities as equally probable.

The Mooi Plaats-Hanover sheet raises another point of interest. du Toit, (1929, p.24) in discussing the relations of the dike and this sheet, remarks:- "Not many miles up the Big Umzimvubu, at Hanover, a slightly-inclined sill, when followed westwards, turns upwards, becomes vertical, and thus acquires the habit of a dike-". The rock of the sheet indeed continues a certain distance along the course of the dike, when it gives way to the typical olivine-dolerite of the dike. That the dolerite of the sheet represents a contact modification of the typical dike-rock is considered doubtful. The Mooi Plaats-Hanover sheet forms locally the highest exposures, and the olivine-dolerite of the dike outcrops at much lower level. Therefore it is preferred here to consider the sheet superimposed on the roofed dike; the magma of the former apparently followed the latter's course for some distance. Unfortunately exposures do not allow for a detailed study between the rocks of the sheet and the dike. At one place on the Hanover side, however, a thin strip of sandstone was found, dividing both intrusions. Evidently the dike had already established a solid zone along its roof, which allowed for the superposition of the later magma. Thus the dike is considered to continue uninterrupted from Taylorville to Hanover, underneath the sheet, and thence into the New Amalfi intrusion.

#### D. Chilled Basalts.

##### Field Occurrences.

Characteristically the chilled modifications may be divided into two main groups; i.e. those associated with the olivine-dolerite magma of the dike, the sheet and its allied side-intrusions, and those belonging to the

magma/....

magma responsible for the formation of the northern side-intrusions and the dolerite above the granophyre band. The second group may represent a different magma type altogether, but is more probably a later phase of activity of the same olivine-dolerite magma, after its partial crystallisation.

The olivine-basalts are found in the dike, as for instance along its southern contact at Calamity Hill. In the New Amalfi sheet they line the eastern contact. In addition they occur as the eastern margin of the granophyre band. Here, however, the chilled phase may be absent over long stretches, when the granophyre comes in direct contact with the underlying, coarse-grained, iron-rich dolerites. A few thin dikes within the granophyre band likewise contain basalts of this type. The dikes usually peter out as higher levels in the granophyre are reached, and their contents are invariably intensely altered.

#### Petrography.

##### Olivine Basalts.

The rocks contain phenocrysts of plagioclase, olivine in large crystals, and clinopyroxene. The groundmass consists of plagioclase, pyroxene and abundant iron-ore together with some small olivines. The groundmass is extremely fine-grained and its nature often obscured by the abundant iron ore granules.

Optical data/...

Optical data.

Phenocrysts				(volume).
Plagioclase.	av. $\beta$ .	av. Composition		9.2
	1.572	An. 72		
Olivine.	$2V_{\alpha}$	$\gamma$	Composition.	3.1
	89°	1.699	Fa. 15	
Pyroxene.	$2V_{\delta}$	$\delta:c$	$\delta$	1.0
	51°	44°	1.704	

Later Basalts.

The porphyritic content consists mainly of plagioclase (An. 69) and a few, small olivines, usually altered to a serpentine. The groundmass closely resembles the coarser grained rocks, and consists essentially of plagioclase, pyroxene, mesostasis and iron ore.

Discussion.

It has been pointed out that the picrites, olivine-dolerites, and iron-rich dolerites are considered as having been derived from the same olivine-dolerite magma. The olivine-basalts are regarded as the chilled phases from this magma, formed by sudden cooling against the country rocks, immediately after injection. The evidence of the variolitic picrites of Mount Fred indicates that the magma, after emplacement, commenced crystallisation with the precipitation of olivine of composition Fa. 15. On the other hand, the chilled phases contain phenocrysts of plagioclase and clinopyroxene, in addition to olivine. This indicates that the magma, in the intratelluric stage, was precipitating plagioclase

(An.72)/...

(An.72), olivine (Fa.15), and clinopyroxene ( $2V_y:51^\circ$ ).

Noteworthy is the fact that the plagioclase is more basic than any recorded in the coarse-grained rocks, whereas the pyroxene also shows optical properties unlike any recorded in such rocks. The writer is of the opinion that intratelluric crystallisation should be sharply separated from crystallisation after emplacement. Indeed there is evidence to assume that intratelluric crystallisation may be reversed after emplacement and that previously formed crystals may be absorbed by the magma before it commences crystallisation under the new conditions of temperature and pressure. In the basaltic lavas it is common to find that the porphyritic pyroxene differs from the groundmass mineral. Generally the former is diopsidic in composition, whereas the latter consists of pigeonite with augite or ferroaugite. Thus the porphyritic contents of the olivine-basalts are not believed to disprove the contention that the same magma, after emplacement, commenced crystallisation with the precipitation of olivine only.

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## V. CHEMISTRY.

### Chemical Analyses.

Seven representative specimens were selected from the collection, and chemically analysed by Mr. F. Herdsman. The results are set out here in tabular form, together with the norms and the modes, calculated from the micrometric data. Apart from the most basic rocks, there exists a fair agreement between the normative and modal compositions of the various specimens.

It is noted that the analyses of Herdsman did not return  $\text{Cr}_2\text{O}_3$ , although qualitative analysis by the author proved the presence of chromium in both analysed picrites.

### Magmatic Variation.

Deer and Wager pointed out that variations of basaltic magmas may be graphically represented by plotting the oxides either against the ratio  $\frac{\text{FeO} + \text{Fe}_2\text{O}_3}{\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3} \times 100$ , or against normative plagioclase, (1939b, p.500). Both methods are suitable for the basic and intermediate rocks of a series, though their uses for the more acid differentiates are naturally restricted. The first method has been adopted here, and the result is shown in diagram 4.

It is clear that the trend of differentiation, as shown by the diagram, agrees closely with the expectations.

Crystallisation started with the precipitation of a little chromiferous magnetite and magnesian olivine, the latter separating in excess of the stoichiometric proportion. This stage in the crystallisation process corresponds with a sharp decline in the curve for  $\text{MgO}$ ,

and

DIAGRAM 4.

Variation of the Rocks derived from  
the Olivine-dolerite Magma.

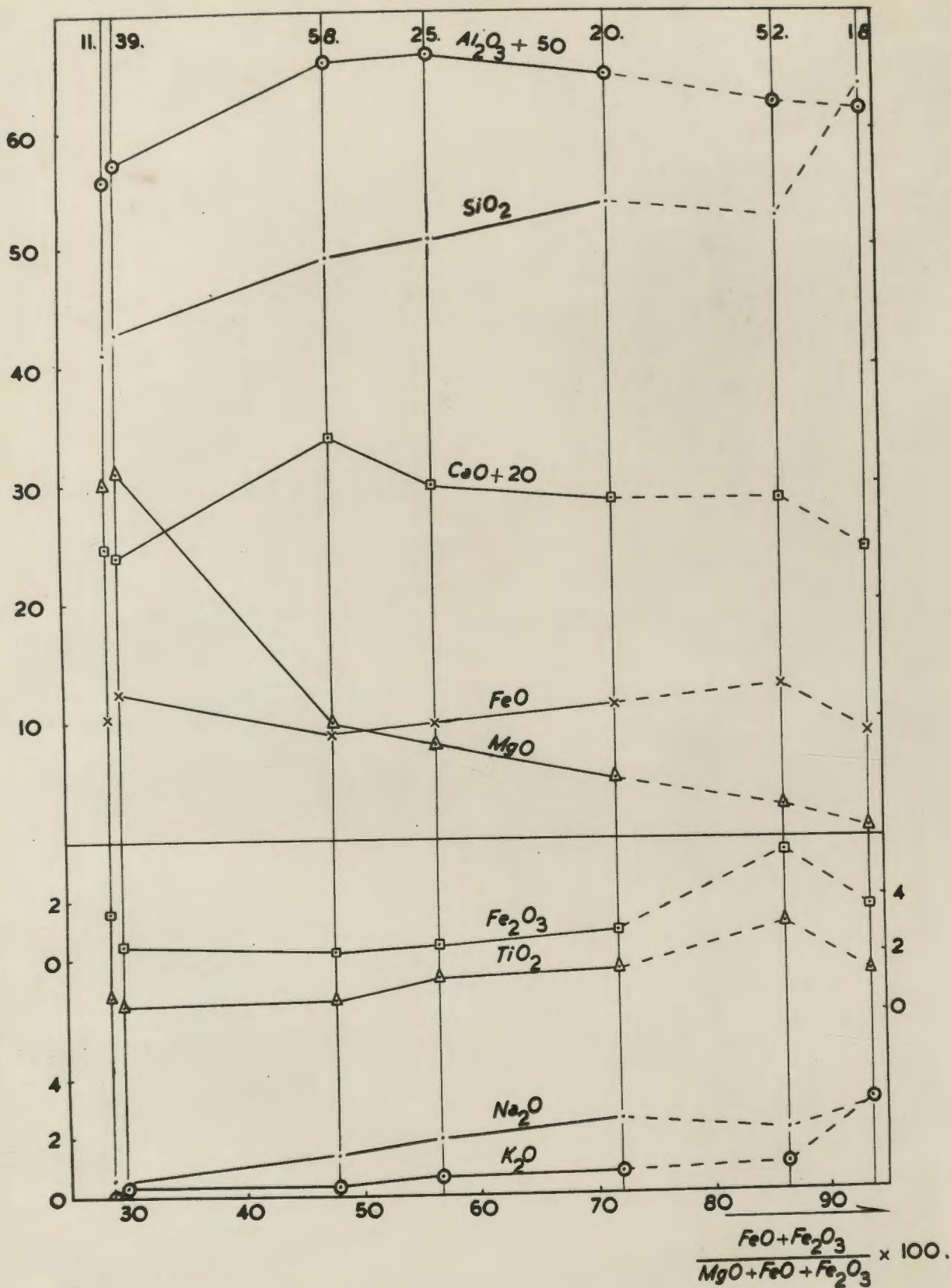


DIAGRAM 4.

Variation of the rocks derived from the Olivine-dolerite Magma.

and a more gentle decline in the curves for FeO and Fe<sub>2</sub>O<sub>3</sub>; whereas there is a complementary increase in the proportions of all the other oxides. The increase continues until basic plagioclase crystallised; probably in considerable quantities. Olivine still crystallised, though in much smaller amounts, and as more fayalitic individuals. Consequently there is a sharp decline in the CaO curve and a more gentle decrease in the curve for MgO. All the other oxides show an increase in their proportions, though this has been adjusted and is more gentle than in the first instance. The curve for FeO also shows an incline, instead of a decline, as olivine has ceased to separate in excess of the stoichiometric proportion and, in the solid solution series of the olivines, Mg<sub>2</sub>SiO<sub>4</sub> separates in advance of Fe<sub>2</sub>SiO<sub>4</sub>.

During the next stage, plagioclase and pyroxene crystallise together, whereas olivine ceases to separate. Plagioclase becomes continuously poorer in anorthite and richer in albite during its crystallisation. The ultimate result of the crystallisation of the pyroxenes is a continuous decrease in MgSiO<sub>3</sub> and a corresponding increase in FeSiO<sub>3</sub>. Thus CaO, MgO and Al<sub>2</sub>O<sub>3</sub> show a decline, while all other oxides increase in proportion.

The closing stages of the differentiation process are more complex. The two analyses 52 and 18, show certain discrepancies which render them useless for purposes of quantitative interpretations. Both specimens occur immediately below the band of granophyric rocks, believed to originate in the metasomatic conversion of Burghersdorp sandstone. The process of metasomatism involved the migration of certain oxides across the contact. Thus the igneous rocks below the granophyric zone both lost and gained in certain constituents. In the case of

52 it is not thought that the gains were substantial. It is, however, obvious that the magma-fraction, represented by 52, lost both in  $\text{Na}_2\text{O}$  and  $\text{SiO}_2$ . In addition, it may have lost other constituents, though this is not demonstrated by the analysis. The mineralogy of the rock shows it to be a continuation of the crystallisation trend of the olivine-dolerite series. In it occur more albite-rich plagioclase, more fayalitic olivine and pyroxene richer in  $\text{FeSiO}_3$ . Therefore it is expected that the magmatic variation is continued in 52 along the same lines as in the previous rocks. Hence we expect a continued decline in the curves for  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$  and  $\text{MgO}$ , with a corresponding incline in the curves for  $\text{SiO}_2$ ,  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ . Comparison with other igneous bodies showing a similar variation, and also theoretical considerations, shows that the expected result would be a particularly pronounced increase in the proportions of  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$  and  $\text{TiO}_2$ , whereas  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  should probably also show a somewhat sharper increase than before.

With the two exceptions noted, the analysis of 52 answers to the above expectations. At the same time it is clear that any loss in  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$  or  $\text{TiO}_2$  would not be immediately shown by either the analysis or the variation diagram. Losses in such constituents would merely tend to decrease the pronounced inclinations expected, and only very large losses would be demonstrated by the resulting rock.

Much the same considerations, even more emphasised, may be applied to 18. If 18 represents yet a further step in the crystallisation history of the magma, we would expect to find primarily in this rock, acid plagioclase, fayalite, a pyroxene close to hedenbergite, and both magnetite and ilmenite. All these are indeed  
found/...

DIAGRAM 5.

Iron-enrichment in Dolerite Intrusions.

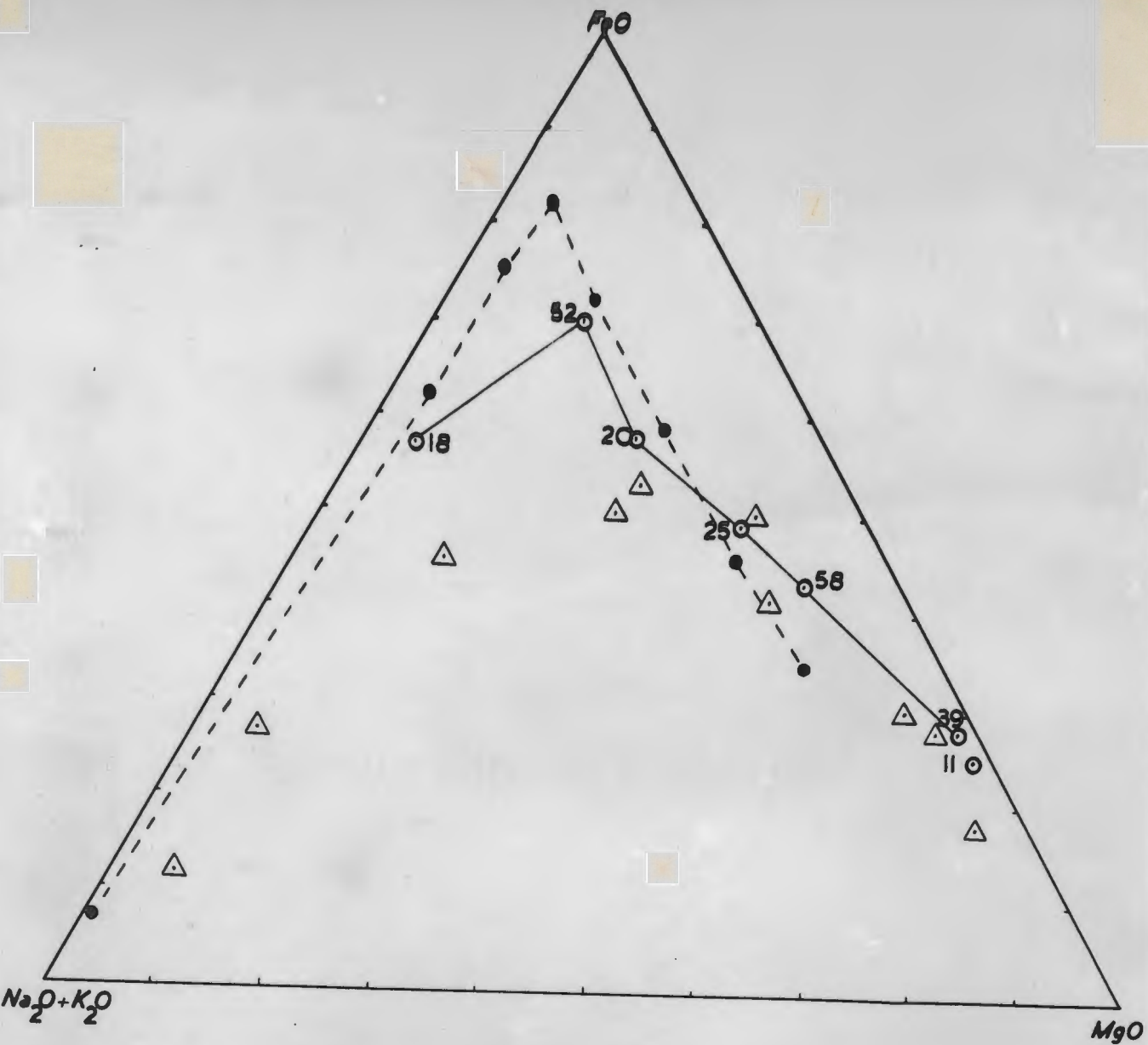


DIAGRAM 5.

*The Skaergaard Intrusion and the Insizwa Lopolith compared  
with*

*the Olivine-dolerite series of Elephant's Head and New Amalti.*

○ — ○ — ○ *Olivine-dolerite series of Elephant's Head and New Amalti.*

● - - ● - - ● *Skaergaard Liquids.*

△ *Rocks from the Insizwa Lopolith.*

DIAGRAM 6.

Iron-enrichment in the Karroo Dolerites.

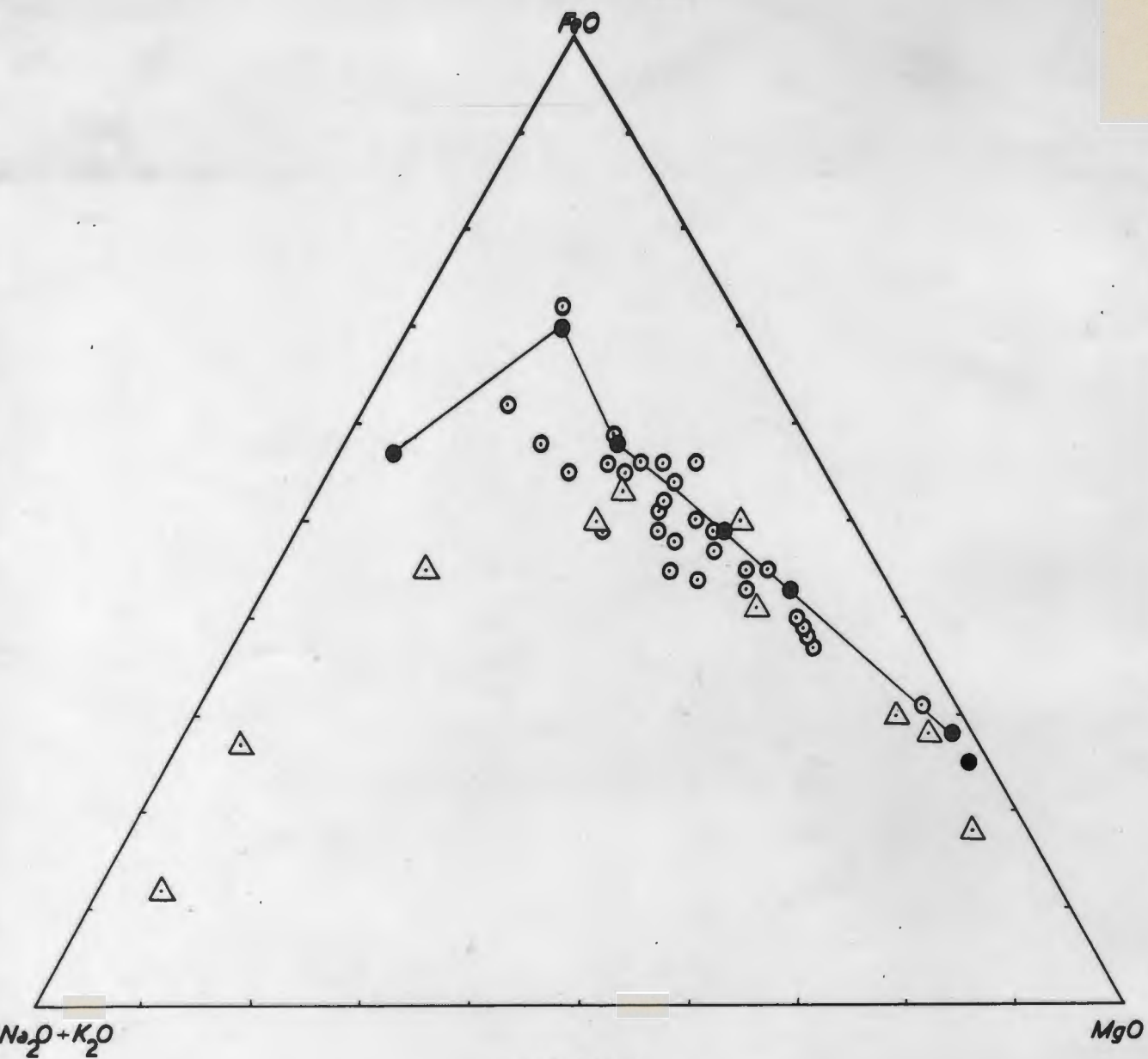


DIAGRAM 6.

*The Olivine-dolerite series of Elephant's Head and New Amalji compared with  
all other analyses of Karroo Dolerites .*

- *The Olivine-dolerite series .*
- △ *Analyses of Insizwa rocks .*
- *Other Karroo analyses .*

the two principal solid solution series, plagioclase feldspars and iron-bearing metasilicates (e.g. pyroxenes)" (Fenner, 1931, p. 549), was first "won" by the pyroxenes, but ultimately by the plagioclases. It is evident that the crystallisation period of the feldspars is much longer than that of the pyroxenes. The ultimate result is therefore by no means surprising.

In diagram 5 the trend of differentiation is further illustrated by plotting the analyses in a triangular diagram. The three corners are respectively MgO, the significant constituent of the more refractory minerals; FeO, the significant constituent of the medium refractory minerals; and (Na<sub>2</sub>O+K<sub>2</sub>O), the significant constituents of the less refractory minerals. In the diagram the trend of differentiation of the Elephant's Head and New Amalfi intrusion is compared with that of the Skaergaard intrusion (Deer and Wager, 1939b, p.314-315), and that of the Insizwa Lopolith (Scholtz, 1936, p. 117 & 143). Of these three, the Skaergaard intrusion shows the strongest crystal fractionation. The Insizwa lopolith only shows medium fractionation, as it was formed by a succession of several intrusions at short intervals (Scholtz, 1936, p. 203). The diagram shows clearly that the iron-enrichment of the middle stages of crystallisation depends primarily on the degree of fractionation of the magma. Moreover, in all three cases the final phase of differentiation proceeds towards the development of rock-types rich in SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, and K<sub>2</sub>O.

In diagram 6 all the available Karroo dolerite analyses were plotted on the same basis. As shown by the diagram, iron-enrichment appears to be inherent in the crystallisation of the Karroo magma.

The original/....

The Original Olivine-Dolerite Magma.

As the chilled contact phase was not chemically analysed, attempts were made to arrive at some idea as to the composition of the original olivine-dolerite magma. The analysis of the variolitic picrite was recalculated for this purpose, as waterfree and adjusting  $Fe_2O_3$  to 0.5%. Next 60% olivine Fa 20 was subtracted from the recalculated analysis and the result again recalculated to 100%. As a comparison, the procedure was repeated with the subtraction of 60% olivine Fa. 22. The results are tabulated here. For comparative purposes the average of Frankel's four analyses of younger Karroo intrusions, recalculated as waterfree and minus  $Cr_2O_3$  (Frankel, 1942, p. 18), is also included in the table. Finally, the composition of a magma with 48.0%  $SiO_2$  was deduced from the variation diagram, and is given here.

	11a.	A.	B.	C.	D.
$SiO_2$	43.3	48.5	48.0	49.1	48.0
$Al_2O_3$	6.1	15.2	15.2	13.6	14.6
$Fe_2O_3$	0.5	1.2	1.2	1.1	0.5
$FeO$	12.0	6.8	9.0	9.6	9.5
$MgO$	31.6	12.0	10.3	13.0	12.5
$CaO$	4.8	12.0	12.0	9.8	12.3
$Na_2O$	0.6	1.5	1.5	2.0	1.2
$K_2O$	0.1	0.2	0.2	0.5	0.4
$TiO_2$	0.8	2.0	2.0	0.9	0.6
$P_2O_5$	trace	-	-	0.2	0.2
$MnO$	0.2	0.6	0.6	0.2	0.2
Total	100.0	100.0	100.0	100.0	100.0

- 11a. The analysis of the variolitic picrite (11) recalculated as waterfree to 100%, adjusting  $Fe_2O_3$  to 0.5%.
- A. The result of subtracting 60% olivine Fa.22 from 11a. and recalculating to 100%.
- B. The result of subtracting 60% olivine Fa. 20 from 11a. and recalculating to 100%.
- C. The average of Frankel's four analyses of younger Karroo intrusions, recalculated waterfree and minus  $Cr_2O_3$  to 100%.
- D. The composition of a magma with 48.0%  $SiO_2$  as deduced from the variation diagram.

Generally speaking there is a fair agreement between the compositions of B, C and D. The calculated compositions A. and B. are relatively poorer in FeO than either C. or D. In this respect the author definitely favours the values for MgO and FeO, as given under D.

The most significant differences between B., C. and D. are in the proportions of CaO, Al<sub>2</sub>O<sub>3</sub> and Na<sub>2</sub>O. Both Al<sub>2</sub>O<sub>3</sub> and CaO are higher in B. and D., while Na<sub>2</sub>O is lower. Evidently the original magma at Elephant's Head was richer in basic plagioclase than the magma of Frankel's "Younger Karroo Intrusions". In accordance with this view are the facts that; (1) the author found 9% plagioclase as phenocrysts in the chilled phase, whereas Frankel records that "small, isolated feldspar laths are not common" in the glassy margins of his intrusions, and (2) the author's micrometric data for plagioclase in the normal olivine-dolerites of Elephant's Head range from 50-58%. whereas Frankel's data vary between 29-38%.

Thus, as a rough approximation, the composition given under D. appears to correspond best with the expected composition of the original olivine-dolerite magma.

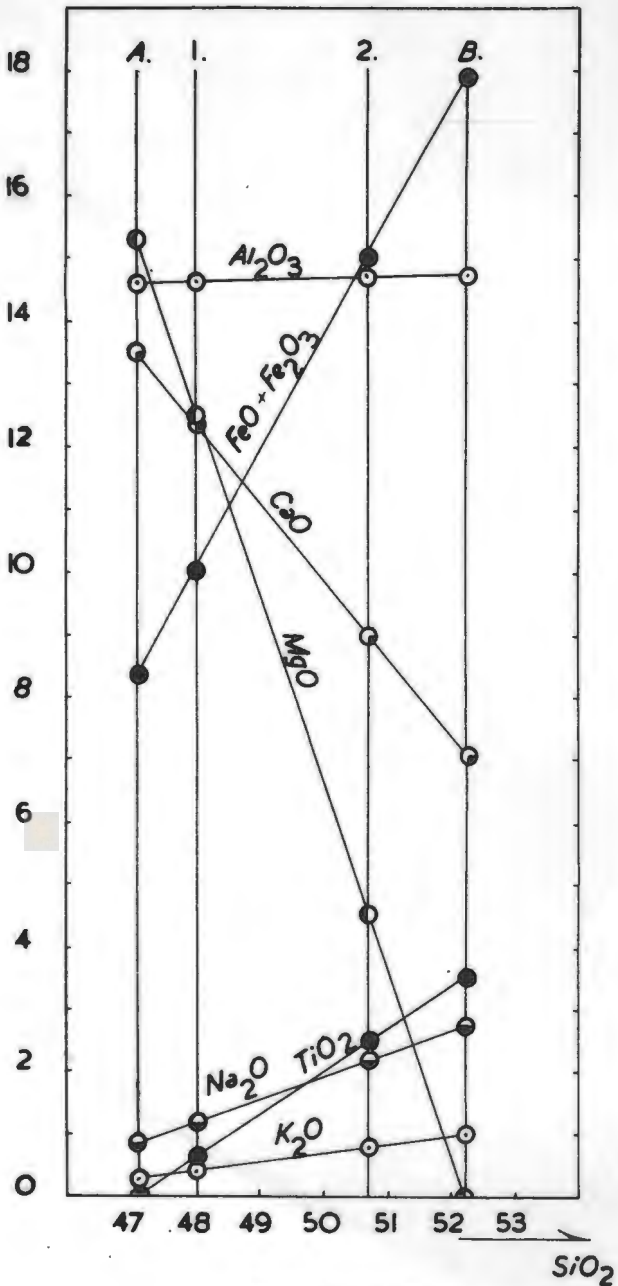
#### The Tholeiitic Magma.

In diagram 7 the tholeiitic magma is compared with the original olivine-dolerite magma, as calculated above. The results of this comparison are tabulated here.

1. 2. /....

DIAGRAM 7.

The Tholeiite Compared with  
the Original Olivine-dolerite Magma.



**DIAGRAM 7.**

*Addition and subtraction diagram of the original Olivine-dolerite magma (1) and the Elephant's Head Tholeiite (2).*

	1.	2.	B.	A.	Norm of A.	
SiO <sub>2</sub>	48.0	50.7	52.3	47.2	Qu.	-
Al <sub>2</sub> O <sub>3</sub>	14.6	14.7	14.9	14.6	Or.	1.7
Fe <sub>2</sub> O <sub>3</sub>	0.5	3.8	18.2	8.4	Ab.	6.8
FeO	9.5	11.2			An.	35.3
MgO	12.5	4.6	-	15.2	(Wo.	13.3
CaO	12.3	9.0	7.0	13.5	Di.(En.	8.8
Na <sub>2</sub> O	1.2	2.2	2.8	0.8	(Fs.	3.6
K <sub>2</sub> O	0.4	0.8	1.1	0.3	(En.	2.4
TiO <sub>2</sub>	0.6	2.5	3.7	-	Hy.(Fs.	1.1
P <sub>2</sub> O <sub>5</sub>	0.2	0.3	-	-	Ol.(Fo.	18.7
MnO	0.2	0.2	-	-	(Fa.	8.3
Total	100.0	100.0	100.0	100.0		100.0

1. Composition of the original olivine-dolerite magma, as deduced above.
2. The tholeiite of Elephant's Head type, recalculated as waterfree.
- B. Composition of the material to be added to the olivine-dolerite magma to obtain the tholeiitic magma.
- A. Composition of the material to be subtracted from the olivine-dolerite magma to obtain the tholeiitic magma.

An inspection of the table shows that the composition of B.-the material to be added to 1. to obtain 2.- is in many ways remarkable. On the other hand, it is obvious that the composition of A. - the material subtracted from 1. to form 2. - is more reasonable. The norm of this result has been calculated on the assumption that all iron is present as FeO. There is little justification for this assumption, but Fe<sub>2</sub>O<sub>3</sub> is difficult to assess with any accuracy, and thus calculation as "all FeO" simplifies the procedure. The norm shows that A. corresponds to a rock, mainly composed of basic plagioclase, diopsidic pyroxene and magnesian olivine. Similar diagrams were used to compare the tholeiite with the original magma, calculated from the variolitic picrite, and the average of Frankel's four analyses. In all these cases it was found that the material to be subtracted has a composition corresponding to mixtures of olivine, plagioclase/...

plagioclase and pyroxene, whereas the composition of the material to be added is rather unreasonable.

It has been stated previously that the porphyritic elements of the chilled basalt consist of basic plagioclase, magnesian olivine and diopsidic pyroxene. These minerals are again recorded as forming the constituents to be subtracted from the original magma to form the tholeiitic magma. Thus there seems to be some justification for the assumption, that the tholeiite was derived from the olivine-dolerite magma by the separation of crystals of olivine, plagioclase and pyroxene (together probably with a little picotite) in depth.

Views on the Course of Crystallisation  
of Basalt Magma.

Bowen (1928) has repeatedly stressed his views on the course of fractional crystallisation of basalt magma, basing his ideas on a great number of chemical investigations of silicate systems. Bowen's ideas are here summarised as:-

- (i) Quick cooling of basalt magma will produce a dolerite.
- (ii) Medium fractionation of basalt magma results in a dioritic residual liquid.
- (iii) Strong fractionation of basalt magma produces a residual liquid, approaching the composition of biotite-granite.

On the other hand, Fenner argued that strong fractionation of basalt magma will tend towards iron-enrichment, and thus the final residuum will be neither dioritic nor granitic in composition. The works of Bowen and Fenner are too well-known to need further quotation here. The two opposing schools of thought,

as represented by the writings of Bowen and Fenner, have strongly influenced petrological ideas regarding the course of fractional crystallisation of basalt magma. Of late more and more evidence has been forwarded, indicating a pronounced iron-enrichment in the crystallisation sequence of basalt magma. Deer and Wager (1939b) reviewed such evidence in their brilliant study of the Skaergaard Intrusion of eastern Greenland, and repetition is not thought necessary here. In addition Deer and Wager demonstrated that:-

- (a) The Skaergaard magma is, slightly modified, representative of the world's average basaltic magma.
- (b) the Skaergaard magma underwent strong fractionation.
- (c) the course of crystallisation of the Skaergaard magma was first towards the production of a phase rich in iron, and finally towards a residuum, rich in soda and silica.
- (d) the final residuum is essentially the granitic residual liquid advocated by Bowen.

Deer and Wager also compared the Skaergaard crystallisation trend with that of a great many other intrusions. In all these cases a close similarity was noted. The present study is also in direct support of the views expressed by these two authors.

Thus both Bowen's and Fenner's ideas prove correct, in that fractional crystallisation of basalt magma does yield a final granitic residuum, though this is arrived at via an intermediate phase, rich in iron. Actually most dolerite intrusions show clearest the first phase of crystallisation, towards an iron-rich residuum.

The final/.....

The final granitic phase is contained interstitially within the rocks, or represented by a few narrow, felsitic veins. The Palisade intrusion is a case in point (Walker, 1940). It cannot be surprising that the bulk of the granitic phase is so small. It represents the final residual liquid and Deer and Wager (1939b, p. 308) give the volume as only 1-2% of the total. In addition, it has already been stated that much of the residuum may be entrapped interstitially within the crystal framework.

Many problems are attached to the crystallisation of basalt magma. Daly's average calc-alkaline series - basalt, andesite, dacite and rhyolite - is sometimes considered a perfect example of Bowen's contentions. The series shows no trace of iron-enrichment. Deer and Wager do not exclude the possibility that the calc-alkaline series may be the result of a special type of crystal fractionation, but they consider it likely that "the series is essentially the result of hybridisation between - granite and basalt".

Many intrusions develop pegmatitic facies as the iron-rich phase is approached. Here again the Palisade sill is mentioned as a typical example. The development of dolerite-pegmatites proceeds under special conditions, as was shown so clearly by Tomkeieff (1929). The course of crystallisation is altered and the composition of the crystallising constituents deviates from the compositional trends of the minerals in the normal-grained rocks. Chemically the dolerite-pegmatites are well-known to be out of alignment in the normal differentiation diagrams. Generally speaking, the effect of the development of pegmatitic facies is to ease down the tendency for iron-enrichment, and to prevent the formation of extreme types. The excess iron is concentrated within  
the/....

the pegmatitic segregations and hence the magma proceeds crystallisation in the sodic direction.

The author corroborates Deer and Wager's views as to the course of crystallisation in basalt magma. At the same time he considers Bowen's views of the utmost importance, noting, however, that such views are based on studies of dry silicate systems in the laboratory. It is suggested that the primary enrichment in iron, recorded in the crystallisation of basalt magma, is intimately associated with a concentration in volatiles. This volatile-concentration further promotes the iron-enrichment. Finally pegmatitic segregations may be formed, containing the excess iron and volatile matter of the crystallising magma. In certain rare cases pegmatitic schlieren are not formed, when fractional crystallisation continues in the direction of iron-enrichment and extreme rock types are produced. In both instances the final trend of crystallisation is towards soda-enrichment, as the separation of excess iron is not accompanied by that of excess soda.

The formation of pegmatitic facies appears to be more usual than the production of such extreme iron-rich types as recorded by Deer and Wager and the present author. The conditions promoting the development of the one phase over the other are, however, still unknown, and speculation in this field is thus not justified.

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VI. PETROLOGY.

Compositional Trends in the Rock-forming Minerals.

The ranges in composition of the minerals, described in the rock-series of Elephant's Head and New Amalfi, yield some interesting facts.

The plagioclases show little change in composition in the more basic rocks, varying from An. 70 in the picrites, to An. 66 in the olivine-dolerites. In the narrow zone of the iron-rich dolerites, however, there is a rapid increase in the albite content of the series. The nearest olivine-dolerite contains plagioclase An. 66, which, in the overlying zone, becomes progressively richer in albite, to reach An. 31 in specimen 18.

The compositional trend of the olivines is even more marked. In the more basic rocks there is a progressive change, from Fa. 15 in the variolitic picrites, to Fa. 46 in the olivine-dolerite underlying the differentiated zone. It is remarkable that the olivine crystals are non-zonal. Rather, different rocks are marked by olivines of slightly different compositions. In the variolitic picrites a range Fa. 15-17 was recorded; in the normal picrites Fa. 17-23, and in the olivine-dolerites ranges varying within the limits of Fa. 28-46. The absence of zoning seems to suggest that olivine crystals react more readily with the magma than, for instance, crystals of plagioclase or clinopyroxene. The preservation of crystals, richer in  $Mg_2SiO_4$ , is apparently due to the withdrawal of such crystals from further interaction with the magma. This is achieved by; (1) rapid cooling, (2) sinking of crystals to lower levels in the magma chamber, and (3) the development of thin films on the surface/.....

surface of crystals, protecting the cores from further attack by the magma. The magmatic attack seems to have been active in two successive stages; first to produce olivine richer in fayalite, and second to produce the saturated metasilicate, orthopyroxene.

In the lowest rocks of the iron-rich dolerites olivine is absent. Higher up, however, the mineral reappears as Fa. 80, and continues to crystallise until crystals consist of pure fayalite. These observations are in strict analogy to the theoretical deductions of Bowen and Schairer (1935), who investigated the system  $MgO-FeO-SiO_2$ . Under conditions of strong fractionation the system first precipitates olivine of changing composition. Next the liquids pass into the pyroxene field, and pyroxene alone is precipitated. Finally, there is a return to the boundary line between the two fields, when olivine and pyroxene crystallise simultaneously. In the latter case olivine is more iron-rich than before its disappearance.

The relations of the orthopyroxenes are slightly more complicated. The compositional trend shows a progressive enrichment in  $FeSiO_3$ , from Of. 15 in the picrites, to Of. 79 in the highest iron-rich dolerite containing orthopyroxene. The exact status of the mineral is, however, obscured by the fact, that it bears a reaction-relation to olivine and pigeonite. In addition its crystallisation overlaps that of the clinopyroxenes. In the picrites, orthopyroxene (Of. 15-18) is of earlier formation than clinopyroxene. The orthopyroxene of the olivine-dolerites (Of. 25-42) is essentially contemporaneous with clinopyroxene. In the iron-rich dolerites, orthopyroxene (Of. 50-80) crystallised after clinopyroxene.

It is/....

It is significant that orthopyroxene follows the trend of the olivine, both in composition and crystallisation period. The magnesian and medium olivines crystallised prior to bronzite and hypersthene. The more fayalitic olivines are contemporaneous with the ferro-hypersthene. In concordance with the theoretical expectations, pure ortho-ferrosilite did not crystallise, but quartz and fayalite formed instead. The crystallisation of orthopyroxene is thus considered here in relation to olivine and pigeonite, and separated from the crystallisation of the clinopyroxenes.

A noteworthy phenomenon of the orthopyroxene series is the occurrence of a "graphic intergrowth" on a minute scale in crystals of a certain range of composition (Of. 20-35). Similar observations were made by many authors, and there is a close agreement in the statements regarding the range of composition, within which the intergrowth is observed (Walker 1940, p.1073); Hess and Phillips, 1940, p.282-284; Walker and Poldervaart, 1941b, p.435). No such agreement exists in the views expressed as to the nature and orientation(s) of the intergrowth. Its extremely fine grain renders accurate determinations of optical constants frequently impossible. The present author could only make rough determinations of  $\gamma$  in these orthopyroxenes, whereas it proved impossible to obtain uniform extinction in any position on the Universal Stage.

The relations of orthopyroxene (with intergrowth) and pigeonite are worthy of comment. The following observations were made in the New Amalfi sheet:-

- (1) Normal dolerite. Contains orthopyroxene<sup>t</sup> (Of. 20-35), both earlier and later than clinopyroxene; the bulk being later. The orthopyroxene shows the graphic intergrowth. Pigeonite is absent.
- (11) Dolerite near contacts. Contains no orthopyroxene, but early pigeonite ( $\delta$  : 1.703) and late pigeonite ( $\delta$  : 1.734). Both have the optic axial plane  $\perp$  (010). They occur respectively as columnar cores and ophitic margins to crystals of clinopyroxene. Late pigeonite predominates over early.
- (111) Dolerite centre of sheet. Contains rare columnar cores of early pigeonite ( $\delta$  : 1.700), surrounded by margins of orthopyroxene (Of. 20-25), showing the intergrowth.

During a general survey of the Karroo dolerites the author collected numerous data on the pyroxenes occurring in these rocks. It is intended to publish the results of these studies shortly in a separate paper on pyroxenes. For the present study the relations between early pigeonite and orthopyroxene appear to have been established. The conclusions are mostly in agreement with the views expressed by Hess (1941, p.580-581). It appears that:-

- (a) Pigeonite with the optic axial plane  $\perp$  (010) and orthopyroxene showing a graphic intergrowth (Of. 20-25) bear a complementary relationship to one another.
- (b) Early pigeonite crystallised under high temperature conditions, in advance of orthopyroxene.

(c)/.....



DIAGRAM 8.

Course of Crystallisation of the

Clinopyroxenes.

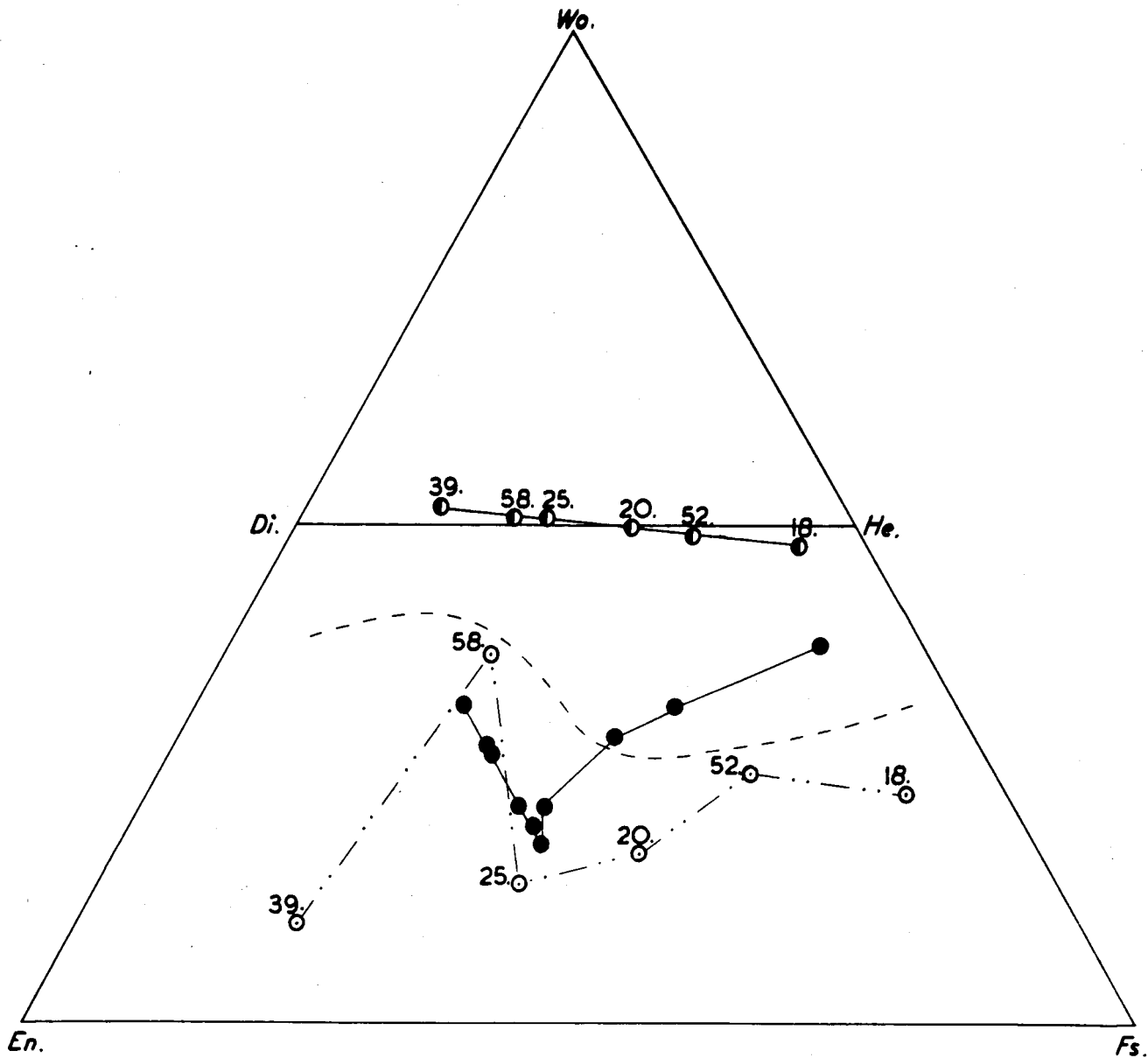


DIAGRAM 8.

*Course of Crystallisation of the Clinopyroxenes.*

- *Optically determined clinopyroxenes.*
- *Hess' Pyroxene Course of Crystallisation.*
- *Normative Pyroxene.*
- *Normative "Diopside".*

here tabulated, together with the inferred compositions.

No.	$2V_{\gamma}$	$\delta:c$	$\gamma$	Wo.	En.	Fs.
1.	49°	38°	1.713	32	44	24
2.	46°	38°	1.716	28	44	28
3.	44°	36°	1.718	27	44	29
4.	40°	44°	1.721	22	44	34
5.	34°	35°	1.723	20	44	36
6.	31°	33°	1.725	18	44	38
7.	41°	45°	1.725	22	42	36
8.	50°	45°	1.734	29	32	39
9.	52°	43°	1.740	32	25	43
10.	56°	45°	1.758	38	9	53

The compositions are plotted on a triangular Wo-En-Fs diagram, together with the "pyroxene course of crystallisation of normal mafic magmas" of Hess (1941, p.585)(diagram 8). Significant is the deep depression in the crystallisation trend, illustrating the tendency for the development of pigeonitic types. Indeed, the author does not exclude the formation of true pigeonites ( $2V < 30^{\circ}$ ) during this stage, though stipulating that such pigeonites would have the optic axial plane parallel to (010). Thus a sharp, genetic division is drawn between pigeonites with the optic plane  $\perp$  (010), bearing a reaction-relationship to olivine and orthopyroxene, and pigeonite with the plane  $\parallel$  (010), concordant with the clinopyroxene course of crystallisation. In the latter case a continuous decrease in the optic axial angle from core to margin is implied, whereas no such continuity exists in the former.

The deep depression in the clinopyroxene trend

of/.....

crystallisation is fully confirmed by the author's observations on a great many Karroodolerites. In fact, the first part of the trend is typical for the clinopyroxene sequence of the bulk of the normal Karroo dolerites. Hess' trend of crystallisation shows a similar depression, though by no means as deep as is recorded by the author. It seems therefore, a characteristic feature of the clinopyroxene course of crystallisation, that:-

- (1) The first and last part runs parallel to the En-Fs line of the diagram.
- (2) The centre part is parallel to the Wo-Fs line of the diagram.
- (3) The length of the central part may differ greatly in different rocks of very similar chemical composition.

It is not within the scope of this study to enter into an explanation of the above observations. Record must, however, be made of the fact that the break in the clinopyroxene crystallisation coincides with the cessation of early crystallising olivine. Pigeonite, likewise ceases to crystallise at this point in the crystallisation sequence of the magma.

A noteworthy feature of the Karroo augites is their conspicuously low extinction angle. The observed values are consistently lower than the diagrammatic data given by Deer and Wager (1938, p.21). More diopsidic pyroxenes, as well as the ferroaugites, show a better agreement. It is thought that the abnormally low values for the extinction angle are due to the presence of other oxides, contained as impurities in the crystal. No information is given as to the nature of such impurities, or their control on the optical data.

The data/....

The data for the four chief groups of rock-forming minerals show a progressive enrichment in soda in the plagioclase series, whereas an equally progressive enrichment in ferrous iron is indicated in the groups of the olivines, orthopyroxenes and clinopyroxenes. The latter trend appears to be even more marked than the soda-enrichment.

Among the accessory minerals, iron ore is the only constituent meriting further comment. Rough qualitative tests on the ore of the rock-series indicate a progressive enrichment in  $TiO_2$ , which reaches a maximum just below the top of the iron-rich zone. Yet higher up in the series a rapid fall in the  $TiO_2$  content of the ore is indicated. A small amount of chromiferous magnetite crystallised at an early stage, prior even to olivine. It appears, therefore, that the magma precipitated  $Cr_2O_3$  at a very early stage in its crystallisation, whereas  $TiO_2$  was concentrated in the later rest-magmas.

#### Course of Crystallisation.

The crystallisation of the first tholeiite magma is very simple and easily traced. The chilled modifications contain phenocrysts of olivine, plagioclase and clinopyroxene, with plagioclase as the dominant constituent. After emplacement, crystallisation started with plagioclase and a small amount of olivine. This phase was followed by the simultaneous precipitation of plagioclase and clinopyroxene. Next iron ore separated, followed closely by the consolidation of the interstitial mesostasis. The serpentinisation of the olivine and the amphibolitisation of the mesostasis probably belong to

the/.....

the closing stages of magmatic activity. Crystallisation was slow and there was ample opportunity for interaction between the solid and liquid phases. Hence zoning is slight in both the plagioclase and the pyroxene crystals.

The olivine-dolerite magma precipitated olivine, plagioclase and clinopyroxene under plutonic conditions. After hypabyssal injection, however, the early stages of crystallisation were marked by the separation of chromiferous magnetite and magnesian olivine. During the middle stages plagioclase, orthopyroxene (or pigeonite), and clinopyroxene successively joined and followed the crystallisation of olivine. The latter ceased crystallisation as Fa. 46, just before the precipitation of orthopyroxene. Next iron ore and ferriferous orthopyroxene were precipitated and, after a pause, fayalitic olivine joined the crystallisation of these two minerals. Finally, orthopyroxene ceased crystallisation and quartz and fayalite separated together. To the end-chapters of this third stage in the crystallisation sequence belongs the separation of biotite, hornblende, zircon, apatite and the interstitial micropegmatitic intergrowth of quartz and anorthoclase. During the deuteric stage, processes of amphibolitisation and albitisation left their mark, whereas pectolite and some of the brown serpentine of specimen 18 also formed during this period. Finally the hydrothermal stage bears responsibility for much of the serpentinitisation and kaolinisation observed in the higher differentiated rocks.

Mechanism/.....

Mechanism of Differentiation.

A comparison of the igneous rocks of the dike and the sheet results in the observation that the former contains basic and medium differentiates, whereas the sheet contains medium and "acid" rocks. Hence it seems highly probable that the dike acted as the primary feeder of the sheet. A study of the dike disclosed the presence of picrites near or at the bottom of major undulations in that intrusion. Reasons have already been given why the picrites are considered to have been formed by gravitational accumulation of olivine in situ. In addition to the reasons given previously, it is noted that the plagioclase of the most basic picrites is poikilitic in habit. In a former paper (Walker and Poldervaart, (1942a, p.62-63) it was pointed out that : "those sills in which early olivine has settled in situ, show a marked increase in size and a change in the habit of the plagioclase in the portions which have been enriched in the orthosilicate. The feldspar in such cases becomes poikilitic and is often slightly more calcic than that of the associated dolerites. In picrite sills - where differentiation has not taken place in situ, the habit of the plagioclase remains lath-shaped as in the associated dolerites." In the dike both picrite-types are met with, the poikilitic types being richer in olivine and underlying the second type. Such phenomena are indeed to be expected in the case of the Elephant's Head dike.

In diagram 9 the features of the differentiation process in the dike were emulated. It is noted that :-

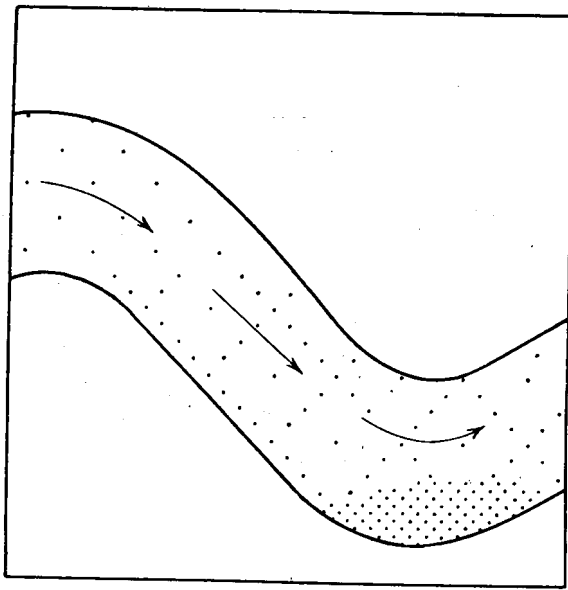
- (1) There was marked and prolonged flow of magma through the dike.

(2)

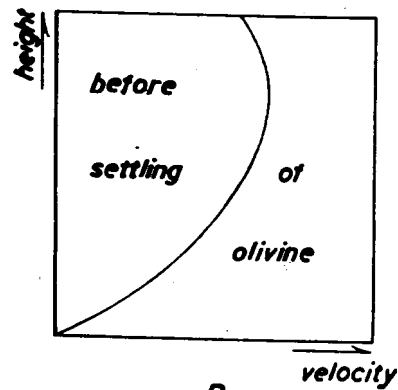
DIAGRAM 9.

Mechanism of Differentiation

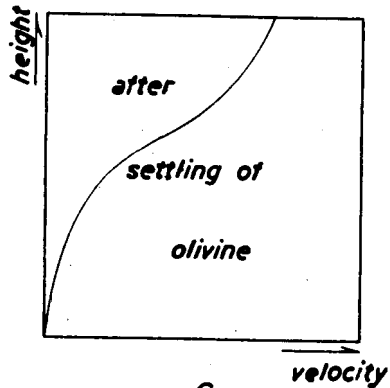
in the Dike.



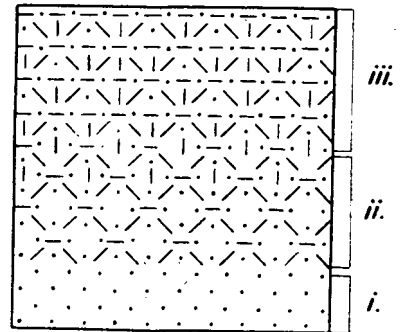
A.



B.



C.



D.

DIAGRAM 9.

- A.** A major undulation in the Dike, showing the direction of flow and the settling of olivine crystals by gravity, enhanced by magma-flow.
- B.&C.** The flow front in the lower half of a-b, before and after settling of the olivine crystals.
- D.** The igneous rocks in the lower half of a-b.
- i: picrite with poikilitic plagioclase .
  - ii. picrite with lath-shaped plagioclase .
  - iii. olivine-dolerite with lath-shaped plagioclase .

- (2) Chromiferous magnetite and magnesian olivine separated at an early stage.
- (3) The settling of the solid particles was controlled both by the flow of the magma and the specific gravity of the crystals. Thus conditions were ideal for the separation of early-formed, heavy crystals. Such crystals accumulated towards the bottom of the dike's undulations.
- (4) The accumulation of solid particles caused a difference in the shape of the "flow-front" of the magma, wherever such accumulations were effected.
- (5) In the lower parts of the accumulations, magma-flow had virtually stopped. Hence poikilitic, large plagioclase crystals were developed here. In the upper parts some flow of magma persisted and thus small, lath-shaped plagioclase crystallised here.

The igneous rocks of the dike show little sign of parallelism. The magma-flow may, however, have stopped after the crystallisation of only half the mineral constituents, in which case no parallel arrangements are expected. The author thus considers that, during its long traverse through Basutoland, the olivine-dolerite magma started to precipitate some magnetite and olivine. These settled out in the undulations of the dike in the Cape Province. When, therefore, the New Amalfi sheet was entered the magma had shed the bulk of its magnesian olivine and hence fractional crystallisation proceeded easily towards the formation of types, later in the differentiation series.

The possibility that the olivine-dolerites of the dike represent magma, injected after the formation of the picrites, is not excluded. Their injection, if later, must have followed immediately after the formation of the picrites, as no intrusive contacts are encountered. Moreover, it is clear, that the same magma that produced the olivine-dolerites, was responsible for the formation of the picrites. Thus the exact time of injection of the olivine-dolerites in the dike is relatively unimportant and does not affect the views expressed above.

In the sheet no picrites were met with, but the lowest portions of the sheet are not exposed. A slow rise of the later rest-magmas is implied in the rock-sequence of the intrusion. Convection currents may have been responsible for this sequence, though their action must have been limited in such a small intrusion as the New Amalfi sheet. Possibly the acidic rest-magmas, in which the volatile constituents were concentrated, filtered upward through gravitative action. Such a mechanism seems to be implied by Scholtz (1936, p.203) in his study of the Insizwa lopolith. Finally, a filter-press action may have been exerted by the stoping of the band of Burghersdorp sandstone. It is, however, considered unlikely that the stoping process was effected at an advanced stage in the magmatic crystallisation. Consequently this process is not thought of great importance in the production of the differentiation sequence of the New Amalfi sheet.

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VII. Mechanism/.....

VII. Mechanism of Intrusion and Form of the Dike.

The Elephant's Head Dike shows three prominent features which distinguish it from the usual dike-intrusion. They are:-

- (1) the intrusion has a flat or slightly domed roof, in addition to two parallel, vertical walls.
- (2) the character of the dike is sinuous in a parallel, vertical section.
- (3) the dike-contents show great variations in type and chemical composition.

Reasons have been given, why the picrites are considered to have been formed by the gravitative accumulation of olivine crystals in situ. It was also pointed out that their occurrence is confined to the hollows in the undulations of the dike. The latter fact was used as evidence for the assumption that the picrites were formed in place and were not intruded as a separate, ultrabasic magma. Likewise, it can be used as argument for the suggestion that the intrusion is floored, as well as roofed. Indeed this suggestion is a direct inference of the previous one. In a former chapter, the field relations at Mount Fred were also interpreted in terms of the dike being floored. It was found that such an extrapolation explained comprehensively all the relations observed in the field and the laboratory. No exposures of a floor were recorded in the area studied. Thus the suggestion must, of necessity, remain purely conjectural, although the author regards it as highly probable.

The undulatory/....

The undulatory character of the dike seems accentuated in certain strata, being less pronounced in others. In the stretch from Hanover to Calamity Hill gentle transgressions are inferred from the grain-size and the composition of the rocks exposed. The dike's course through the Molteno beds is marked by astonishingly steep transgressions, of which the major undulation at Elephant's Head has been given as an example. At Mount Fred and Ramkakala exposures are continuous, but here too, rather deep undulations are inferred from the rock-types encountered. From the information supplied by Stockley, it appears that the dike's Basutoland outcrop is likewise continuous. The author has not information regarding the accuracy of this statement, but regards it as probable that detailed study will reveal major undulations and gaps in the Basutoland exposures as well.

A further noteworthy point is that the outcrop of picrite and olivine-dolerite may be at any level within the dike. At Mount Fred the picrites occur near the floor of the intrusion and at any rate some 200 feet below its roof. At Calamity Hill, however, the basic rocks demonstrably occur very near the roof of the dike. The second intrusion is thus subject to appreciable differences in level within the dike. Some variation in its dimensions is also inferred.

Records of curiously shaped dikes are rare. The well-known Cleveland dike of northern England forms a notable exception. This intrusion shows little sign of differentiation (Holmes, 1929, p.39) and there appears to be no justification to consider the dike floored. Buie (1941, p.1780-1798) described and figured a remarkable differentiated intrusion in the Highwood Mountains, called by him "the Headed Dike". Somewhat modified,

Buie's/.....

Buie's "headed dike" reproduces the essential features of the Elephant's Head dike.

Daly (1933, p.89-90) briefly discussed the ribbon-type of intrusion, which, in the example discussed by him, forms long, narrow apophyses from the differentiated sill at Pigeon Point (Minnesota). This type of intrusion is characterised by clean-cut, rectangular cross-sections with a flat or slightly domed roof. The intrusions described are very small, but Daly does not exclude the possibility that similar features might be produced on a much larger scale. Finally, Washburne (1933) described several "still-dikes" from Oregon, which recall the ribbon injections of Daly and show a great similarity to the Elephant's Head dike.

The dike probably originated in a series of shallow faults, which may have deepened towards Basutoland. The fact that several other dikes strike against the Elephant's Head intrusion, but fail to cross it, nor continue on the other side, seems in accord with this view. The faults may represent steeply-inclined or vertical fractures in the sedimentary beds. In this respect it is significant that :-

- (a) the dike shows such strong undulations in the Molteno beds.
- (b) tholeiites of the Elephant's Head type were not recorded beyond the spur of Molteno sediments terminating at Calamity Hill.

Hence it is suggested that the Molteno beds were traversed by shallow steeply-inclined fractures. These may have differed in depth and thus caused the dike to assume its undulatory character. The finer-bedded Burghersdorp sediment did not lend itself to such pronounced fracturing, and thus the earlier tholeiite magma stopped a short

distance/..

distance from the Molteno beds. The later olivine-dolerite magma apparently possessed a greater impetus and advanced further into the Burghersdorp strata, to discharge itself into a sheet at the earliest opportunity. Undulations in the Burghersdorp beds are gentle and the sheet was injected along the first major argillaceous horizon encountered by the magma.

The same line of thought was followed by Washburne to account for the Oregon "still-dikes". He emphasises the shallow nature of the fractures along which the magma was injected and also the implications of the shape of the resulting intrusions. du Toit (1920, p.14) pointed out that certain sedimentary strata (notably the Stormberg series) contain a large number of dikes, whereas in others, especially the Beaufort series, there is a marked preference for concordant sheet injection. The Karroo intrusions of the Transkei fully bear out this statement. Thus there appears to be an intimate relation between the nature and mode of bedding and jointing of the sediments, and the character of the intrusions, injected into the strata.

Finally it is pointed out that the flow of the magma is inferred to be from Basutoland down towards New Amalfi; the Elephant's Head dike acting as the principal feeder of the New Amalfi sheet. In the Matatiele district a number of large dikes were encountered, all of which start in Basutoland and end in a sheet in the Upper or Middle Beaufort beds. All the dikes are roughly parallel and run in a direction NNW-SSE. The Fishback dike (du Toit, 1929, p.25) is the nearest to the Elephant's Head dike and contains dolerite, very similar to the normal olivine-dolerite of Elephant's Head.

The two/....

The two intrusions of New Amalfi and Elephant's Head might well serve as an example of the "descensional lit-par-lit stoping" mode of injection as suggested by du Toit (1920,p.33). The author regards it as highly probable that further studies in the Transkei will reveal yet more evidence for du Toit's suggestion, that the Karroo magma was injected in a descensional manner.

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VIII METASOMATISM OF BURGHERSDORP SANDSTONE.

Field Occurrences.

The shallow basin of the Umzimvubu River at New Amalfi finds its western limit in a conspicuous chain of hills and kopjes, culminating in the Confluence peak. The summit of these kopjes consists everywhere of pale, brownish grey-weathering granophyre, which often forms small scarps of sub-angular joint blocks. Thus the granophyre forms a well-defined, 60-80 foot band, stretching all along the western margin of the sheet, from Confluence peak to Hanover. Westwards the granophyre is overlain by olivine-poor dolerites, resembling the "dolerites near contacts", described previously. The contact is sharp and a decrease in the grain-size of the dolerite indicates a certain amount of chilling. A few narrow veins of granophyre emerge from the main zone, and are intrusive into the dolerite. Eastwards the band of granophyric rocks is lined with chilled olivine-basalt. The chilled phase may, however, be absent over long stretches of the boundary, when the granophyre directly overlies the iron-rich dolerites, described previously.

Within the granophyric zone, appreciable differences in grain-size are observed. Generally, a considerable increase in grain-size is noted near the vertical joint planes, which dissect the exposures. Along such planes the rock is extremely coarse-grained, and the interlocking of ragged prisms of greenish-black ferromagnesian, several inches in length, may produce rude grid-iron structures. Such features are, however, by no means common and confined to major joint planes.

Several/....

Several rounded sandstone xenoliths were encountered in the granophyre zone. The sedimentary material resembles the fine-grained Burghersdorp sandstone, and the xenoliths may be in all stages of digestion. Generally, a core of yellow sandstone is surrounded by one or more transitional zones, which show sharp margins against each other. Typical is the following sequence:-

core:	fine-grained, yellow sandstone.
first zone:	white granophyre, containing irregular, drawn-out purple patches.
second zone:	fine-grained granophyre with stumpy, greenish black ferromagnesian.
normal rock:	coarse-grained granophyre, showing glistening, elongated feldspar crystals and long, feathery pyroxene blades, set in a quartzofeldspathic base.

#### Petrography.

Throughout the zone the rocks may show limited variations, of which differences in grain-size have already been noted. The proportions of quartz, plagioclase and micropegmatite are also subject to appreciable changes. Finally, the dominant ferromagnesian, clinopyroxene, is in some of the rocks largely substituted by a very dark coloured biotite. Such changes might well arise from the variability of the original sediment itself. The Burghersdorp sandstones are in parts more arenaceous and feldspathic whereas in others they resemble the impure, argillaceous siltstones of the Middle and Lower Beaufort beds. Thus certain variations in the make-up of the resulting metasomat-

granophyres/.....

ic granophyres might be expected.

The relations of the sandstone xenoliths to the surrounding granophyres are highly interesting. The sedimentary core shows a mosaic of interlocking grains of quartz and feldspar, together with a few small patches of a fine micropegmatite. Granules of iron ore and aggregates of golden-brown serpentine occur in minor quantities. Among the heavy residue minerals, sphene, zircon and apatite predominate, whereas garnet and tourmaline are of rarer occurrence. Comparison with several sections of original and contact-metamorphosed Burghersdorp sandstones revealed a very close agreement. As already noted, some sandstones may be finer-grained and more argillaceous in character, but the majority are fairly pure, feldspathic sandstones.

Surrounding the core, a narrow transitional zone of a heterogenous rock occurs. The matrix consists of a coarse, intensely altered micropegmatitic intergrowth, through which thin rods of iron ore and irregular crystals of green clinopyroxene are scattered. Embedded in this base occur numerous drawn-out or rounded purple patches. These consist of minute granules of plagioclase ( $av. \beta : 1.552, An. 41$ ) and purple clinopyroxene ( $\gamma : 1.726$ ), closely packed together. Some sort of distribution is often discernible in the patches. Centrally a few larger pyroxenes occur. Next comes a zone of small, interlocking granules of both pyroxene and plagioclase in roughly equal proportions. This is succeeded by another zone of slightly larger pyroxenes, whereas outermost plagioclase predominates.

Surrounding/.....

MICROPHOTOGRAPH.

Metasomatic Granophyre.

(Index No. 51).



Metasomatic Granophyre.

(Index No. 51).

The rock is very similar to 18, but contains more plagioclase, while fayalite is absent.

Note the cloudy appearance of the plagioclase.

Ordinary light x 10.5 diameters.

Surrounding the patchy purple rock, there is a second transitional zone of more uniform composition. Essentially it is a fine-grained granophyre; showing slender plagioclase laths, green pyroxene prisms and stumpy rods of iron ore, whereas the remainder is made up of micropegmatite and quartz. The habit of the pyroxene is sub-ophitic, but the crystals may include grains of quartz and apatite. Remnants of the purple patches are represented by small accumulations of plagioclase laths and purple-green pyroxene, both of larger dimensions than in the previous transitional zone.

The normal granophyre consists chiefly of quartz, micropegmatite, plagioclase and pyroxene. Plagioclase (av.  $\beta$ : 1.546, An. 28) occurs as broad, zonal laths, surrounded by haloes of micropegmatite. In addition some oligoclase occurs as irregular, untwinned grains in association with quartz. Pyroxene builds elongated, sub-ophitic crystals of purple-brown or green colour. The optical properties of the green variety are  $2V_y$ :  $54^\circ$ ,  $\delta$ :  $c$ :  $45^\circ$ ,  $\delta$ : 1.755, whereas the purple-brown variety shows nearly identical constants. Iron ore occurs as large, skeletal masses. Biotite occurs in some specimens, partly or wholly replacing pyroxene. The mineral has  $\delta$ : 1.679 and shows pleochroism from  $\gamma$ : black to  $\alpha$ : yellowish brown. In addition to the above, zircon and apatite occur as accessory minerals.

All the rocks suffered extreme deuteric and hydrothermal alteration. Plagioclase is cloudy, whereas the feldspar of the micropegmatite is undeterminable. Clinopyroxene shows a marginal alteration to hastingsite and brown serpentine. Radiating needles of pectolite are often found filling small vesicles in the rocks.

Micrometric/....

Chemical Analyses.\*

Index No.	49.	50.	51.
SiO <sub>2</sub>	76.92	62.64	61.84
Al <sub>2</sub> O <sub>3</sub>	12.38	13.96	10.52
Fe <sub>2</sub> O <sub>3</sub>	1.39	1.12	3.66
FeO	1.45	6.54	9.24
MgO	0.22	1.83	0.56
CaO	0.28	3.91	4.97
Na <sub>2</sub> O	2.17	5.02	2.83
K <sub>2</sub> O	3.88	1.90	2.58
H <sub>2</sub> O-	0.39	0.28	0.19
H <sub>2</sub> O+	0.77	1.02	1.82
TiO <sub>2</sub>	0.20	1.53	1.51
P <sub>2</sub> O <sub>5</sub>	trace	0.11	0.34
MnO	trace	0.13	0.23
CO <sub>2</sub>	trace	0.18	trace
	<hr/>	<hr/>	<hr/>
total	100.05	100.17	100.29

Norms.

Quartz	48.35	13.62	22.50
Orthoclase	22.69	11.12	15.46
Albite	18.18	42.54	23.89
Anorthite	1.33	9.82	8.28
Corundum	4.23	-	-
Diopside.			
{Wo.	-	3.16	5.99
{En.	-	1.11	0.70
{Fs.	-	2.13	5.90
Hy.....			
{En.	0.55	3.46	0.70
{Fs.	1.07	6.56	5.92
Ilmenite	0.46	2.93	2.90
Magnetite	2.07	1.67	5.34
Apatite	-	0.34	0.80
CaCO <sub>3</sub>	-	0.44	-
H <sub>2</sub> O	1.16	1.30	2.01
	<hr/>	<hr/>	<hr/>
total	100.09	100.20	100.39

Modes.

Plagioclase.		9.9	20.1
Pyroxene.		26.7	14.1
Iron Ore.		3.7	6.2
Biot. + Hornbl.		2.8	3.7
Micropeg. + Qu.		56.9	48.0
Serpentine.		-	7.9
Sp.Gr.	2.48	2.73	2.79

49. Sandstone core of xenolith in granophyre band, summit of kopje, 2 miles N. of New Amalfi post-office.
50. Fine-grained, ganophyric transitional zone, surrounding the same xenolith.
51. Normal, coarse-grained granophyre, 20 feet E. of 49 and 50.

- 50, 51, 53. Granophyres from summit of kopje,  
2 miles N. of New Amalfi post office.
81. Granophyre along main road from Matatielo  
to Zwartberg; overlying specimen No. 18.

The sedimentary core of a xenolith, the fine-grained granophyric transitional zone, and the normal granophyre nearby were chemically analysed by Mr. F. Herdsman. The results are tabulated here, together with their norms and modes.

The analyses show clearly that the process of converting the sandstone was a highly selective one. The irregular variation of the oxides in the three analyses precludes the possibility of the granophyre having been formed by simple admixtures of sandstone and either the original olivine-dolerite magma, or differentiated portions of that magma. Other evidence, collected in the field and the laboratory, is also against this hypothesis. It has been shown that :-

- (1) the granophyric rocks occur in a well-defined zone in the upper parts of the New Amalfi sheet.
- (2) the granophyre band shows sharp boundaries against the dolerites, both above and below the zone.
- (3) the sandstone xenoliths within the zone, and also the transitional modifications surrounding the xenoliths, show clear-cut margins, without any sign of gradation.

The /....

The above characteristics have been recorded in three other Karroo examples of metasomatism of sediment by dolerite (Walker and Poldervaart, 1942b). The latter character is regarded as a typical phenomenon of pyrometasomatism (Reynolds, 1936, p. 403). Thus it appears that the process of alteration has been a molecular one, and may be called metasomatic.

In order to obtain an idea as to the losses and gains of material, effected by the conversion, the analyses were recalculated to constant volumes. The results of the calculations are tabulated here.

Analyses recalculated to Constant Volumes.

Index No.	49.	50.	51.
SiO <sub>2</sub>	190.0	171.6	171.8
Al <sub>2</sub> O <sub>3</sub>	30.7	38.3	29.3
Fe <sub>2</sub> O <sub>3</sub>	3.5	3.0	10.3
FeO	3.7	17.8	25.7
MgO	0.5	4.9	1.7
CaO	0.7	10.7	13.9
Na <sub>2</sub> O	5.4	13.7	7.8
K <sub>2</sub> O	9.7	5.2	7.3
H <sub>2</sub> O	3.0	3.6	5.6
TiO <sub>2</sub>	0.5	4.1	4.2
P <sub>2</sub> O <sub>5</sub>	-	0.3	0.8
MnO	-	0.3	0.6

Gains and Losses of the two Granophyres, as compared with the Sandstone.

	50.		51.	
	Loss	Gain	Loss	Gain
SiO <sub>2</sub> .....	18.4	.....	18.2	.....
Al <sub>2</sub> O <sub>3</sub> .....	.....	7.6	1.4	.....
Fe <sub>2</sub> O <sub>3</sub> .....	0.5	.....	.....	6.8
FeO .....	.....	14.1	.....	22.0
MgO .....	.....	4.4	.....	1.2
CaO .....	.....	10.0	.....	13.2
Na <sub>2</sub> O .....	.....	8.3	.....	2.4
K <sub>2</sub> O .....	4.5	.....	2.4	.....
H <sub>2</sub> O .....	.....	0.6	.....	2.6
TiO <sub>2</sub> .....	.....	3.6	.....	3.7
P <sub>2</sub> O <sub>5</sub> .....	.....	0.3	.....	0.8
MnO .....	.....	0.3	.....	0.6

As shown, /.....

As shown, the sandstone lost in  $K_2O$  and  $SiO_2$  in both cases. Again in both cases, the sandstone gained in  $FeO$ ,  $MgO$ ,  $CaO$ ,  $Na_2O$  and  $TiO_2$ . Finally,  $Al_2O_3$  was gained to form the transitional granophyre, but lost in the formation of the normal granophyre.  $Fe_2O_3$  was lost in the first instance, but gained in the second. Qualitatively there is a certain agreement between the losses and gains of the two granophyres. It is, however, clear that there are great differences in the amounts of the various oxides gained and lost. The transitional granophyre shows a particularly high  $Na_2O$  content, whereas the normal granophyre is conspicuously rich in  $FeO$  and  $Fe_2O_3$ . The author can but quote Miss Reynolds, that:- "the circumstances which contributed towards the present distribution of the elements in the transfused xenoliths, include:- (a) sequence of introduction into the xenoliths; (b) relative rate or power of diffusion through the xenoliths; (c) sequence (in both time and space) of fixation by the xenoliths" (1936, p.398).

In the present case, the responsible magma was highly differentiated. Hence it is only reasonable to presume that the emanations derived from the magma, would likewise be of a constantly changing character. At first they may have carried some  $CaO$  and  $MgO$ . At a later stage, when differentiation proceeded towards iron-enrichment, it is more likely that the emanations chiefly carried  $FeO$ ,  $Fe_2O_3$  and  $TiO_2$ . During the final magmatic stage, differentiation proceeded principally towards soda-enrichment, and hence it is reasonable to suppose that the emanations carried mainly  $Na_2O$ .

With all these variable factors operating, it is scarcely surprising that the resulting metasomatic granophyres are of such different compositions. Indeed, the

irregular /.....

irregular variation of the oxides is a strong indication that the conversion of the sandstone was produced by a molecular, metasomatic process, rather than by processes of assimilation and magmatic mingling.

Unfortunately, the losses and gains of the magma cannot be forecast. It has already been pointed out that the rocks below the granophyre band show certain obvious discrepancies in their compositions. 52 is clearly exceptionally low in  $\text{Na}_2\text{O}$ . 18 is low in  $\text{CaO}$  and perhaps also in  $\text{Na}_2\text{O}$ , whereas the proportions of  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  are too high. But at the same time it was noted that losses in  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$  and  $\text{TiO}_2$  cannot possibly be detected in the analyses. This applies even more to losses of  $\text{CaO}$  and  $\text{MgO}$ , which probably migrated at an early stage in the magmatic history. The micrometric data of the granophyres show that some of the rocks contain considerably more plagioclase than the analysed specimens. In some parts of the granophyre band, the gains in lime must, therefore, be appreciably higher than is shown by the available analyses.

The metasomatic processes did not stop at the purely magmatic stage, but emanations continued to diffuse through the rocks in the hydrothermal stage. Primarily this may account for the replacement of pyroxene by biotite, hastingsite and serpentine. Secondly it accounts for the marked decomposition shown by all the rocks of the granophyric zone.

The sandstone was apparently rendered plastic by heat and by the emanations, derived from the magma. The habit of the pyroxenes shows that the crystals grew in a viscous medium, which enabled them to push aside the adjacent minerals. Hence sieve textures are not found in these rocks. It was also noted that granophyric veinlets, emerging from the main zone, are intrusive in the overlying

the overlying dolerite. These veins indicate that the metasomatised rock finally acquired rheomorphic properties, and in turn intruded the dolerite. Signs of mingling between dolerite and granophyre are lacking, nor were examples of gradation between the two rock-types observed. Hence the granophyre was at no time completely liquid, and only acquired its mobility as a plastic, highly viscous substance.

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IX. REACTION PHENOMENA OF MOLTEÑO SEDIMENT.

Field Occurrences.

The transgressive roof and the side-walls of the dike at Elephant's Head consist for a large part of pale-coloured granophyric rocks. This is particularly the case at the SW. and SE. sides of the dolerite-block, where good exposures are obtained. The rocks are medium to fine-grained. Differences in grain-size and colour ratio were found to correspond with differences in the nature of the Molteno sediment at the same level. Traces of the original bedding are often preserved as horizontal bands of different grain-size. Very near the top of the peak a mixed rock was collected, consisting of drawn-out patches and veins of white Molteno quartzite, surrounded by dark igneous rock. It has already been noted that the exposures at the Elephant's Head peak consist of tholeiite only. Thus the reaction-products are considered to be the result of interaction between Molteno sediment and tholeiite magma. The sediment itself consists of horizons of coarse, feldspathic grits and sparkling sandstones, alternating with fine-grained, sandy shales and occasional mudstones. Near the dike the sediment is considerably metamorphosed and shows marked columnar jointing.

At Calamity Hill a similar zone of reaction-rocks was found. The zone extends along the roof of the dike, just where it enters the spur of Molteno sediment. Field relations are not so clear at Calamity Hill, as no rock is exposed between this zone and an outcrop of picrite some 60 feet lower. Hence it cannot be stated definitely that the magma responsible for the conversion of the sediment was the primary tholeiitic magma. The great similarities between the reaction-products at Calamity Hill and

Elephant's/....

Elephant's Head make it highly probable, however, that this was indeed the case. The reaction-rocks are medium grained and contain large lumps of unconverted Molteno quartzite, or xenocrysts of quartz or feldspar. The original sediment of this horizon is a coarse, feldspathic grit.

#### Petrography.

The sandstone horizons of the Molteno beds offer great variation in grain-size, varying from coarse, pebbly grits to medium-grained sandstones. The rocks consist mainly of quartz, microcline, orthoclase and plagioclase. As impurities occur sheaves of brown serpentine and iron ore in very small quantities. Among the heavy mineral residue zircon predominates, whereas sphene and garnet were also recognised. More argillaceous varieties show a greyish brown argillaceous matrix, and iron ore and serpentine also occur in greater abundance.

Upon metamorphism the clastic grains of quartz and feldspar were regenerated to form large, interlocking grains, surrounded by smaller grains. The regenerated individuals show a patchy extinction and often their origin is indicated by sutured lines traversing the crystals. A little interstitial micropegmatite may also occur, together with patches of brown serpentinous material, in which iron ore granules and slender plagioclase laths are recognised. In the poort at Mahainkwe, a coarse grit was metamorphosed, to produce a rock, of which du Toit (1929, p.25-26) remarks that it :- "resembles in thin section a silicious pegmatite. The clastic grains of quartz, orthoclase, microcline and plagioclase have been regenerated and the areas now interlock, just as in a granite/....

MICROPHOTOGRAPH.

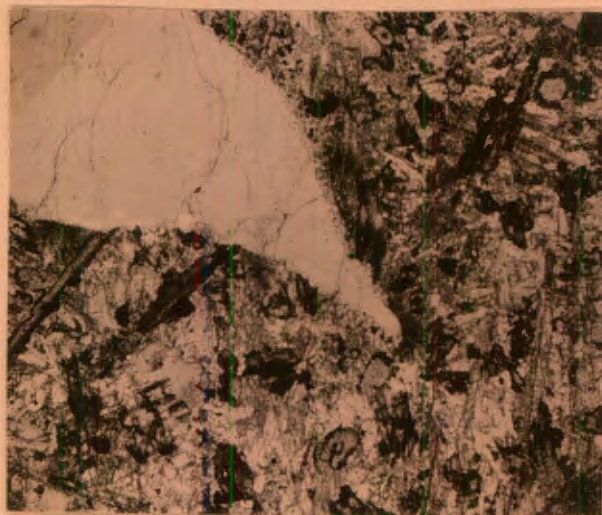
Molteno Quartzite Xenolith in  
Granophyre.  
(Index No. 33).

Xenolith of Molteno Quartzite

in Granophyre.

(Index No. 33).

Note the characteristic elongation of  
the granophyre.  
It shows a narrow, felsic margin against  
the xenolith is corroded and rounded.



Xenolith of Molteno Quartzite  
in Granophyre.

(Index No. 33).

The xenolith is corroded and rounded.  
It shows a narrow, felsic margin against  
the granophyre.

Note the characteristic elongation of  
both plagioclase and pyroxene in the  
granophyre.

Ordinary light x 10.5 diameters.

granite" (specimen 31).

As might be expected, the reaction-rocks show considerable differences in their mineralogical make-up. The products of the more arenaceous horizons are medium-grained and consist essentially of quartz, micropegmatite, plagioclase and pyroxene. Some rocks consist mainly of micropegmatite, but generally there is a more even distribution of the four chief constituents. Both plagioclase (av.  $\beta$  : 1.563, An. 58) and pyroxene show a pronounced tendency for elongation. The latter builds long, sub-ophitic prisms of a very pale colour. Its optical properties are  $2V_{\gamma}$  :  $48^{\circ}$ ,  $\delta$  : c :  $45^{\circ}$ ,  $\delta$  : 1.712. Iron ore occurs as octahedral granules or skeletal crystals. In the more argillaceous products, pyroxene is largely replaced by biotite and hornblende. The biotite is of a dark-brown colour, resembling the mineral of the metasomatic Burghersdorp sandstones.

Inclusions of undigested sediment in the reaction-rocks are strongly corroded and rounded. They are surrounded by a narrow zone of corrosion-products; mainly feldspar and quartz. One xenocryst of microcline shows a curious reticulate texture, similar to the phenomenon described and photographed by Reynolds (1941, p.9). The appearance suggests that the larger individual is breaking up into smaller crystals.

All the reaction-products are intensely altered. Plagioclase is cloudy, whereas pyroxene likewise becomes cloudy and grey in colour. Subsequently the pyroxene is altered to biotite, hornblende, chlorite and serpentine. In some rocks all the pyroxene is altered and only pseudomorphs in chlorite or serpentine are preserved.

Small calcareous pellets in the more argillaceous sediments are often preserved in a metamorphosed state

in the/.....

in the resulting reaction-rocks. Such pellets are converted to aggregates of calc-silicate minerals, such as epidote, clinozoisite, idocrase, prehnite, tremolite and sphene, whereas some calcite generally remains. Marginally diopside and green, probably sodic, pyroxene are recognised. It is noteworthy that the minerals of the calcareous kernels are always perfectly fresh, even if the surrounding rock is intensely altered.

The mixed rock, collected at Elephant's Head, shows veins and drawn-out patches of metamorphosed Molteno sandstone, contained in a somewhat modified, tholeiitic base. The base consists mainly of clinopyroxene, which builds euhedral, equidimensional crystals in sizes up to 1 m.m. diameter. The mineral is pale brown in colour and shows optical properties, identical with those of the normal tholeiitic pyroxene. The remainder consists of cloudy, tabular plagioclase, coarsely developed mesostasis and skeletal iron ore. The latter is normally 0.2 m.m. in diameter, but one mass measured 3 m.m. diameter. Bounding the sandstone, many prismatic pyroxenes occur. These are generally arranged perpendicular on the boundary and show dusty margins, which may be slightly embayed. Similar pyroxenes also occur within the veins, at points where some mingling between igneous and sedimentary material has taken place. The pyroxene is pale in colour and has  $\gamma$  : 1.721.

- 
33. Reaction-product of Molteno sandstone,  
roof of dike, W. of road, Calamity Hill.
77. Reaction-product of Molteno sandstone,  
S. wall of dike, Elephant's Head Peak.

Chemical Analyses\*

Index. No.	31.	33.	70.
SiO <sub>2</sub>	92.68	60.88	49.80
Al <sub>2</sub> O <sub>3</sub>	3.65	12.42	14.38
Fe <sub>2</sub> O <sub>3</sub>	trace	0.33	3.67
FeO	0.87	7.86	11.03
MgO	nil	4.52	4.52
CaO	0.30	7.44	8.82
Na <sub>2</sub> O	0.36	1.96	2.23
K <sub>2</sub> O	1.69	1.01	0.82
H <sub>2</sub> O-	0.08	0.20	0.15
H <sub>2</sub> O+	0.12	1.41	1.66
TiO <sub>2</sub>	0.10	1.44	2.54
P <sub>2</sub> O <sub>5</sub>	trace	0.09	0.29
MnO	trace	0.16	0.16
CO <sub>2</sub>	nil	0.29	trace
	<hr/>	<hr/>	<hr/>
total	99.85	100.01	100.07

Norms.

Quartz	82.80	21.12	6.18	
Orthoclase	10.01	6.17	5.00	
Albite	3.14	16.56	18.34	
Anorthite	1.39	22.10	26.97	
Corundum	0.71	-	-	
Diopside	[	Wo.	5.08	6.26
		En.	2.43	2.90
		Fs.	2.57	3.30
Hy.....	[	En.	8.87	8.40
		Fs.	9.39	10.16
Ilmenite	0.15	2.80	4.71	
Magnetite	-	0.53	5.34	
Apatite	-	0.30	0.67	
CaCO <sub>3</sub>	-	0.68	-	
H <sub>2</sub> O	0.20	1.61	1.81	
	<hr/>	<hr/>	<hr/>	
total	99.85	100.21	100.04	

Modes.

Olivine.	-	0.5
Plagioclase.	23.2	33.4
Pyroxene.	21.9	26.5
Iron Ore.	3.7	13.5
Biot + Hornbl.	5.7	5.6
Microp.+Qu.	45.5	20.5**
Serpentine.	-	-

31. Metamorphosed, coarse-grained Molteno sandstone along road, poort at Mahainkwe.
33. Reaction-product of Molteno sandstone, roof of dike, W. of road, Calamity Hill.
70. Tholeiite, top of Elephant's Head peak.

\* analyst F. Herdsman.

\*\*mesostasis

Chemistry.

A specimen of coarse-grained, metamorphosed Molteno sandstone, and a medium-grained granophyric reaction-product were submitted to Mr. F. Herdsman for chemical analysis. The results are tabulated here with their norms and modes. The analysis of the Elephant's Head tholeiite is again quoted in the table.

It is plain that the available data are insufficient to enable definite conclusions to be drawn. The analysed Molteno sandstone was collected at Mahainkwe Poort, whereas the granophyre was found at Calamity Hill. It is, however, thought that the original sediment at Calamity Hill was very similar to the Mahainkwe Poort sediment. The unconverted sedimentary xenoliths in the Calamity Hill granophyre have an identical appearance under the microscope. Reasons have already been given why it is considered that, both at Elephant's Head and Calamity Hill, the tholeiitic magma was responsible for the conversion of the sediment.

The non-linear variation of the oxides is clearly shown in diagram 10, where the analyses were plotted against silica percentage. The diagram seems to preclude the possibility that the granophyric reaction-products were formed by a simple assimilative process. Other evidence also indicates that the conversion was principally metasomatic. The reaction-products again occur in definite zones. Traces of the original bedding are preserved in the converted rocks. Calcareous pellets in the original sediment are reproduced as kernels of calc-silicate minerals in the granophyres (Walker and Poldervaart, 1942b).

On the/....

DIAGRAM 10.

Variation of the Reaction-series

Tholeiite-Granophyre-Molteno Sandstone.



DIAGRAM 10.

Variation of the reaction-series

Tholeiite - Granophyre - Molteno Sandstone.

On the other hand, the mixed rock at Elephant's Head indicates that a small amount of mingling between dolerite and sediment did take place. Yet it is not thought that this influenced the composition of either the tholeiite magma or the sediment to an appreciable extent.

The diagram shows that the sandstone lost  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  in its conversion, whereas it gained in practically all the other constituents. Losses of the magma are particularly heavy in regard to  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$  and  $\text{FeO}$ . These losses are reflected in the mixed rock of Elephant's Head, where there is a great lack of plagioclase feldspar near the sandstone inclusions, while a pyroxene, poorer in iron, is formed in large amounts.

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X. CONCLUSIONS.

The following points are now regarded as established :-

1. The Elephant's Head dike possesses a roof. In a parallel section the dike shows an undulatory outline. Undulations are more marked in some strata than in others.
2. The dike was formed by a succession of two intrusions; the first being tholeiitic, while the second magma was an olivine-dolerite magma.
3. The olivine-dolerite magma also intruded the New Amalfi sheet. The dike was therefore the principal feeder of the sheet.
4. The olivine-dolerite magma became strongly differentiated upon crystallisation. Differentiation was effected by settling of olivine crystals, followed by pronounced crystal-fractionation.
5. During the middle stages of crystallisation, differentiation proceeded towards iron-enrichment. After reaching a maximum in the concentration of iron, differentiation proceeded towards enrichment in soda, potash, silica and alumina.
6. A block of Burghersdorp sandstone was stoped down from the upper contact of the New Amalfi sheet. Upon immersion in the dolerite magma, the sandstone was converted into granophyric rocks of igneous appearance.
7. The process of conversion of Burghersdorp sandstone to granophyre was metasomatic. The introduction of material was molecular and highly selective. The magmatic emanations were released over a prolonged period, extending well into the hydrothermal stage.

8. Along/.....

8. Along the dike, the Moltenc sediments were likewise converted to granophyric rocks. These granophyres are different in appearance and composition from the granophyres originating in the metasomatism of Burghersdorp sandstone.

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XI. LITERATURE.

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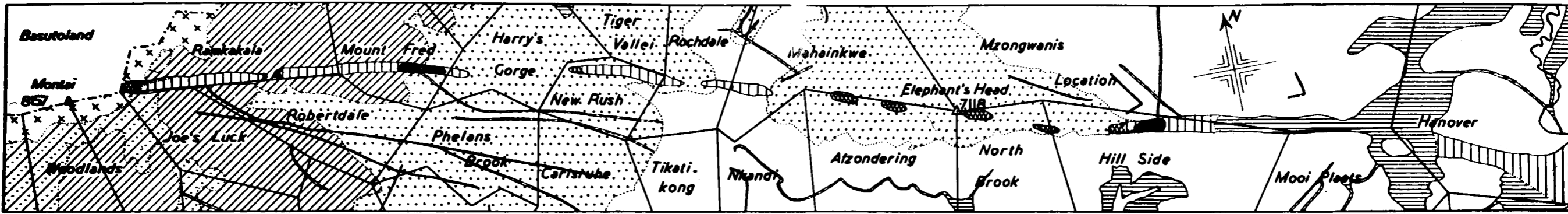
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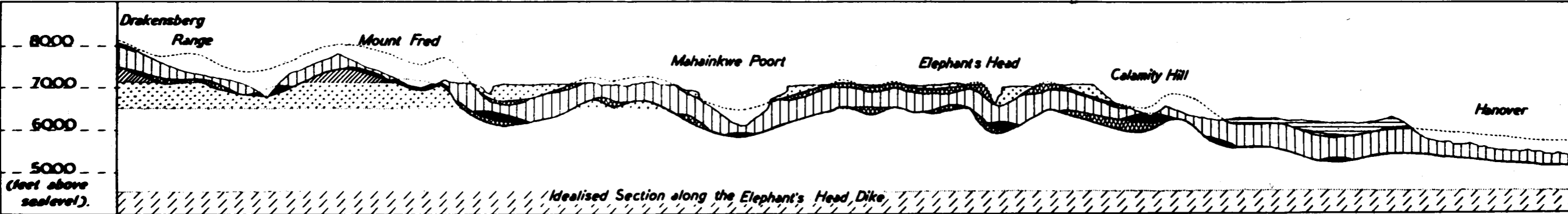
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GEOLOGICAL MAP OF THE ELEPHANT'S HEAD DIKE.



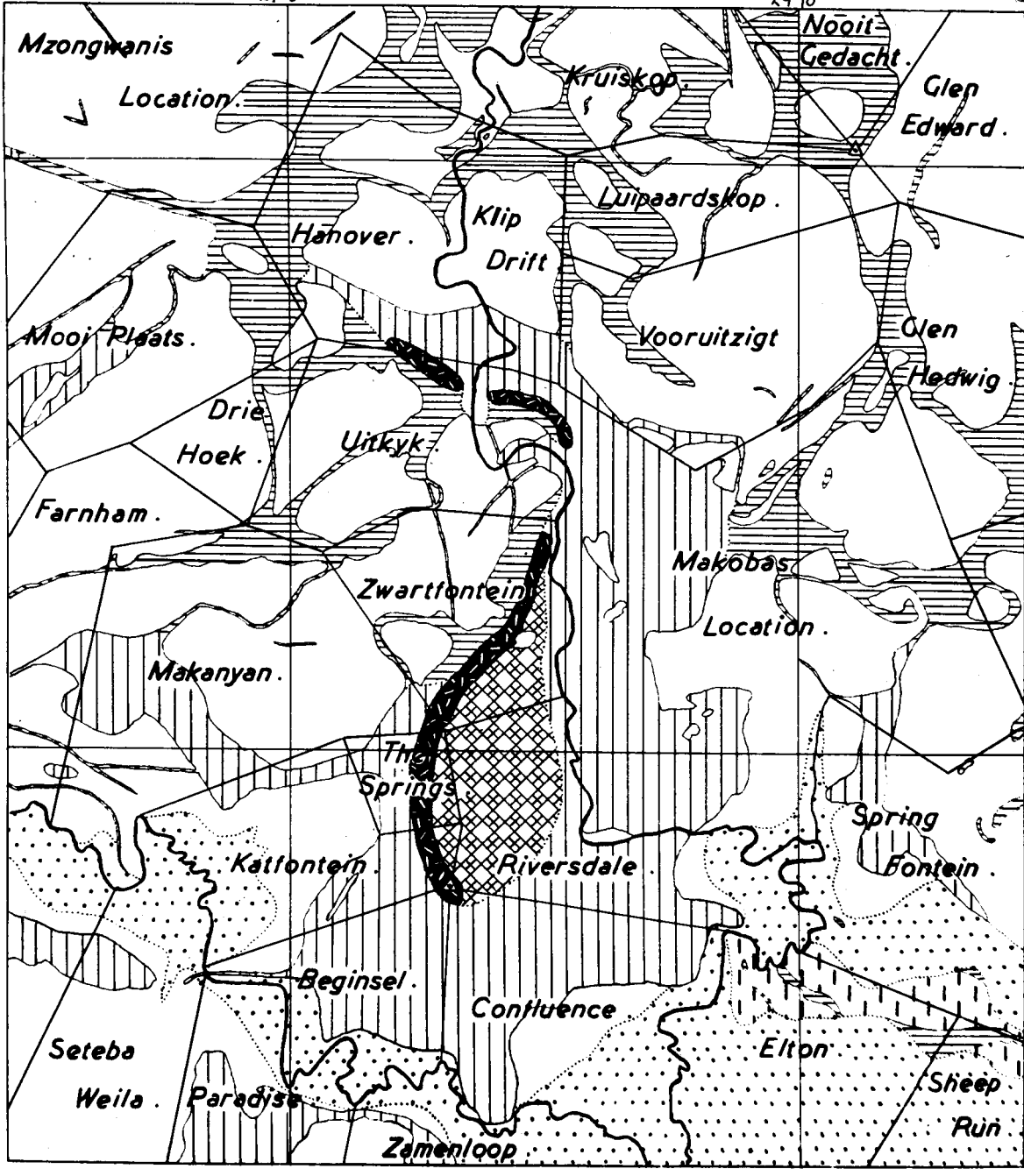
*Idealised Section along the Elephant's Head Dike*

INDEX.

SCALE : 1.55 Miles = 1 Inch.

- |  |  |
|--|--|
| <ul style="list-style-type: none"> <li> Stormberg Laves.</li> <li> Cave Sandstone.</li> <li> Red Beds.</li> <li> Molteno Beds.</li> <li> Burghersdorp Beds.</li> <li> Middle Beaufort Beds.</li> </ul> | <ul style="list-style-type: none"> <li> Karoo Dolerite of other Intrusions.</li> <li> Olivine Dolerite.</li> <li> Picrite.</li> <li> Tholeiite of Elephant's Head Type.</li> </ul> |
|--|--|

*The width and the height of the Dike were exaggerated to show the distribution of the various Rock Types.*



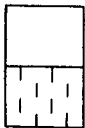
MAP OF THE NEW AMALFI SHEET.

LEGEND.

SCALE: 1 inch = 1.68 miles.



*Soil of the Cedarville Flats.*

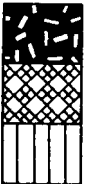


*Upper Beaufort or Burghersdorp Beds.*

*Middle Beaufort Beds.*



*Dolerites with small olivines.*



*Metasomatic Granophyres.*

*Iron-rich Dolerites.*

*Olivine-Dolerites.*

MAP OF THE NEW AMALFI SHEET.

