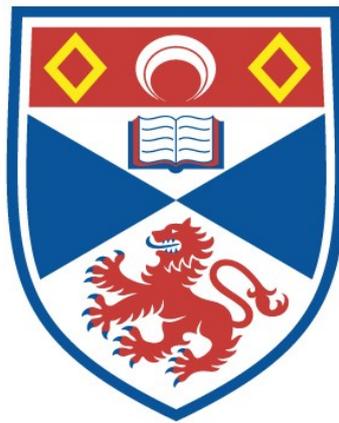


THE BASIC INTRUSIVES AND ASSOCIATED ROCKS
OF THE SHOSHONG-MAKHWARE AREA
BECHUANALAND PROTECTORATE

Patrick Louis Cedric Grubb

A Thesis Submitted for the Degree of PhD
at the
University of St Andrews



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OF THE SHOSHONG - MAKHWARE AREA
BECHUANALAND PROTECTORATE.

being a Thesis presented by
PATRICK LOUIS CEDRIC GRUBB
to the University of St. Andrews in application
for the degree of Ph.D.

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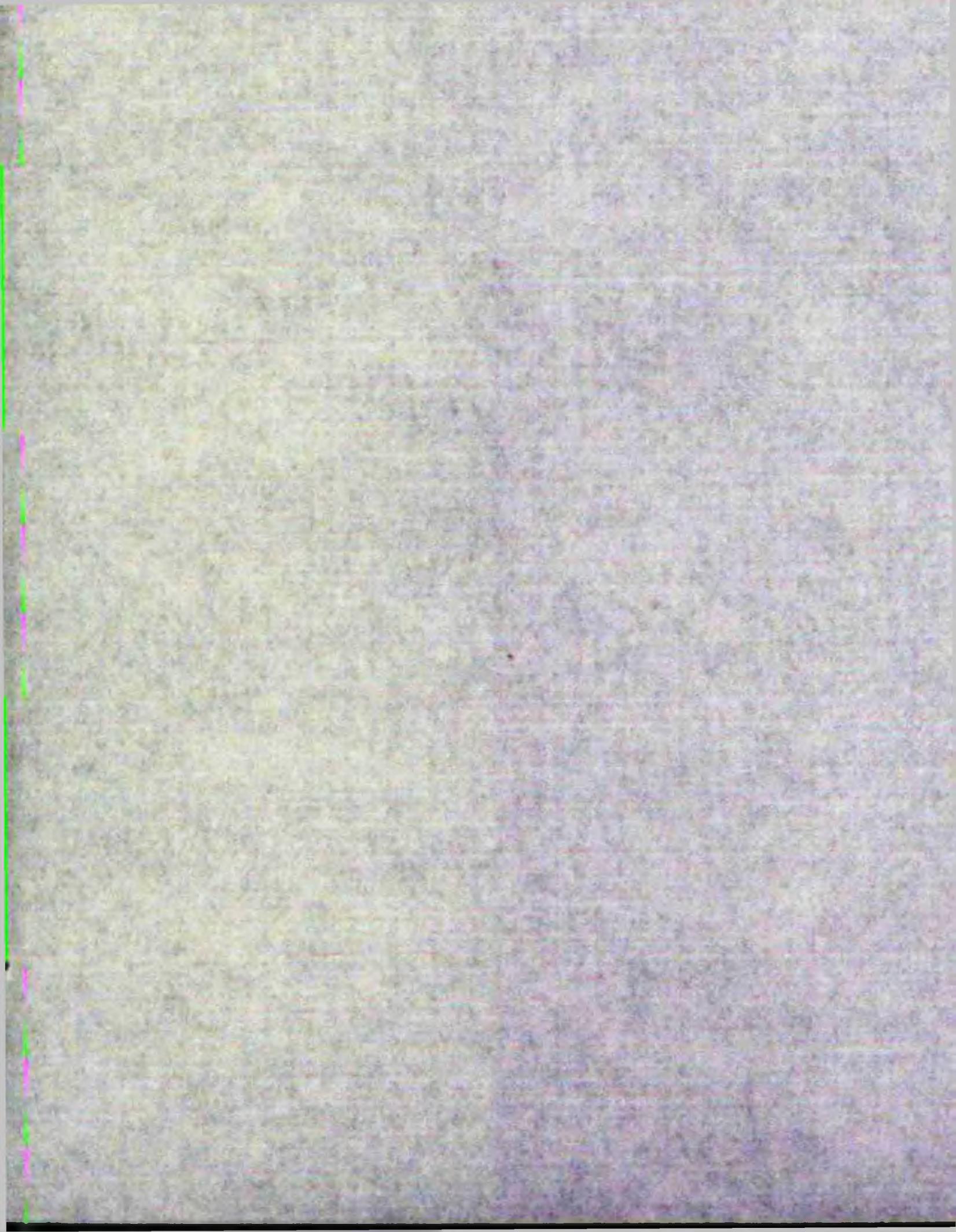
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DECLARATION.

I hereby certify that the following Thesis is based on the results of experiments carried out by me, that the Thesis is my own composition, and that it has not previously been presented for a higher degree.

The research was carried out in the Geological Survey Department of Bechuanaland, and in both Departments of Geology at the University of St. Andrews.



CAREER.

I matriculated in the University of Cape Town in 1954 and followed a course leading to graduation until 1957.

On 1957 I commenced research on "The basic intrusives and associated rocks of the Shoshong-Makware area, Bechuanaland Protectorate", which is now being submitted as a Ph.D. thesis.

The field work of this research was carried under the auspices of the Geological Survey Department in Bechuanaland.

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I.

Introduction.

The Shoshong-Makware area, which covers approximately 1200 square miles west of the Mahalapye-Palapye rail track in Latitude 23°S . and Longitude 26.5°W ., contains several tholeiitic intrusions. These are probably differentiates of subterraneous magma body, which was roughly contemporary with the Bushveld Igneous Complex in the Union.

Previous Investigations.

The first recorded account of the Shoshong sill appeared in 1920, when Dr. A.L. du Toit included this within the non-alkaline post-Waterberg intrusives of the Union.

In 1950 after the establishment of a permanent geological survey in the protectorate, Mr. D. Green made a reconnaissance survey of the entire Mahalapye-Shoshong area.

Subsequently in 1952, mention of the Shoshong sill was again made by Dr. A. Poldervaart in a comprehensive petrological account on the Karroo dolerites and basalts of the eastern part of the Protectorate.

After completion of the present author's field work in 1958, Mr. D. Cullen extended a detailed stratigraphic correlation of sediments to the south of Shoshong northwards into the Shoshong-Makware area.

Finally in 1959, certain critical stratigraphic sections were re-examined by Messers C. Boocock and C. Jennings, whose conclusions have been most valuable in dating these intrusives.

Present Investigation.

The present author first visited the area in July 1957 and subsequently spent four months remapping and collecting the necessary material for a more detailed laboratory study. Mapping was done with the aid of aerial photographs, and where these were not available, resort was made to triangulation survey methods, using a prismatic compass. Inclinations of joints, faults and bedding planes were determined with the aid of a Brunton Compass.

The laboratory work was carried out in both Departments of Geology in the University of St. Andrews, and also at the University of Cape Town. Particular attention was paid to the petrology, mineralogy and chemistry of the intrusives. A description of the techniques applied is given.

Acknowledgments.

The writer wishes to extend his sincere appreciation to Professor F. Walker for his stimulating interest and encouragement in this work. The field work was carried out under the generous auspices of the Geological Survey Department in Bechuanaland, and thanks are especially due to the Director, Mr. C. Boocock. Without the excellent photography of Mr. R. Johnston and thin-section preparations of Mr. C. Methven, this research would have been greatly hampered. Finally, the author would like to thank all those who, in numerous ways have helped to contribute to this, - both at the Universities of St. Andrews and Cape Town, and in the Geological Survey of Bechuanaland.

2. Field Characters.

A. Physiography.

The Shoshong-Makware area forms an extensive flat pediment, broken only by granite kopjes and steep mesa-like dolerite ranges (Plates 7). These ranges, which are equivalent to the Theebus and Tafelberg forms of the Karroo (Walker and Bolderwaard 1949), do not exceed 400 ft. in height above the surrounding pediment.

Post-consolidation faulting has had noteworthy effects on both the physiography and drainage pattern of the area. This is especially evident in the Makware hills, where a large north-south normal and smaller east-west fault now form the picturesque Kuchwe gorge (Plate 8). Similarly, in the western Shoshong hills the prominent gorge

SYSTEM	SEDIMENTS	INTRUSIONS	AGE
Recent	Alluvium		Pleistocene
Kalahari	Chalcedonic siltstones		Tertiary - Mesozoic
Karoo	Ferruginous arkoses & felspathic shales		Permian

U N C O N F O R M I T Y

Dyke Microgranitic
suits Basic

R E G I O N A L D I A S T R O P H I S M

Loskop- Waterberg	Quartzites, shales & conglomerates.	Makhware, sill Maiyabane, Mapaija, & Takane sheets.	
	UNCONFORMITY		
Transvaal	Shales and siltstones. Quartzites. Arkose group.	Shoshong sill { Unit 2 { Unit 1	Pre-Cambrian

U N C O N F O R M I T Y.

Basement Complex	Amphibolites	Mahalapye granite pluton.	
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TABLE 1.

containing the main Kalamare-Shoshong motor track over its origin to a large normal fault striking $N 15^{\circ} E$.

B. General Geology

The greater part of this area consists of a Pre-Cambrian (Mahalapye) granite pluton, which, in the western, northern, and north-western margins, is unconformably overlain by a thin cover of Pre-Cambrian to Permian sediments. During and after the main Bushveld magmatic cycle, these were injected by a series of sills and dykes, ranging from dolerites to microgranites in composition, (Plate 1), and Table 1.

The Mahalapye Granite.

The Mahalapye granite is part of an extensive pluton, which extends from the Makware hills in the north to just a few miles south of Shoshong. It contains numerous migmatites, garnetiferous schist xenoliths, amphibolites, and permeation gneisses, in all stages of granitisation. Its roof zone is characteristically foliated (Plates 9 & 10) and dips at 10° to 40° in a westerly direction, - though angles of up to 85° were measured in the more folded regions of Kalamare.

It is suggested by Green (1950) that the amphibolite xenoliths which are composed almost entirely of actinolite, may be remnants of the Transvaal Ultrabasic Belt caught up and recrystallized in the younger granite.

The normal Mahalapye granite is a coarse equigranular rock with stumpy crystals of greenish-grey oligoclase and pink perthitic orthoclase, - and in this, Foiderveart (1951) claims it is very similar to the Marico River and Nutton Kop granites.

The Shoshong Series.

Resting unconformably on the Mahalapye granite platform is a thick, but variable, succession of Transvaal

or Pre-Cambrian sediments. Sometimes their lowest members are coarse poorly-bedded arkosic rocks, which probably belong to the Arkosic group of Cullen (1957/1958), but more often they comprise a prominent series of fine-grained white to brownish quartzites with a thin conglomeratic base of quartzite, arkosic, jaspillitic, and granitic pebbles. These in turn, are overlain by grey flaggy shales, siltstones, and white current-bedded quartzites of the Upper Quartzite and Shale Group. (Cullen 1957/1958).

The Loskop - Waterberg sediments.

These sediments are all included in an "Undifferentiated Waterberg/Loskop System" (Boocock, Personal Communication). They rest unconformably upon the Mahalapye granite and Shoshong quartzites, and consist predominantly of coarse red conglomerates and pink or white quartzites of variable grain-size, (Plate 11).

The Karroo System.

The Karroo sediments have a fairly wide areal distribution, and rest unconformably on an uneven platform of granite and Shoshong sediments. They are predominantly granitic and suggest conditions of rapid formation under torrential conditions, (Plate 12). Lithologically, they include coarse pebbly arkoses, ferruginous felspathic grits, and subordinate pink sandy shales.

The Mesozoic Sediments.

In the west, where the Karroo plateau dips gently in towards the main Kalahari basin, it is capped by thin chalcidonic silcretes which have abundant ferricrete nodules and unusual mode of weathering (Plate 13).

Passarge (1904), on fossil evidence, suggested an Eocene age for these, and later du Toit (1954) confirmed that they are at least Pre-Pleistocene.

Recent Sediments.

These deposits are by far the most abundant,

consisting predominantly of a red granitic alluvium with lesser amounts of black and red doleritic clays and river sands.

Cambrian - Devonian Igneous activity.

After the compaction and lithification of the Shoshong sediments at least five basic sills and sheets were intruded. While these are probably late Pre-Cambrian in age, the later dyke suites may be placed as post-Waterberg in time.

Regional Diastrophism.

The intrusion and solidification of these sheets was followed by a period of effective north-south compression. This resulted in a complex pattern of folding, faulting and jointing, with two main fault sets subsequently acting as feeder channels for the dyke suites.

C. Form of Intrusions.

The Shoshong sill, which intrudes the roof zone of the Mahalapye granite, is the largest of these sheets (being about 400 ft. thick), but has a characteristically uneven floor. Because of this, a series of basin-shaped depressions with intervening humps can be recognised (Plate 2), and this has affected its subsequent solidification history.

The Makhware sill, on the other hand, forms a 200 ft. thick transgressive sheet, which is roughly confined to the unconformity at the base of the Shoshong series.

Even more complex is the intrusion form of the Takane 'sill'. Poldervaart (1952) and Green (1950) believe that this comprises four different sheets, but the present author regards it as a single sheet that was broken up into three sub-units by two horizons of intruded sediments.

The Mapaija and Maiyabane sheets are of little interest, except that they may formerly have been inter-connected with the Takane sheet.

D. Field variation in Sheets.

Zonal differentiation or distribution of rock types in individual sheets.

The Shoshong sill is a multiple intrusion, which was formed by two successive influxes of magma. It is differentiated (having a high proportion of orthopyroxene phenocrysts near its base), and because of this, four distinct petrographic zones can be recognised (Plate 2).

The Makhware sill is less spectacular in having only a lower section of dark-grey diorite, and an overlying zone of pink granophyric diorite or 'Red Rock', - although this sometimes is capped by a thin zone of red hornblende-granophyre.

In the Takane sill, the complete section comprises a basal zone of dark quartz dolerite overlain by quartz-diorites which become progressively lighter and more acid with height until normal granitic-looking rocks predominate (Fig. 38). An equivalent, though less perfect succession was observed in the Mepaija intrusion, but no variation was observed in the Maiyabane sheet.

Rhythmic Layering and Flow Structures.

Rhythmic layering, or 'banding' parallel to the floor contact is common in the Shoshong sill, but although conspicuous on weathered surfaces (due to the differential weathering of alternate leucoeratic and ortho-pyroxene-rich bands (Plate 14), it is difficult to see in thin sections or polished specimens (Plate 15). Individual bands range from 1 to 2 inches in thickness and are completely gradational into their immediate neighbours. Such banded zones, which are confined to "basin-shaped depressions" about 160' above the Sill floor, do not themselves exceed 10 ft. in height.

No rhythmic layering was observed in the remaining intrusives but flow structures are common in certain dykes and in the upper sections of the Makhware sill (Plate 16).

In both cases, the orientated elements are dark hornblende clots which in the dykes are arranged parallel to the contacts.

The large Mahalapshwe dioritic dyke nine miles north-west of Mahalapye shows a well-developed flow-structure of tabular plagioclases in the 4 ft. thick marginal zones, but this arrangement becomes progressively less perfect towards the centre.

Pegmatitic Segregations.

Patches and schlieren of dolerite-pegmatite are common in the upper levels of these sills (Plate 17).

In the Makhware sill they are few in number and confined to the transitional zone between the basal diorite and the upper Red Rock.

In a few unusual instances dolerite-pegmatite is also found in basal chilled phases, and as at Alewyn's Cat Walker and Peldervaart (1940) it is especially common in the vicinity of transfused xenoliths.

Veining.

Late-stage veins are abundant in the Sheshong sill and vary considerably in shape and size. The micro-granites and albite-splites, which are the earliest of these, are the more ramifying and may be up to two feet in width, while the later prehnite and amphibole-bearing types are confined to joint planes with a maximum width of only two inches, (Plates 18 & 19).

In the remaining intrusives, veins are smaller and more scarce, although petrologically, they are often similar to those of Sheshong.

Xenoliths.

Due to the extreme reactivity of these magmas few large xenoliths have been preserved. In the Makhware sill for example, xenoliths are often indistinguishable, and seldom exceed three inches in diameter. Two varieties

are recognised: the first a uniform light-pink micropegmatitic form with small hypersthene crystals, and the second, a composite type with dark cores of hornblende and clinozoisite etc. surrounded by pink micropegmatitic margins of variable thickness. One large granite xenolith however, occurs 2 miles north-west of Kuchwe, this being about 20 ft. long and in all stages of comminution and replacement by a hypersthene-hornblende-granophyre.

Another xenolith occurs at Dtsokwan, but this has now been almost entirely replaced by a hornblende-granophyre.

In the Shoshong sill two large granite xenoliths were observed. The smaller of these is $1\frac{1}{2}$ ft. long, and occurs in the chilled roof phase $1\frac{1}{2}$ miles east of Mosulutsane. Like the Makhware xenolith, it also shows varying degrees of invasion and replacement by pyroxene-hornblende-granophyre (Fig. 30).

The second is less spectacular due to its almost complete resorption in the enclosing dolerite-pegmatite.

Finally, in the Takane sill both Green and Polder: vaart (1950 & 1951) have recorded a 'dolerite mixed breccia' composed of fragmentary quartzites and flagstones embedded in a doleritic matrix. No such exposures were observed by the present author, but in several localities "intrusion breccias" were observed at the immediate contact of the sill. These consist of siltstone fragments embedded in a lighter syntectonic matrix (Plates 2 & 49). Besides, the chilled phases contain numerous small siltstone xenoliths up to $\frac{1}{2}$ inch long, and these have now been transfused into hypersthene-bearing micropegmatitic hornfelses, (Plate 22).

Metamorphism.

In these intrusives contact metamorphism was slight compared with their active metasomatic effects.

Being the largest intrusion and with the highest initial temperature on emplacement, the Shoshong dolerite caused the most extensive metamorphism of the granite country rock by producing a 10 ft. thick zone of granophyric granite above the roof contact and a 15 to 20 ft. zone of coarse red non-granophyric granite below the floor. Similar, though less conspicuous effects were also observed in the granite intruded by the Makhware sill. Contact metamorphism of the ferruginous Waterberg quartzites at the base of this sill, has however, produced a 10 ft. thick zone of dense hard black magnetite quartzite, which is best exposed on Kuchwe hill (Plate 21).

In the Takane sill, only low grade contact metamorphism is encountered so that the Shoshong shales are locally transformed into a fine-grained quartz-biotite-albite-hornfels with small lenticular segregations of these same minerals along former bedding planes.

Jointing and weathering.

Jointing is comparable with most hypabyssals, which have suffered little or no subsequent deformation although horizontal division planes are also common, these having initiated the peculiar terrace or 'trap' features on the southern slopes of the Shoshong range just east of the village. (fig. 1).

FIG.1. TRAP-STRUCTURE IN THE SHOSHONG
DOLERITE SILL.



In the remaining intrusives joints are more widely spaced and weathering correspondingly more pronounced, so that outcrops are generally poor and inconspicuous (Plate 3).

In the Shoshong sill there is a tendency for the dolerite-capped hills to weather more rapidly in the middle than on the margins, so that a marginal bastion of loose boulders often surrounds a basin of black soil or 'Mukutwane'.

D. Relationships of the Shoshong-Makhware intrusives.

The above sheets share several features which suggest that they were derived from the same tholeiitic magma. It seems most probable therefore, that the Shoshong sill having the highest initial temperature was the first to be intruded, and that it was later followed by the Mapaija, Maiyabane, Takane, and Makhware sills in that order. The dyke suites however, were emplaced during a later Post-Waterberg cycle as shown in Table 1.

Petrologically the rocks comprising these basic intrusives form a tholeiitic series, which is characterised by the presence of quartz and/or orthopyroxene and showing a fair degree of iron enrichment (Fig. 26&35). In mineral composition, they range from hypersthene-dolerites with very little olivine to acid quartz-hornblende-diorites and even adamellites. Of these the Shoshong sill is the most basic and uniform in composition, being almost entirely composed of hypersthene-dolerite with minor acid differentiates. The four remaining sheets - Makhware, Takane, Maijabane, and Mapaija - contain a wider range of rock types and the chilled margins are characteristically porphyritic.

The basic members of the dyke suites are quite distinct from the sheets in that they are more gabbroic in texture and often show a fair degree of hydrothermal alteration.

MINERALOGY.A. General Statement.

The mineralogy of the Shoshong-Makware intrusives is simple, the chief constituents being plagioclase, pyroxene, micropegmatite, and accessory apatite, magnetite, hornblende, olivine, and clinzoisite.

B. Methods.

All refractive indices were determined by immersion using sodium light and with an accuracy ± 0.002 .

Optic axial and extinction angles were measured with a four axis universal stage, and where more accurate determinations of the former were required, the poles of optic axes were re-checked by the method of Turner (1940). Greater accuracy in the determination of extinction angles was obtained by the method of Kemoto (1938) as modified by Turner (1942). The probable accuracy of these angles is $\pm 1^\circ$.

Measurements of crystal dimensions were made with a Weston micrometer or a Doller Integrating stage, while microscopic data were obtained by a Swift Point counter.

Sieved crushes of all rocks discussed were optically examined, and the molecular compositions of the constituent minerals determined by one or two optical constants - optic axial angle and/or refractive indices -.

All plagioclases were determined by one of three methods, although method 2 was used only in cases where results were unobtainable by 1 and 3:

- (1) Refractive index values n^1 and n^2 on (001) and (010) cleavage fragments.
- (2) Carlbad - Albite extinction angles.
- (3) The Federov-Nikitin method for the wandering of the poles of faces with fixed optical vectors.

C. Plagioclase.

As in all the basic intrusives of the area, plagioclase is the most abundant component by volume. Individual

crystals are commonly twinned on the albite and carlsbad laws, while Baveno and Pericline twinning are common only in the Shoshong Sill.

Micrometric data.

Although the individual lengths of crystals vary considerably in each igneous body, the ranges are comparable for most intrusives except the basic dyke suite (Table 6).

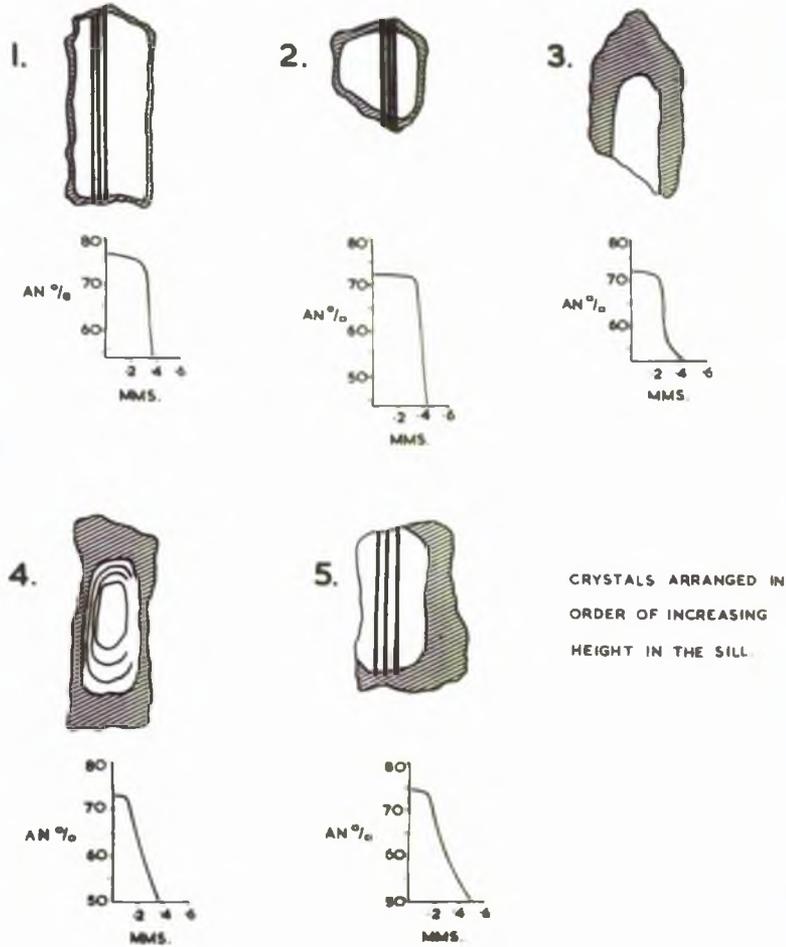
TABLE 6.

<u>Makhware Sill</u>	<u>Shoshong Sill</u>	<u>Takane Sill</u>
Quartz Monzonite	Upper pegmatitic	Quartz-hornblende
0.95 mm.	dolerite 3.01 mm.	diorite 1.64 mm
'Red Rock'	Downes Mountain	
0.94 mm.	type 0.73 mm.	Quartz-diorite 1.20-1.25 mm
Basal Diorite	Hypersthene-phyric	Chilled dolerite
0.61 mm.	dolerite 0.61 mm.	0.50 mm
		Metasomatised siltstone 0.37 mm
<u>Mapaija sheet</u>	<u>Malyabane sheet</u>	<u>Basic Dyke suite</u>
Pegmatitic Dolerite	Quartz-dolerite	
3.00 mm.	1.01 mm.	Major diorite dyke 1.51 mm
Quartz-dolerite		Quartz-diorite 2.70 mm
0.78 mm.		

Zoning.

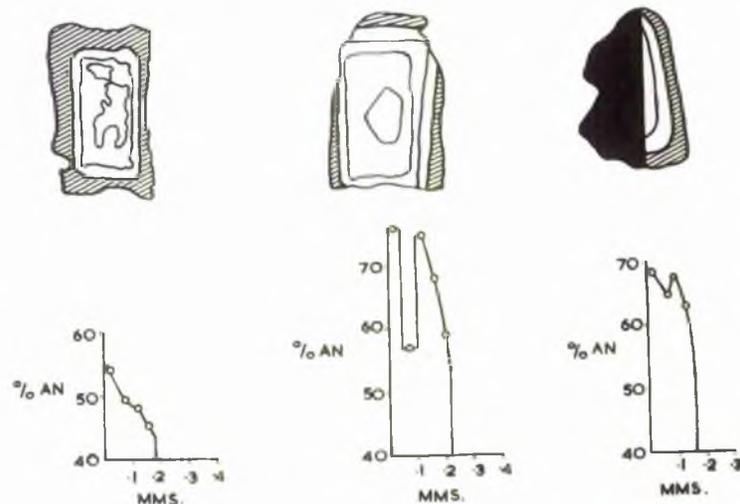
Although a common feature in most basic rocks of this area, this is restricted to oscillatory and progressive zoning with resorption and repair. Examples of this are most spectacular among the bytownite phenocrysts of the Makhware basal diorite (fig. 2) which become progressively more zoned with increasing height in the sill.

FIG. 2. ZONED PLAGIOCLASE PHENOCRYSTS
IN THE MAKHWARE BASAL DIORITE.



In the Shoshong sill examples of large complex zoned phenocrysts are poorly represented. Three of these together with their corresponding compositional variations are illustrated in fig. 3.

FIG. 3. ZONED PLAGIOCLASES
IN THE SHOSHONG SILL.



Composition.

Plagioclase shows a steady increase in the albite molecule with increasing height in the sill - especially in the Makhware and Takane sheets (figs. 4, 5,), but the Shoshong sill shows only a small total variation (fig. 11). The basic dyke suites are similar to the former two in that they range from An 28 to An 63 (Table 30).

High and Low Temperature Forms.

The relationship discussed by Muir (1955, p. 562) for several well-known dolerites, between the temperature state of plagioclases and the subsolidus condition of the associated pyroxenes, has proved to be closely similar to the situation encountered in the Shoshong sill. The main difference is that, whereas in the former the pigeonite - orthopyroxene inversion narrowly precedes the high-low plagioclase inversion, this interval is greater in the

COMPOSITION OF PLAGIOCLASES AT TSHUHUNG.

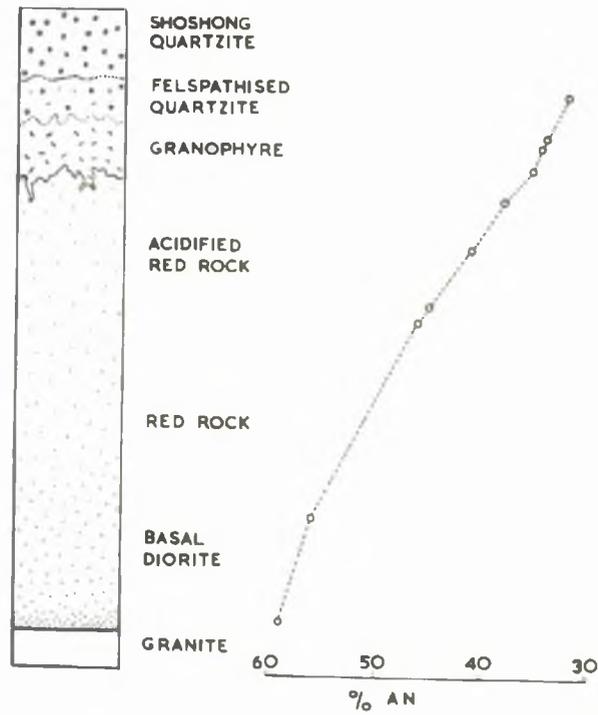


FIG. 5

COMPARATIVE COMPOSITION OF PLAGIOCLASES IN THE MAKHWARE BASAL DIORITE.

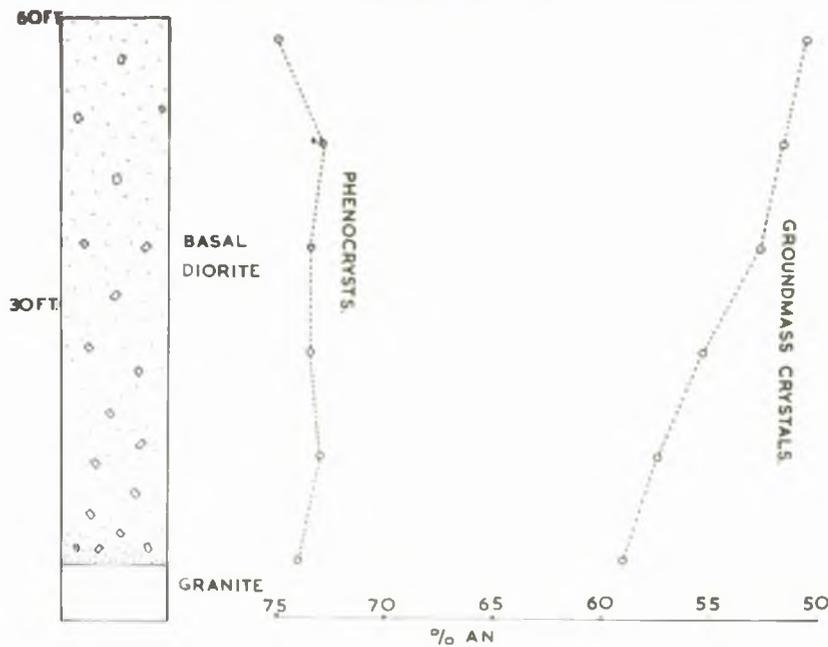
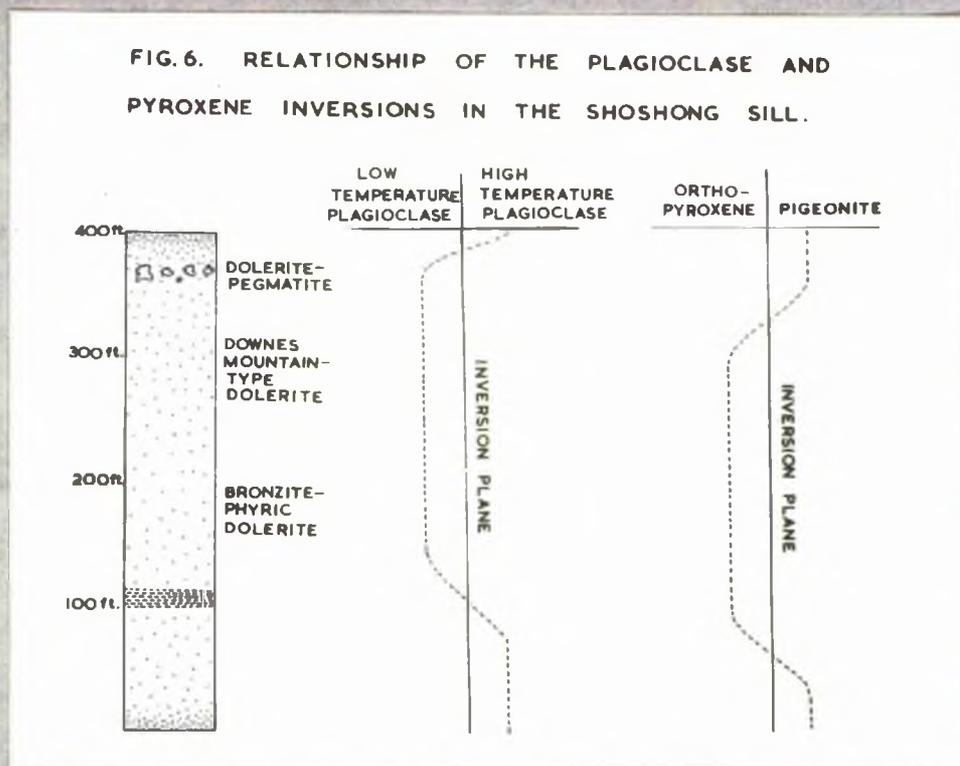


FIG. 4.

Shoshong sill (fig. 6). A more detailed discussion of this, follows in the Appendix.



D. Pyroxene.

Three varieties of pyroxene occur in these intrusives - orthopyroxene, pigeonite, and augite -. Of these, augite is the most abundant, while pigeonite and orthopyroxene are common constituents in the Shoshong sill. They are less abundant in the remaining intrusives and pigeonite is completely absent from the main basic dyke suite. In the Kalamare gabbro dyke, orthopyroxenes were originally present, but have been almost completely pseudomorphed by a brownish-green serpentine. Large brownish augite crystals predominate in all the less altered basic Mahalapye dykes.

Orthopyroxene.

Distribution.

With the sole exception of the Shoshong dolerite, orthopyroxene crystallized as an early constituent and is now confined mainly to the lower horizons of each sill. In the Shoshong sill, however, secondary or inverted orthopyroxene tends to become more abundant with height.

Besides this, in the vicinity of transfused xenoliths, a few small, late pleochroic ferrohypersthene (En 50 Fs 50) can sometimes be distinguished.

Micrometric data.

In table 7, the variations in length of individual crystals are summarised:-

<u>Shoshong Sill</u>	<u>Table 7.</u>
Phenocrysts in Hypersthene-phyric dolerite	2.6 - 3.0 mm.
<u>Makware sill</u>	
Phenocrysts in chilled basal diorite	0.50 - 0.73 mm.
" " normal " "	0.73 - 1.10 mm.
<u>Mapaija sill</u>	
Phenocrysts in chilled diorite	0.80 - 1.97 mm.
<u>Takane sill</u>	
Phenocrysts in chilled dolerite	0.69 - 0.80 mm.
Crystals in normal quartz-dolerite	1.50 - 2.10 mm.

Despite a general overlap, these values indicate a closer relationship between the last three intrusives than between them and the Shoshong intrusion. This fact is supported by other petrological evidence, as shown later.

Composition.

The compositions of orthopyroxenes in these intrusives are remarkably similar (Table 8).

<u>Shoshong sill</u>	<u>Makware sill</u>	<u>Takane sill</u>	<u>Mapaija sill</u>	<u>Kalamane Dyke</u>
Hypersthene-phyric dolerite	Basal diorite	Chilled dolerite	Quartz-dolerite	Gabbro
Fs 21 - 42.	Fs 20 - 26	Fs 22	Fs 22	Fs 20
Altered host rock beside vein	Pyroxene in xenolith			
Fs 43	Fs 50			

The unusually wide compositional variation of orthopyroxenes in the Shoshong dolerite is due largely to the

ubiquitous zoning of phenocrysts, (Fig. 49) but in spite of this orthopyroxenes show a steady increase in ferrosilite with height (fig. 11).

Exsolution.

As this phenomenon has been the subject of a closer investigation in the Shoshong dolerite, the following account forms only a general summary of its more striking microscopic characters. (See appendix for further discussion).

There are two important forms of exsolution in these orthopyroxenes; - The first of these, which comprises the exsolution of augite lamellae parallel to (001) and (100) in the host mineral, may be equated with the "graphic intergrowth" described by Walker (1940, p. 1073), (Plates 58 & 59). The second, - though less common -, consists of a peculiar mottled extinction observed in the cores of larger phenocrysts, (Plate 61). An identical feature was described in the Hanover dolerite as exsolution of hypersthene-augite on a submicroscopic scale. (Foldervaart, 1947, p. 167).

Both the above exsolution variants are common in the Shoshong sill, - especially the "graphic intergrowth". This is generally marginal, but in more ferriferous orthopyroxenes may be complete (Plate 59), whereas in twinned inverted pigeonites exsolution parallel to (001) produces a typical herringbone structure, which is common in the upper two thirds of the Shoshong sill, (Plate 27). The width of these lamellae varies between 0.02 and 0.04 mm.

Although less spectacular in appearance, both forms of exsolution occur in the Takane quartz-dolerite. Graphic intergrowth is marginal, but with a dearth of later (100) lamellae, while (001) lamellae are rather poor and irregular.

Finally, orthopyroxenes in the chilled selvages of the Takane, Kapaija and Makhware sills are generally exsolved, throughout, but the lamellae are extremely fine.

Optical Properties.

Optical properties of representative crystals from

each sill are given in Table 9.

Table 9.

		Shoshong sill	Makhware sill	Takane sill	Mapaija sill
		Hypersthene- dolerite	Basal diorite	Quartz dol- erite	Quartz-dol erite
Refractive Indices	α	1.677	1.678	1.681	1.685
	β	1.685	1.685	1.687	1.692
	γ	1.688	1.692	1.693	1.698
2V		77°	67°	70°	71°
$\alpha \wedge z$		Up to 10°			
Sign		Negative	Negative	Negative	Negative
Pleochroism	X	Pink		Pinkish	
	Y	Light pink	Slight	Light pink	slight
	Z	Greenish		Colourless to greenish	

Pigeonite.

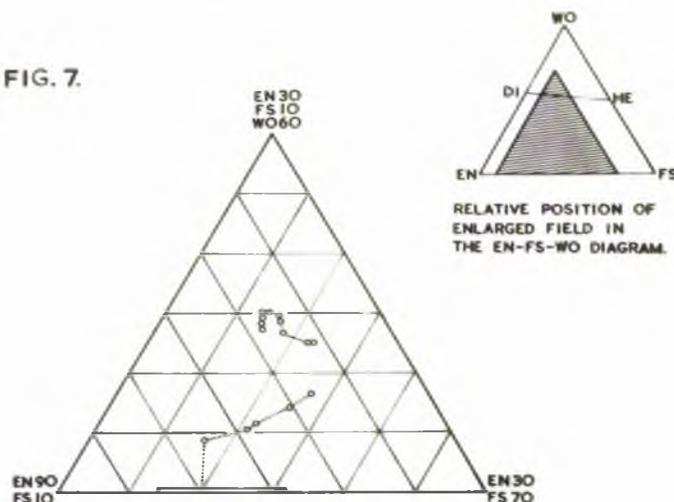
Pigeonite is the least common pyroxene of these intrusives, yet it occurs as two distinct varieties, - one with the optic plane perpendicular to (010) and the other with this plane parallel to (010). The first of these are often found as resorbed cores to larger augite crystals or else as thin margins to orthopyroxene phenocrysts, while the second, or 'Late' variety, forms twinned prismatic crystals with a characteristic basal parting and resulting 'herring-bone structure'.

All stages of the pigeonite-orthopyroxene inversion are represented in the Shoshong sill, but in the Basal Diorite of the Makhware sill, pigeonite is rare, although more common in the overlying Red Rock, where it often forms resorbed cores to larger augite crystals.

The compositional trend of pigeonite in the Shoshong sill shows a steady increase in iron with height. (Fig. 7).

CRYSTALLIZATION TREND OF PYROXENES IN
THE SHOSHONG SILL.

FIG. 7.



Their optical properties are listed in Table 10.

Table 10.

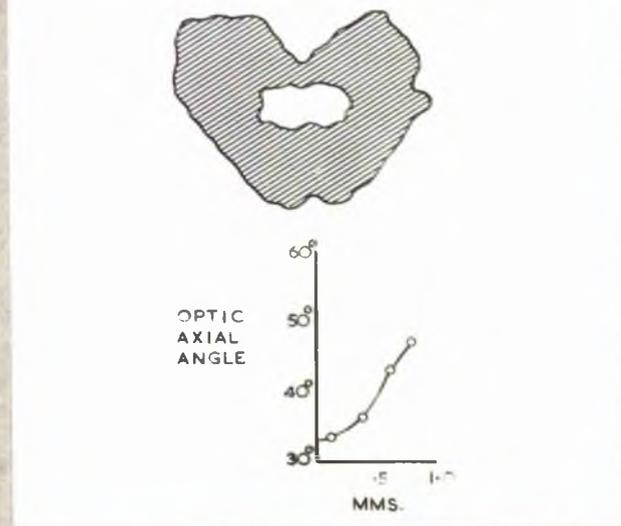
	Shoshong sill Hypersthene - phyric dolerite	Takane sill Quartz-dol- erite.	Makhware sill 'Red Rock'
Refractive	1.683	1.688	1.683
Indices	1.685	1.689	1.688
2V	15°	5°	9°
Optic Sign	Positive	Positive	Positive
Extinction			
c Z	47°		
Orientation of Optic Plane	Perpendicular (010)	Perpendicular (010)	Perpendicular (010)

Augite.

Being the earliest and most abundant pyroxene of these intrusives augite shows little variation in form or in its relations towards other constituents. Typically it forms colourless to light brown subhedral prismatic crystals, simply twinned on (100), and with a subophitic relationship towards plagioclase. In the more micropegmatitic rocks, augite crystals are more elongated and better formed.

Marginal zoning is commonly encountered, - particularly in the Makhware and Takane sills (fig. 8) -, and sahlite striations are frequently seen.

FIG. 8. COMPOSITIONAL VARIATION
OF A ZONED AUGITE CRYSTAL IN
MAKHWARE RED ROCK.



The alteration of augite by uralitisation is a widespread phenomenon.

In the gabbroic Mahalapye dyke suite they are large purplish brown non-ophitic and unzoned, but as in the basic sheets show some sahlite striations, while in one specimen small blebs of coarsened (hypersthene ?) were found.

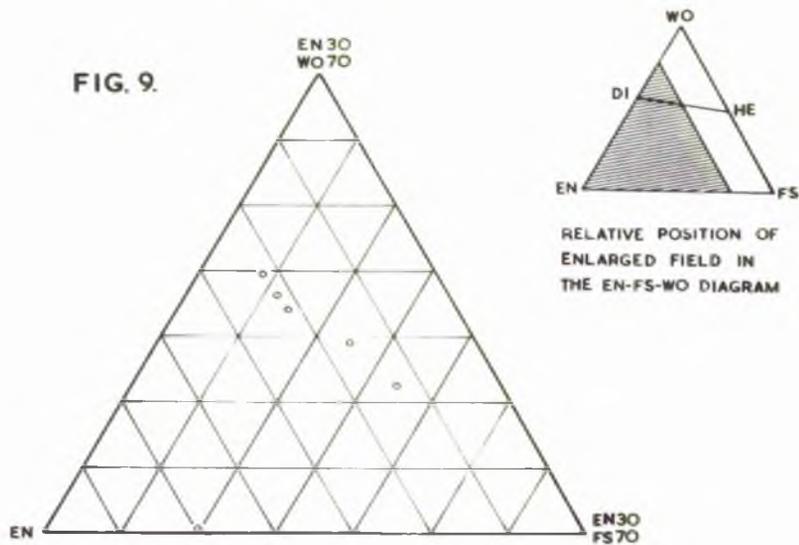
Composition.

Despite its uniform appearance, augite shows some significant variations in composition. (Figs. 7, 9 & 10). In the gabbroic dyke suite, it appears to be more diopside-rich than in the corresponding sheets, while in the Takane and Makhware intrusions, it is richer in ferrosilite than in the Shoshong dolerite.

The compositional trend of augite in the Shoshong sill differs from most differentiated tholeiitic provinces, for from the lower chilled margin it increases rapidly in wollastonite up to a peak at the base of the second intrusive phase, before eventually following the normal trend of iron-enrichment (Fig. 7).

The optical properties of representative augites are shown in the accompanying Table 11.

COMPOSITIONAL VARIATION OF PYROXENES
IN THE BASIC DYKE SUITE.



COMPOSITIONAL VARIATION OF PYROXENES
IN THE MAKHWARE SILL.

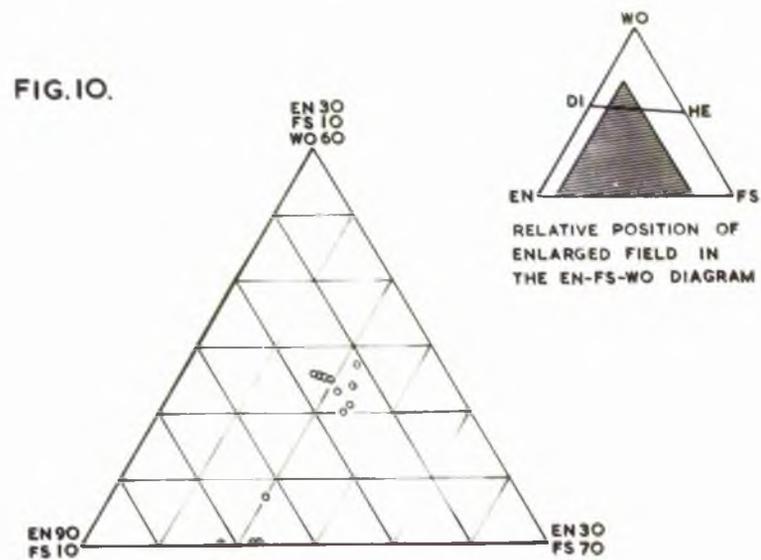


TABLE 11.

	Shoshong Sill	Makhware Sill	Takane Sill	Basic Dyke Suite
	Hypersthene-dolerite	Basal Diorite	Quartz-dolerite	Kalamare Gabbro
Refractive Indices	α 1.687	1.689	1.698	1.693
	β 1.694	1.699	1.699	1.704
	γ 1.712	1.714	1.722	1.723
2V	49°	40°	42°	39°
Optic sign	Positive	Positive	Positive	Positive
Extinction $c \wedge z$	50°			47°

E. Amphibole.

Three main types of amphibole can be distinguished in these intrusives: -

1. Primary hornblende, a direct crystallization product of the residual magma.
2. Uralite hornblende, a replacement product after pyroxenes through hydrothermal alteration.
3. Reaction hornblende, a common constituent of metasomatic granophyres, diorites, granites, and also of transfused granite xenoliths.

(Minor variants of these also exist, as discussed below)

In Table 12 the optical properties and corresponding atomic compositions are compared. The former, which were obtained by reference to Tröger's graph (1956, p. 77), are significant - each variety having a limited compositional range, which is dependant on its own particular mode of origin. Iron-rich "reaction hornblende", for example, was formed during the metasomatism of acid country rocks by iron-rich residual magmas (p. 39-40), while "Uralite hornblende", being richer in magnesium, - was produced by hydrothermal leaching of $FeSiO_3$ from the original pyroxenes.

Although "uralite" hornblende is a direct alteration

TABLE 12.

	PRIMARY HORNBLENDE	URALITE HORNBLENDE	'REACTION' HORNBLENDE			
Shoshong Sill., Dolerite - Pegmatite,	Shoshong Sill., Horn of granulophyre vein.	Takama Sill., Quartz-hornblende diorite.	Makhsara Sill., Hornblende Granulophyre.	Shoshong Sill., Monulutsans xenolith.	Shoshong Sill., Minsaphaleng xenolith.	
α	1.636	1.670	1.673	1.661	1.663	
β	1.646	1.681	1.681	1.688	1.677	
γ	1.652	1.690	1.690	1.697	1.689	
2V	72°	67°	61°	17°	66°	
Sign	Negative	Negative	Negative	Negative	Negative	
Extinction	21.4°	20.6°	13°	15°	16°	
Light Brown	Pale yellow-green	Brown	Yellow green	Yellow to khaki	Khaki	
Brown-green	Light green	Brown-green	Green	Light-green brown	Light brown-green	
Formula	Dark brown-green	Bluish green	Dark green	Dark green	Dark brownish green	
Form	Small interstitial sub-to euhedral crystals	Medium-sized prismatic crystals with ragged terminations	Elongated porphyroblastic prisms but occasionally peltitoblast-like.	Large porphyroblastic crystals as in the Takama diorite	Aggregates of small stumpy prisms forming rims to quartz xenocrysts.	
Atomic Composition	Mg ₆₀ Fe ⁺⁺ Ti Mn ₄₀	Mg ₈₀ Fe ⁺⁺ Ti Mn ₂₀	Mg ₄₀ Fe ⁺⁺ Ti Mn ₆₀	Mg ₅₇ Fe ⁺⁺ Ti Mn ₆₃	Mg ₄₈ Fe ⁺⁺ Ti Mn ₅₂	
					Mg ₄₅ Fe ⁺⁺ Ti Mn ₅₇	

product of clinopyroxenes, an intermediate step occurs in the uralitisation process of orthopyroxenes. This is well shown in the Takane dolerite, where orthopyroxene first becomes marginally replaced by a multiple-twinned cummingtonitic amphibole, and then changes to a light-green uralite hornblende bespeckled with numerous tiny magnetite grains.

Iwao (1937), who records similar features in some basic xenoliths, suggests that there is a chemical and structural relationship between these, so that the sequence: hypersthene - cummingtonitic amphibole - common hornblende is probably a replacement-reaction series.

Finally, in the Shoshong dolerite-pegmatite a few small green-blue arfvedsonitic amphibole crystals sometimes occur - individually or as radiating clusters in graphic intergrowth with quartz.

F. Micropegmatite.

The nature and proportion of this constituent depends primarily on the mineral association and relative position of the host rock in the sill. In the basal sections of the Makhware, Takane, and Mapaija sheets, it forms a fine white intergrowth which becomes coarser and more abundant with height, the feldspar becoming pinkish in hue. In the Shoshong sill it is more uniform, although coarse patches do occur in dolerite-pegmatites.

The composition of the orthoclase member varies between $Or_{59}AbAn_{41}$ and $Or_{64}AbAn_{36}$, and is the same as that in the transfused granite xenoliths and granophyric roof granites.

G. Biotite.

A common accessory of these intrusives, biotite includes both golden-brown and green varieties, although the former is by far the most common. It is more abundant in the upper levels of sills and is often poikilitic. Throughout it displays a marked reaction relationship towards early magnetite, - especially in the magnetite-rich chilled selvages of the

Makhware, Mapaija, and Takane sills, where small magnetite grains are enclosed by larger flakes of biotite.

H. Accessories
Magnetite.

This constituent, which is mostly of late formation, forms crystals of various shapes and sizes, - early crystals being small well-formed octahedrons as in the chilled selvages of the Takane, Makhware, and Mapaija sheets, while late magnetite crystals are larger and more skeletal in form. The latter variety, which is most common in the basic dyke suite and in the upper levels of these sheets, are often intergrown with ilmenite on a microscopic scale.

Olivine.

A rare constituent, olivine occurs only in the Shoshong and Takane sills and in one dolerite dyke. It is almost completely pseudomorphed by blue or yellow-green serpentine, which is bespeckled with a fine magnetite dust. Crystals are typically resorbed and enclosed by larger orthopyroxene phenocrysts.

The optic axial angles and corresponding compositions of the only three crystals, which were measurable, are compared in Table 13.

TABLE 13.

	<u>2V</u>	<u>Optic Sign.</u>	<u>Mol. Composition.</u>
Sekgwaape dolerite dyke	80°	Negative	Fe ₆₀ Fe ₄₀
Bronzite-phyric dolerite (Shoshong sill)	72°	Negative	Fe ₅₀ Fe ₅₀
Takane Quartz-dolerite	66°	Negative	Fe ₃₈ Fe ₆₂

Clinzoisite.

A late constituent, this is almost entirely restricted to metasomatic and hydrothermally altered rocks, as in the upper levels of the Makhware and Takane sheets and in the immediate vicinity of late acid veins in the Shoshong sill.

Crystals are generally prismatic and sub- to euhedral in form.

Apatite.

Apatite is an ubiquitous accessory forming long needles which are confined almost exclusively to the interstitial micropegmatite. It is most common in the Shoshong dolerite.

Prehnite.

Clearly a late hydrothermal mineral, this is confined almost entirely to these veins. Crystals are prismatic and commonly arranged in a stellate or 'bow-tie' structure. The optic axial angle is 69° with a positive sign, and the δ - refractive index 1.637.

Ilmenite.

Although this mineral is often intergrown with magnetite, it also forms individual crystals, as in the Shoshong sill.

Pyrite.

A common accessory found chiefly in the more acid diorites and late sodic veins, pyrite is seldom observed in the Shoshong dolerite, although it is quite common in the Takane sill.

Zircon.

Although usually enclosed by larger biotite crystals large zircons also occur in the orthoclase crystals of most acid quartz-hornblende-diorites at Takane.

Epidote.

Its distribution is almost identical with that of clinozoisite. Crystals are less perfect prismatic in form, but commonly form clusters of small grains in the most acid rocks, such as the Wakhware granophyres.

Sphene.

Found only in the most acid rocks, such as the acid quartz-diorites, granophyres, and late quartz-albite veins, sphene shows good crystal form, although crystals are generally

small in size.

Chlorite.

Secondary chlorite has poor crystal form and occurs as pseudomorphs of early ferromagnesian minerals. In two cases - the metasomatised siltstones and quartzites of the Takane and Makhware sills - chlorite is primary in origin, although its crystal form is poor.

Howlingite.

This constituent is a common alteration product after both pigeonite and orthopyroxene. Typically, it forms radiating clusters of bright red-brown fibres, but, occasionally, larger crystals may be discernible.

Glass.

A little interstitial glass may sometimes be observed in the chilled Basal Diorite of the Makhware sill. Although much of it is now altered to a birefringent palagonite, - when fresh, it is typically dark-brown in colour with a refractive index of 1.553.

4.

CHEMICAL DATA.

A total of six complete analyses were made of the basic intrusives of the area, two being from the Shoshong sill, three from the Makhware sill, and one of a gabbro dyke. These were supplemented by a total of 42 partial analyses involving the determination of FeO by the Pratt method, and alkalis using a flame photometer. In the comparatively fresh rocks of the Shoshong sill, use was made of the method described by Walker (1953) for the calculation of approximate chemical compositions for basic rocks of known mineral compositions. The results obtained for analysed rocks are favourable, although both Fe_2O_3 and alkalis tend to be low. In the former case, however, Walker (personal communication) has suggested that this may be due to the slight oxidation of iron within the crystal lattices of ferromagnesian minerals.

5.

THE SHOSHONG SILL.A. PETROGRAPHY.

The Shoshong sill is subdivided into four main petrographic zones, - chiefly on the basis of its orthopyroxene content.

Chilled Modifications.

Tachylitic chilled selvages are rare, but usually they are variolitic with abundant magnetite granules and only a few small zoned bytownite phenocrysts (An84). The latter become larger and more zoned, and the texture correspondingly more intergranular, with increasing distance from the contact. The most typical chilled selvage, therefore, is a basaltic rock with subophitic pigeonite, bronzite, and augite, and occasional glomerporphyritic clumps of labradorite. Bronzite-phyric dolerite (Hangnest type).

Being essentially a coarse-grained dark rock with the same mineral components as the above, this is conspicuous in its large rectangular orthopyroxene phenocrysts, which have often exsolved large plates of augite, and are occasionally ophitic (with small bytownite chadacrysts (An 77)). Clinopyroxenes, although less striking, are simply twinned, elongated and sub- to non-ophitic. Plagioclase laths are more numerous, but relatively small and unzoned. Micropegmatite is interstitial. In a few sections, serpentinised olivines are enclosed with larger orthopyroxene phenocrysts, (Plate 23).

This rock-type characterises most of the first intrusion and the lower two-fifths of the second.

Mode of Bronzite-phyric dolerite from the 1st intrusive.

TABLE 3.

Plagioclase	35.4
Micropegmatite Quartz and Orthoclase	6.8
Hornblende	
Biotite	3.4

Orthopyroxene	32.8
Clinopyroxene	22.0
Magnetite	1.9

Downes Mountain-type Dolerite.

Forming a prominent zone above the bronzite-phyric dolerite of Unit 2, this is very similar to the Downes Mountain dolerite of Walker and Poldervaart (1949 p.616), in that it has significant proportions of pigeonite and secondary orthopyroxene, but little or no primary orthopyroxene. Clinopyroxene, which is prismatic and sub-ophitic, often contains partly resorbed cores of pigeonite. Plagioclase laths are larger than in the bronzite-phyric dolerite and are more strongly zoned. Interstitial micropegmatite is also more abundant, (Plate 24).

Mode of Downes Mountain Type dolerite from top of Horizon.

	<u>TABLE 4.</u>
Plagioclase	55.2
Micropegmatite	
Quartz	12.3
Orthoclase	
Orthopyroxene	9.6
Clinopyroxene	21.3
Hornblende	
Biotite	1.2
Magnetite	0.5

Dolerite - Pegmatite

Within the upper 35 ft. of the Shoshong sill coarse dolerite pegmatite segregations of various forms and dimensions are common. Among these, two distinct petrographic varieties are recognised, the one being essentially pyroxenic and the other higher in amphibole. A comparison of the modes of these is given in Table 5.

TABLE 5/

TABLE 5.

	Pyroxenic-dolerite-pegmatite	Hornblendic-dolerite-pegmatite.
	Σ	Σ
Plagioclase	46.2	24.1
Quartz	5.23	6.3
Orthoclase	4.82	13.6
Clinopyroxene	22.43	-
Amphibole & Biotite	15.33	37.4
Clinozoisite & epidote	5.72	16.6
Sphene & Magnetite	0.76	2.0

In the pyroxenic dolerite-pegmatites elongated prisms of brownish augite (2V 38°) and pigeonite (2V 24°, optic plane // (010)), zoned labradorite laths (An60), skeletal magnetite, biotite, and dark green hornblende are set in a coarse micropegmatitic matrix, but the pyroxenes do not show any apparent signs of curvature.

The hornblendic-dolerite-pegmatites, on the other hand, consist primarily of large hornblende prisms, and sericitised plagioclase laths (An 55) set in a coarse micropegmatite, while accessories include clinozoisite, sphene and serpentine. (Plate 25).

These two pegmatites which are commonly distributed in a patchy or 'microtaxitic' fashion (Tomkeleff, 1929, p. 105) within the pegmatitic horizon, have gradational contacts up to 5 mm. wide.

Acidified Dolerite.

The contamination of the Shoshong dolerite by foreign granitic material has produced a series of coarse-grained hybrid rocks, which microscopically are somewhat similar to the hornblendic-dolerite-pegmatites described above. They have a high proportion of quartz and orthoclase - usually in graphic intergrowth -, plus dark green hornblende and biotite.

These are best seen near the large xenolith NNE of Mmamphaleng hill.

Modes of typical acidified dolerites are given in table 16.

Late Stage Veins.

Late stage veining, which is particularly common in the upper levels of the sill, can be subdivided into four main groups:-

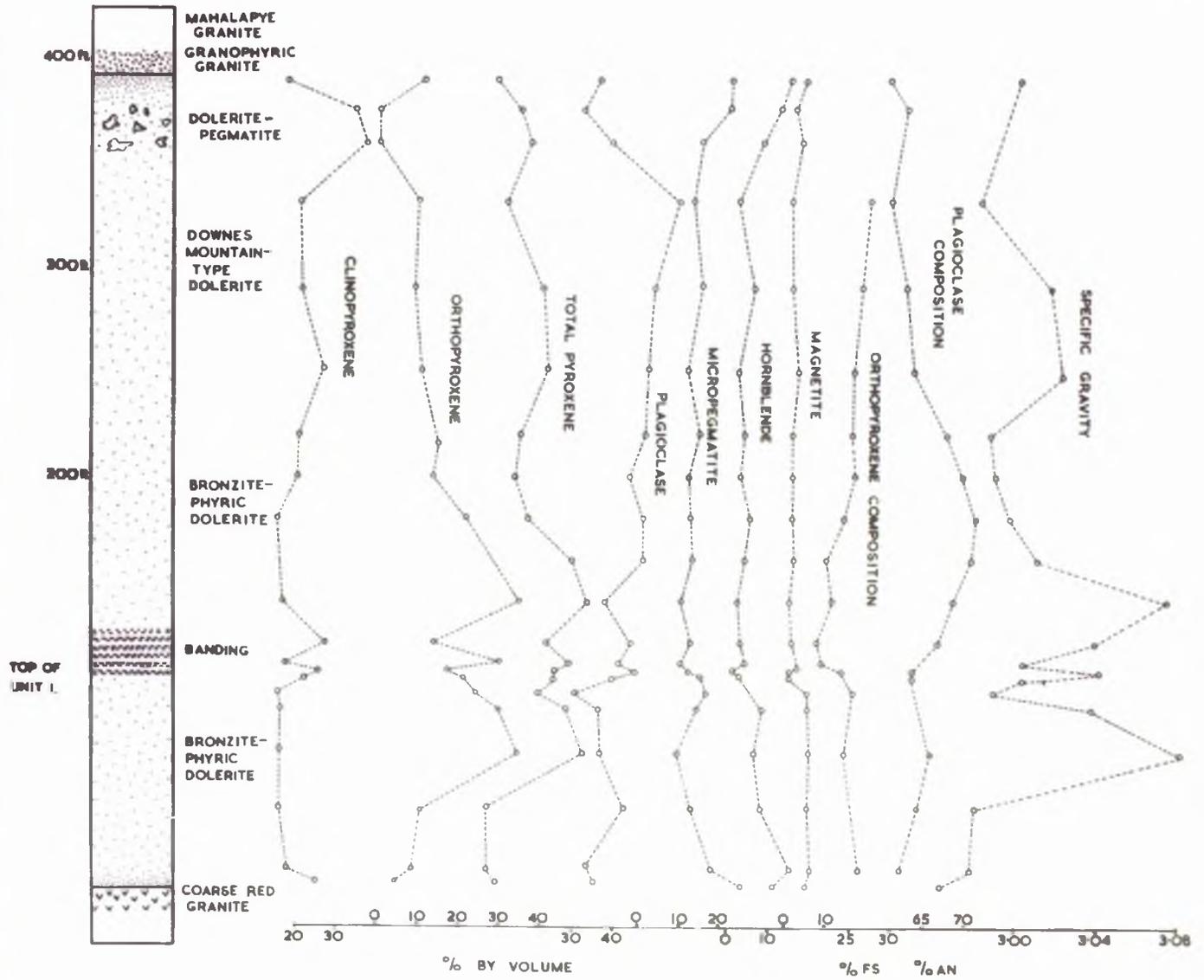
Prehnite veins. Composed essentially of prehnite, uralite-hornblende, sphene, clinozoisite, and myrmekitic intergrowths of quartz and oligoclase, these veins are 1 mm. to 4 mm. thick and follow prominent vertical joints. Their dolerite margins are hydrothermally altered, as shown in (Plate 18).

Amphibole veins. Although similar both in size and shape to the above, these veins are composed almost entirely of a light-green fibrous uralite-hornblende, which has grown perpendicular to the hydrothermally-altered dolerite walls. The remaining constituents - though scarce - are the same as in the prehnite veins.

Albite - aplite veins. The finer grained members of these, which are very similar to examples described by Shannon (1925) and Walker (1940), range from $\frac{1}{2}$ to 2 inches in width. They consist of fine myrmekitic intergrowths of quartz and albite with scattered crystals of quartz, albite, sphene, uralite-hornblende, and clinozoisite.

Near the base of the sill at two localities (Marutwe and Mmamlekeleabe hills), a coarser variety forms dykes up to 18 inches thick following prominent joint directions. Megascopically, these are coarse-grained pinkish rocks with conspicuous prisms of uralite-hornblende up to 1.2 cm. long and scattered epidotic patches. In thin section, they differ from their finer equivalents in showing coarser and more irregular myrmekitic intergrowths, while albite and orthoclase are often intergrown with uralite-hornblende. (Plate 26).

FIG. II. COMPOSITE GRAPH OF A SECTION THROUGH THE SHOSHONG SILL.



Microgranites. These are both texturally and compositionally distinct from the above albite-aplites, being essentially fine-grained microgranites, composed of quartz, pink orthoclase, albite, chlorite, and accessory magnetite, hornblende, sphene, and zoisite.

Their origin is somewhat controversial, but although a few are probably syntectonic, the majority are late hydrothermal products of the Shoshong magma.

B.

PETROLOGY,

Mineral variation from top to bottom of the sill.

As there are no complete sections through the Shoshong-sill, the accompanying diagram (fig. 11) combines three well-defined traverses, which together would represent the entire sequence. The locations of these are shown in Plates 2 & 3.

The degree and extent of mineral variation in the Shoshong sill is largely dependant on the location of the traverses examined; - yet, an additional complication also arises from the composite nature of the sill, and the existence of a thin anomalous zone with occasional chilling and shearing separating the first and second intrusions i.e. (Units 1 & 2 respectively).

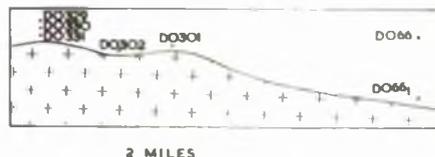
In fig. 11 the modal proportions of clinopyroxene and orthopyroxene show the greatest total variation, and behave in a complementary manner towards one another. Orthopyroxene varies from a maximum of 34% in both units, to nil in the dolerite-pegmatite horizon 360 ft. above the floor. Conversely, clinopyroxene ranges from a minimum of 16% in Unit 1 and in the first 80 ft. of Unit 2, to a maximum of 37% in the overlying dolerite-pegmatite horizon. Total pyroxene therefore shows a greater concentration in Unit 1 and in the first 80 ft. of Unit 2.

The behaviour of other constituents is less regular however. Both plagioclase and micropegmatite show a slight increase with height, - particularly the former, which increases from 36% in the hyperthene-phyric dolerite of Unit 1, to 47.5% at the top of Unit 2.

In sections overlying "basin margins" however, mineral variation is typically irregular, for sometimes acidic rocks were produced through the assimilation of granitic material (Plate 30). In figs. 12 & 13 these variations are compared diagrammatically.

Fig. 12.

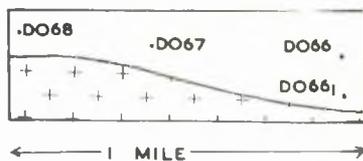
FIG.12. SECTION THROUGH THE DEKOKONG & BOBELANE HILLS.



	Do351	Do330	Do329	Do302	Do301	Do66 ₁	Do66
Plagioclase	39.8	42.1	37.4	36.5	35.2	45.6	41.5
Micropegmatite	17.4	13.3	19.4	15.3	13.6	12.7	10.1
Orthopyroxene	9.1	5.5	6.1	16.0	5.5	15.5	18.0
Clinopyroxene	23.3	25.5	30.5	28.3	34.2	23.0	26.0
Hornblende & Biotite	6.6	9.3	4.9	1.7	5.9	1.7	1.7
Magnetite	3.9	4.4	2.1	2.2	5.1	1.3	2.0

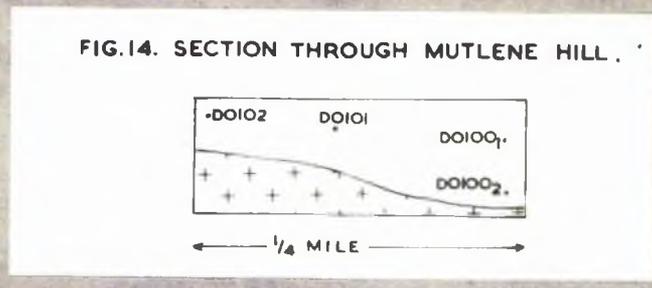
Fig. 13.

FIG.13. SECTION THROUGH BOBELANE HILL.



	Do 68	Do 67	Do 66	Do 66 ₁
Plagioclase	41.3	44.5	45.7	41.5
Micropegmatite	12.2	14.1	12.7	10.1
Orthopyroxene	2.0	13.7	15.5	18.0
Clinopyroxene	33.4	26.0	23.0	26.0
Hornblende & Biotite	9.2	2.1	1.7	1.7
Magnetite	1.8	0.5	1.3	2.0

Fig. 14.



	Dol100 ₁	Dol100 ₂	Dol101		Dol102
Plagioclase	39.5	34.0	36.4	Plagioclase	33.5
Micropegmatite	21.5	10.4	17.3	Quartz	3.1
Orthopyroxene	1.2	34.0	17.92	x) K-Felspar	14.1
Clinopyroxene	30.2	15.3	22.92	Clinopyroxene	1.5
Hornblende & Biotite	9.6	4.2	4.7	Hornblende	43.8
Magnetite	8.7	1.6	0.3	Magnetite	2.7
				Clinozoisite & Accessories	1.3

Contacts as guides to cooling history.

The majority of chilled selvages in the Shoshong dolerite are aphyric, but occasionally small glomero-phyric bytownite crystals (An 84) occur.

A closer examination of these selvages indicates that the order of crystallization during the initial solidification of the sill was: Plagioclase, augite, magnetite, orthopyroxene, hornblende and biotite, and finally micropegmatite. Although magnetite is known to be one of the earliest constituents, no evidence can be found as to the exact time of its formation

relative to pyroxene and plagioclase.

Mineralogy as a guide to the temperature of the magma.

Due to the complex stability relations of individual mineral phases, magmatic temperatures should not be estimated by their mineralogy alone.

The most suitable mineral group for this purpose, however, are the orthopyroxenes: Reference to the binary $MgSiO_3 - FeSiO_3$ diagram of Hess (1941, fig. 9) shows that under anhydrous conditions, the crystallization temperature of bronzite ($En_{79}Fs_{21}$) is $1110^{\circ}C$, but as bronzite is a comparatively late mineral and the chilled phases aphyric, the initial temperature of an anhydrous Shoshong magma would have been greater. This is confirmed by the experimental results of Sosman and Merwin (1913), who found in a fine-grained Palisades dolerite (similar to the Shoshong dolerite) that the initial melting temperature was $1150^{\circ}C$, and only at $1225^{\circ}C$ did this begin to flow.

If, therefore, it is true that the Shoshong magma had no superheat (due to the presence of rhythmic layering - Jaeger and Joplin 1956 -), and also that it had a relatively high volatile content, then the initial temperature was probably about $1100^{\circ}C$, i.e. just above the liquidus (Hess 1956).

Rhythmic Layering: Its nature, Origin and relation to the differentiation of the Shoshong sill.

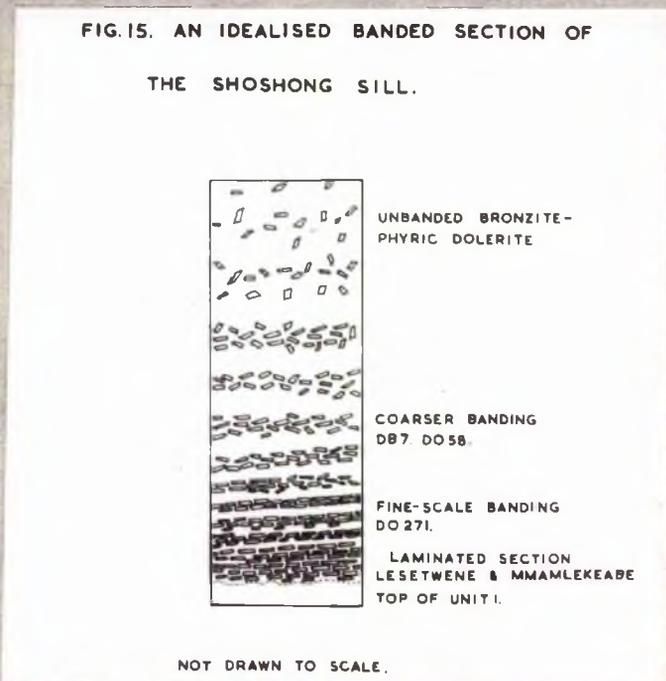
The great interest attached to this phenomenon was realised only after the completion of field work so that, as a further visit to the area was impracticable, only a few specimens have been examined. Still, the foregoing conclusions may at least be pointers to the true origin of banding in the Shoshong sill.

TABLE 14.

	<u>Do 306</u>		<u>DB 7</u>	
	<u>Light band</u>	<u>Dark band</u>	<u>Light band</u>	<u>Dark band</u>
Plagioclase	42.7 %	23.8 %	40.7 %	40.6 %
Micropegmatite	7.0	5.0	14.7	9.7
Orthopyroxene	20.8	53.1	23.4	29.8
Clinopyroxene	27.2	15.1	18.4	17.1
Hornblende & Biotite	2.1	2.5	1.4	2.3
Magnetite	0.5	0.9	1.9	0.5
	<u>100.5</u>	<u>100.3</u>	<u>100.5</u>	<u>100.0</u>

Although an outwardly uniform feature, rhythmic layering shows considerable variation in form, depending chiefly on the proportion of orthopyroxene phenocrysts present. In basal sections, such as at Manakalowe and Lesetwane, where the proportion of orthopyroxene is high (20.6 - 51.3%), bands are thin (0.75 cm. thick) and often indiscernible in the hand specimen. These sections are usually characterised by thin irregular bands, which are composed almost entirely of plagioclase (Plates 28 & 29). Fig. 15 represents an idealised section of rhythmic layering in the sill.

FIG. 15. AN IDEALISED BANDED SECTION OF THE SHOSHONG SILL.



NOT DRAWN TO SCALE.

As previously stated, the contrast between 'light' and 'dark' bands is due primarily to different proportions of orthopyroxene, -this difference being greatest (33.2%) for the basal laminated sections of Manakalowe and Lesetwane hills, and at least (6.4%) in the more coarsely banded section of Malebadi, while in contrast, both plagioclase and micropegmatite show only slightly higher concentrations in the light bands. Table 14.

The textural difference between alternate light and dark bands is very slight, but plagioclases and clinopyroxenes tend to be smaller in the latter, and more zoned - particularly

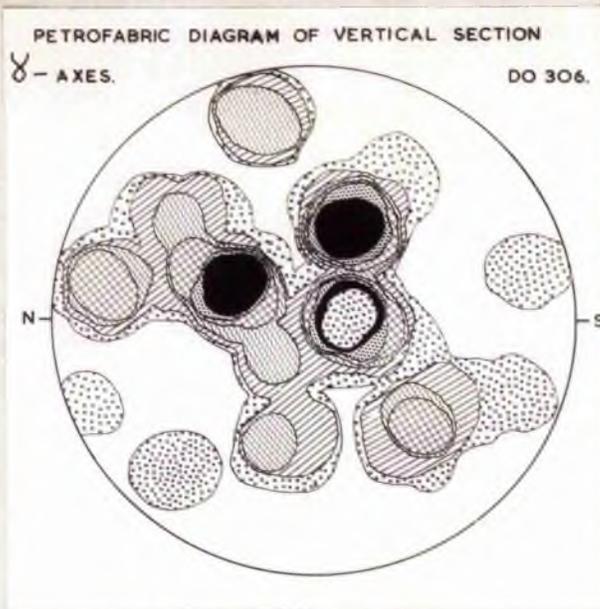


Fig. 16.

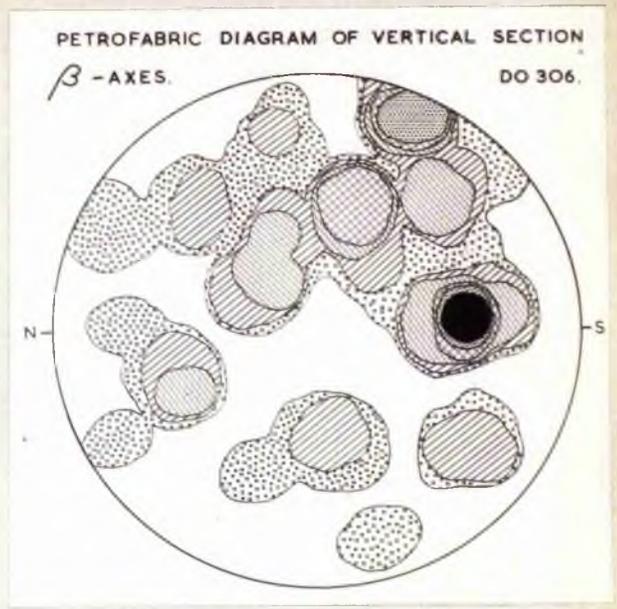


Fig. 17.

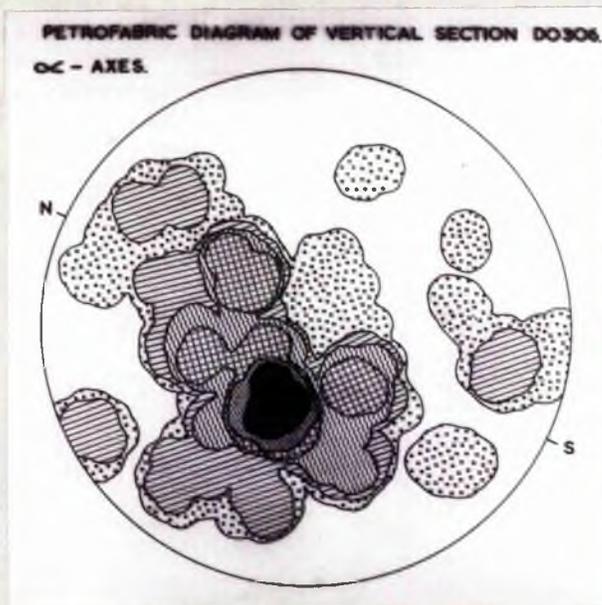


Fig. 18.

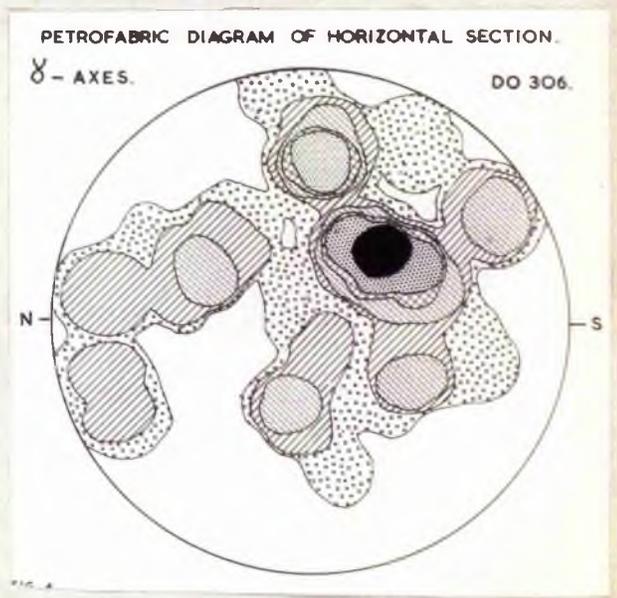


Fig. 19.

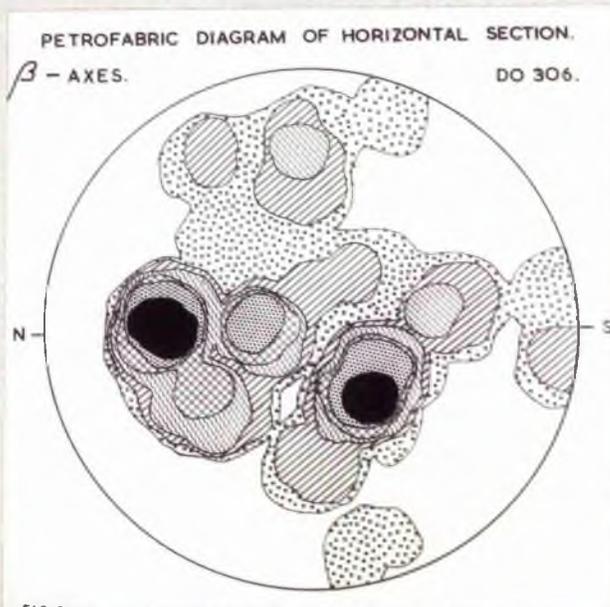


Fig. 20.

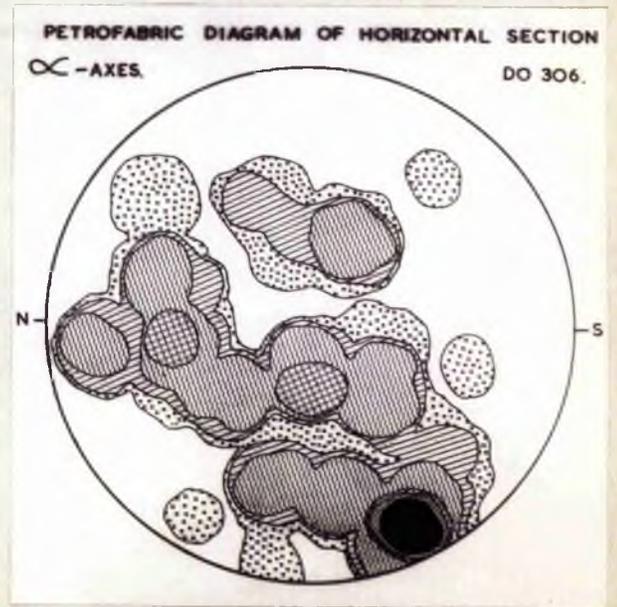


Fig. 21.

PETROFABRIC DIAGRAM OF BANDED SHOSHING DOLERITE
BASED ON γ -ORIENTATIONS OF PYROXENES.

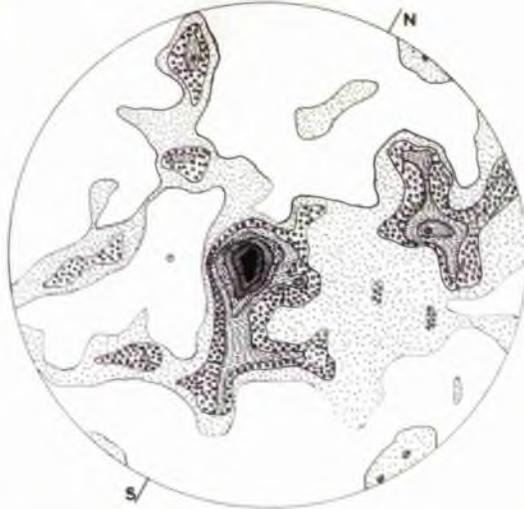


Fig. 22. (Vertical)

PETROFABRIC DIAGRAM OF BANDED SHOSHING DOLERITE
BASED ON γ -ORIENTATIONS OF PYROXENES.

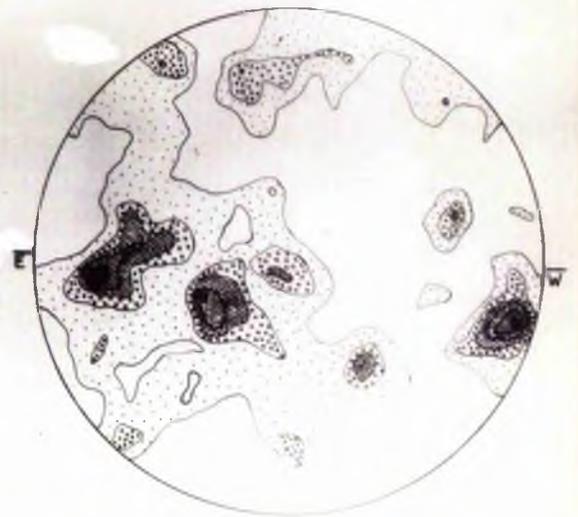


Fig. 23. (Horizontal)

PETROFABRIC DIAGRAM OF VERTICAL SECTION.
 γ -AXES. DO 58.



Fig. 24.

PETROFABRIC DIAGRAM OF HORIZONTAL SECTION.

γ -AXES.

DO 271.

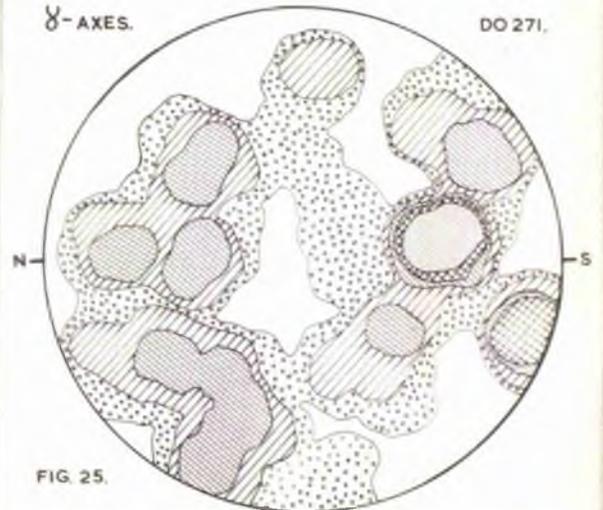
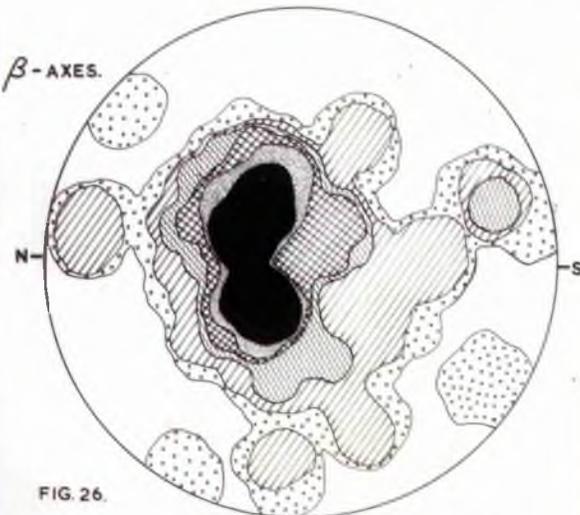


Fig. 25.

β -AXES.



PETROFABRIC DIAGRAM OF HORIZONTAL SECTION. DO 271.

Fig. 26.

PETROFABRIC DIAGRAM OF HORIZONTAL SECTION.

α -AXES.

DO 271.

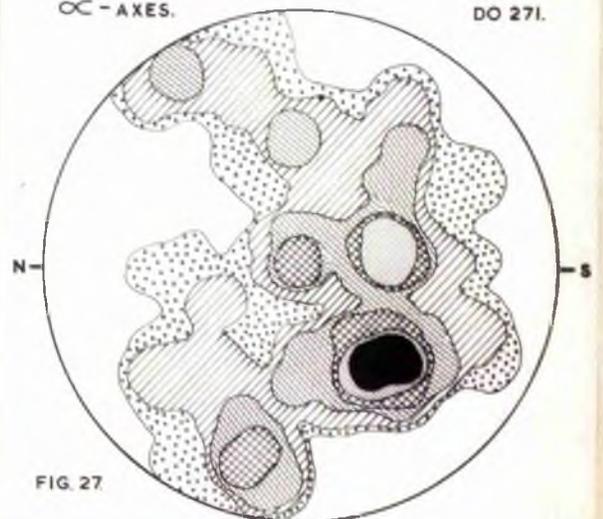


Fig. 27.

the plagioclases - Fig. 3.

Noritic rocks frequently show some directional orientation of their mineral constituents (van den Berg 1946; Schmidt 1952; and Larsson 1934), and in the Shoshong sill this is shown by the orthopyroxenes, which are the primary cumulus phase, (terminology after Wager, Brown and Wadsworth 1960).

These stumpy prismatic phenocrysts, which are slightly flattened parallel to (100), are often oriented with their (100) faces in the plane of banding, so that a typical laminar structure is produced, and occasionally, even some directional orientation of their 'c' - or δ -other axes is evident. (Figs. 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27).

Preferred orientation among the remaining constituents is poorly developed, although the small tabular laths of plagioclase show a slight directional orientation within the plane of pseudostratification corresponding with that of the orthopyroxenes. (Figs. 55, 56, & 57).

In seeking a suitable origin for rhythmic layering in the Shoshong sill, the author has found many analogies with the 'circular depressions and domes' of the Merensky reef, described by Schmidt (1952). In the former, (1952, fig. 3) which are about 200 ft. wide, the reef rock cuts discordantly across the chrome band and feldspathic pyroxenite, into the underlying anorthositic gabbro. By petrofabric analyses, Schmidt found that the most marked directional orientation of orthopyroxenes is aligned at a tangent to the perimeter and at the outermost margin of the depression, although this becomes progressively more haphazard towards the centre.

Consequently, he proposed that after the consolidation

of the pyroxenite, the Merensky Reef was intruded as an extremely mobile magma (1952, p. 276), which was broken up into a series of 'swirling currents and eddies' by the irregularities of the floor. These picked up large pyroxene crystals from the floor and using them as abrasive agents bored down through the chrome and pyroxenite bands into the anorthositic gabbro, to form the circular 'depressions'.

The present author is not in full agreement with "the abrasive boring action of pyroxene crystals", - especially as such dome and depression features could be related to folding of the Merensky Reef foot-wall (Ferringa 1959). However, the suggestion as to the formation of a number of 'swirling currents and eddies' by flow over the irregular floor of the reef, would seem to fit the situation encountered in the Shoshong sill fairly closely. Schmidt suggests that these currents may have been activated by an increase in temperature caused by the influx and mixing of hot reef magma above the pyroxenite floor. "The difference in temperature" he maintains, (p. 278) "could possibly give rise to the formation of currents".

Assuming then that the 'swirling currents' were active in the Shoshong sill during the second intrusive phase, it might be expected that they would first become concentrated within the circular depressions of the floor, but in so doing would perform a circular motion while converging towards the centres and bottoms of each. Furthermore, as in the Merensky reef depressions, the fact that the velocity of these currents is greater at the margins than in the centres, may account for the preferred orientation of orthopyroxenes being more perfect near the former, where they have an apparent dip of 38° to 60° . Thus, by a combination of the normal gravitative accumulation of orthopyroxenes and the action of these currents, the origin of such banded sections could be explained.

The ultimate cause of rhythmic layering within the sill

still remains a problem however, but the most plausible explanation seems to be:- the first currents having a relatively high velocity, would carry a fairly heavy load of orthopyroxene phenocrysts, - these being derived both from the unconsolidated top of the Unit 1 and the primary cumulus of Unit 2, (petrological evidence in support of this being found in the wide assortment of zoned and unzoned orthopyroxenes of different composition within the same band). The first cumulates therefore, would tend to be exceedingly orthopyroxene-rich, (as in the basal laminated sections of Mamlekeleabe and Lesetwane hills), while subsequently, with decreasing proportions of available orthopyroxene, a combination of 'rhythmic differential settling' and winnowing would predominate, thereby producing the normal banded sections as at Maraletsane. (Plate 1A).

By the term 'rhythmic differential settling' the author infers a mechanism similar to that described by Coats (1939, pp. 412-443). The latter has shown experimentally that a slight segregation of felsic and mafic crystals of equal size can be effected by a liquid of medium viscosity and with a density just less than that of the lighter felsic minerals. As this segregation is by no means perfect, it is doubtful whether such a mechanism could be considered as a primary cause for banding, - although, if assisted by a slight agitation of the loose crystal mesh by swirling currents, this could be made far more effective.

A process similar to the 'rhythmic differential settling' - i.e. that of 'filter-pressing' - was also effective in the Shoshong sill. Its chief products; already referred to on p.47, are the thin irregular feldspathic streaks in the basal laminated sections as on Mamlekeleabe hill. This

resulted from the compaction of an unconsolidated cumulate by the sheer weight of the overlying crystal mesh, so that the small crystals of the lighter 'pore material' were segregated into bands or veins, which are generally concordant with the plane of banding or pseudostratification, (Plate 28).

A final point here concerns the degree of intergrowth between the three major constituents of the banded dolerite. This is characteristically slight and for this reason differential crystal settling was made possible, and the above 'banded' sections produced. Thus, Edwards (1942, p. 471) observes that: "A slower rate of cooling, without the formation of ophitic intergrowths between the later formed pyroxenes and plagioclases, would have resulted in the development of alternating layers of pyroxene-rich and plagioclase-rich rock in the sill, above the magnesia floor".

Finally, the thinness of banded sections, the gradational nature of individual layers, and the predominance of mineral zoning within these may be due to the more rapid cooling of the sill, and its small size compared with the Bushveld lopolith and other layered intrusion, -(The time estimated for the complete solidification of the Shoshong sill is 120 to 160 years, as determined by the equations of Jaeger (1959. (9)):-

$$X \text{ m} = 9.5 \lambda (ty)^{1/2}$$

$$\text{or } X \text{ m} = 122 \lambda (k_1 ty)^{1/2}$$

where:-

$X \text{ m}$ = distance in meters of the plane of solidification from the contact.

λ = numerical parameter depending on range of solidification temp. and latent heat of solidification of magma

k_1 = thermal diffusivity of solidified magma

ty = time in years after intrusion.

The fact that these banded sections occur only in Unit 2 and are nowhere less than 60 ft. above the floor, is noteworthy. Similar observations have also been made in other

layered complexes such as the Duluth lopolith (Grout 1918). It seems possible, that when a fresh influx of magma came into contact with the hot unconsolidated mush of an earlier intrusive phase, the viscosity factor was temporarily reduced and a more rapid movement of the currents permitted. Supporting evidence for this may be found in the almost complete lack of chilling between these two Units.

Following the classification of Wager, Brown and Wadsworth (1960), the cumulates of the Shoshong 'banded' series are orthocumulates with orthopyroxene as the primary cumulus mineral, - less significant cumuli including plagioclase and clinopyroxene, while in the dark bands these two minerals form the 'pore material' (1960, p. 77).

In adopting the above classification, it is fully realised that the gravitational settling of orthopyroxene, phenocrysts in Unit 2 is inferred. Both field and petrological observations strongly support this, for in the composite graph (fig. 11), both orthopyroxene and total pyroxenes attain their maximum proportions within, or just above, the banded section, - in accordance with the correspondingly high average specific gravities of these rocks.

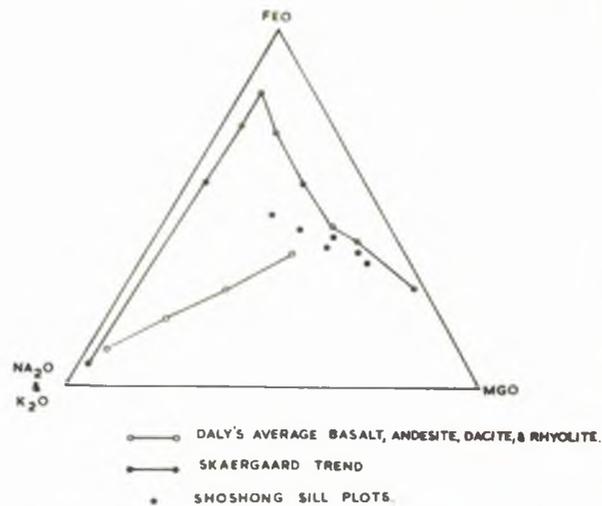
Differentiation in the Shoshong sill.

Differentiation was governed by five factors, - fractional crystallization, gravity settling of pyroxenes, upward displacement of the residual magma, segregation of the late stage residuum as dolerite pegmatite, and the acquisition of both volatiles and felsic components from the granite country rock -.

As in most differentiated tholeiitic provinces, pyroxene fractionation was predominant, and the end-products show a fair degree of iron-enrichment (Fig. 28). Little evidence, however, was found for the crystal-mush-settling hypothesis of Jaeger and Joplin (1955 & 1956), for, although Hess (1956, p. 449) maintains that "igneous lamination is virtually unknown in dolerite sills", he does state that this feature is generally

indicative of individual crystal settling.

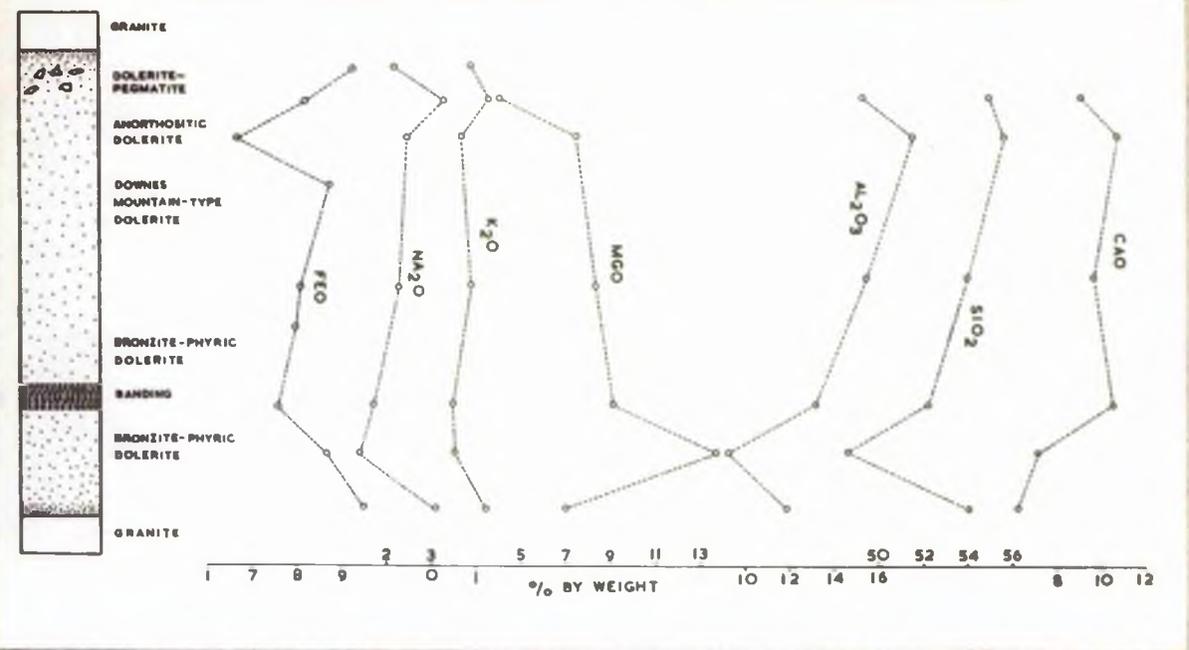
FIG. 28. DIFFERENTIATION TREND OF THE SHOSHONG SILL.



Despite the inadequate number of accurate analyses for the Shoshong sill, a general picture of the differentiation trend is shown by "oxide profiles" (Edwards, 1942, p. 468), where the percentage of each oxide is plotted against its height in the sill. This method has the added advantage that small errors do not significantly alter the general pattern of variation.

The similarities of these in the Shoshong and Mount Wellington sills are remarkable (fig. 29), (Edwards 1942, p. 469, fig. 8).

FIG.29. OXIDE PROFILES FOR THE SHOSHONG SILL.



Both MgO and FeO attain their highest proportions at the level of maximum orthopyroxene accumulation 60 ft. above the floor, - although FeO is slightly higher in the chilled basaltic selvages. Beyond this, MgO decreases with height, and FeO, after falling to a minimum at the base of Unit 2, increases towards the top of the sill.

The Al₂O₃ and SiO₂ profiles, which are directly affected by the settling of magnesian pyroxenes, have an inverse relationship with the MgO profile. They decrease rapidly from the chilled floor to a minimum at the level of maximum Mg-pyroxene accumulation, but thereafter they increase once more.

The CaO, Na₂O, and K₂O profiles, show similar trends the most extreme case occurring at the top of the Downes Mountain-type dolerite horizon at Kgakanwe, which has the highest plagioclase:pyroxene ratio of any rock yet encountered in the Shoshong sill

Late Stage Differentiation.

When most of the Shoshong magma had solidified, the volatile-rich residuum was segregated to form hornblende- and pyroxenic-dolerite-pegmatites. Subsequently, through

TABLE 15.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
FeO	9.30	8.20	8.03	3.79	8.30	10.51	8.10	1.51	2.26	2.47
Na ₂ O	2.21	3.27	2.34	2.93	3.20	3.27	4.19	4.90	7.71	8.00
K ₂ O	0.85	1.30	0.71	4.24	2.42	2.79	1.84	0.15	0.09	0.05
$\frac{K_2O \times 100}{K_2O + Na_2O}$	27.8	28.4	23.3	59.1	43.0	46.1	30.5	29.7	15.3	6.2

1. Pyroxenic dolerite-pegmatite. Do 53 c.
2. Pyroxenic dolerite-pegmatite. Do 56
3. Pyroxenic dolerite-pegmatite. Do 297.
4. Hornblende dolerite-pegmatite. P. 30
5. Mmamphaleng granite xenolith. D. 4.
6. Mmamphaleng granite xenolith. D. 3.
7. Dolerite-pegmatite. Do 47. Mapaija sheet.
8. Albite-aplite vein, 2 inches thick. Co 9.
9. Albite-aplite dyke, 18 inches wide. Q 8. Marutwe hill.
10. Albite-aplite dyke, 18 inches wide. West of Tshubung hill. GV 19.

further differentiation, soda-rich hydrothermal solutions were produced. These consolidated as albite-aplite veins and caused extensive alteration of the dolerite along joint planes.

Partial analyses of these differentiates are compared in Table 15. The pyroxenic dolerite-pegmatites show maximum iron-enrichment but are low in K_2O , while the corresponding hornblendic types are high in K_2O and low in FeO . The albite-aplite veins, however, are extremely high in Na_2O , but low in both K_2O and FeO .

Such rapid compositional changes in the last differentiates of basic magmas are also known in the Palisades sill (Walker 1940), and in the Goose Creek diabase (Shannon 1925). In the latter, Shannon describes a normal diabase-pegmatite dyke which grades down into an albite-pegmatite below. In the transitional zone, there is an almost complete lack of plagioclase which is compositionally intermediate between labradorite and albite. A small proportion of these albitic bodies, he suggests, may be due to "hydrothermal action by a magma of extremely differentiated composition", rich in water and soda upon a diabase-pegmatite, which had just solidified. Still, the greater proportion however, are probably magmatic, - i.e. extreme differentiates of the dolerite-pegmatite bodies. In the Palisades sill Walker (1940, p. 1093) suggests that hot solutions rich in silica and alkalis diffused upwards into the chilled roof phases, causing extensive replacement of the plagioclase by micropegmatite, and of the ferromagnesian (notably titanomagnetite) by biotite, and thereby "the liquids seem to have freed themselves of potash almost entirely".

In spite of this, it seems more probable that the larger albitic bodies of the Shoshong sill (Table 15 Nos. 8 & 9) were formed by the extreme differentiation process described by Shannon. The unusually high proportion of K_2O entrapped in the hornblende dolerite-pegmatite may have produced a corresponding increase in the Na_2O/K_2O ratios of the residual liquid, from which the albite-aplites crystallized.

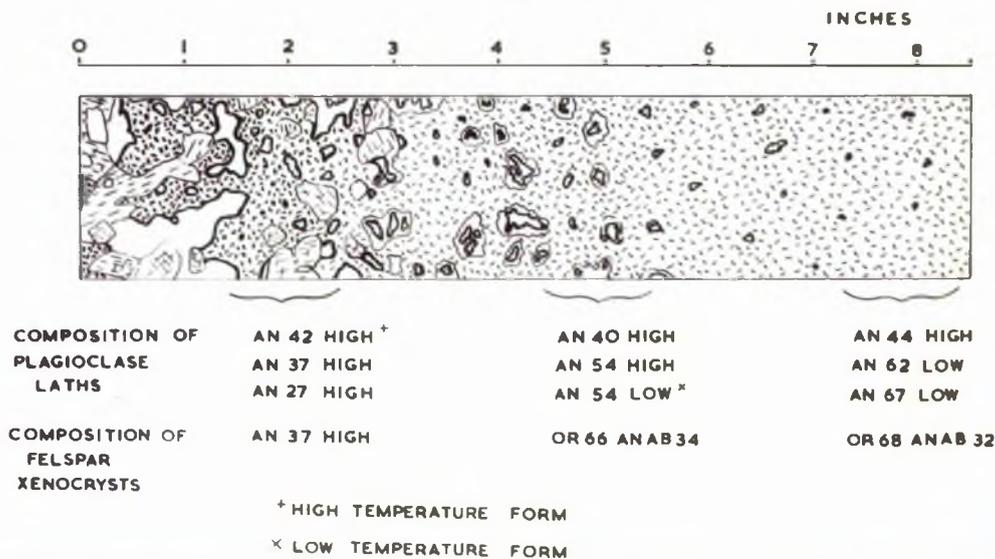
Reaction of the magma with the country rock.

Mention was made on p. 20 of the only two (granitic) xenoliths found in the Shoshong sill. The ensuing discussion, is based primarily on these.

In the Mesulutsane xenolith, specimens collected along an $8\frac{1}{2}$ inch section from the granite core into the enclosing dolerite, illustrate the complete assimilation and replacement of this by a fine-grained granophyre, (Fig. 30).

Coarse intergrowths were first formed between the quartz and orthoclase of the granite, while, at the same time, oligoclase crystals were replaced by a fine myrmekite. These two intergrowths were then merged to form an oligoclase-hornblende-granophyre composed of small oligoclase laths, a little hornblende and biotite, nests of chlorite and epidote, skeletal magnetite,

FIG.30. SECTION SHOWING THE ASSIMILATION OF A GRANITE
XENOLITH AT MOSULUTSANE.



and a few quartz xenocrysts. Further out from the xenolith, this granophyre became darker and more basic in composition while the quartz xenocrysts were each enveloped by a characteristic rim of dark green reaction hornblende (Table 12 & Plate 31). Pyroxene was also present, this being chiefly in the form of small pigeonite prisms, although some had already inverted to orthopyroxene (optic angle 71° with exsolved augite lamellae parallel to (001) and (100)). In the final stage, however, the predominant host rock is a basic augite granophyre with only a few scattered quartz xenocrysts.

The second, or Wmamphaleng, xenolith is still more complex. A series of specimens collected along a vertical section through the pegmatitic zone, shows that it is bounded above and below by a typical pyroxenic-dolerite-pegmatite, of which the lower member is the coarser and more prominent.

Due to the predominance of active residual solutions in this horizon, recrystallization of the granite xenolith has been so extensive that its original form is now hardly perceptible. The main indications of its 'foreign' nature, are the numerous large quartz crystals and its overall red or

pink appearance, but, like the dolerite-pegmatite, they contain large subhedral prisms of hornblende and sericitised labradorite (An 53), abundant biotite, skeletal magnetite, and a coarse micropegmatitic intergrowth. At its transition into the underlying dolerite-pegmatite, it becomes finer and conspicuous pigeonite crystals, - now almost completely pseudomorphed by bowlingite - appear. The modal analyses set out in Table 16 show that the 'xenolith' rocks contain the highest proportions of quartz, orthoclase, and "reaction" hornblende, the least plagioclase and pyroxene, but that the plagioclase in these xenoliths is more sodic in composition.

Table 16.

	Chilled roof selvage	Upper Pyroxene- dolerite- pegmatite	Normal Xenolith rock	Transition Xenolith rock	Lower Pyroxene dolerite pegmatite	Lower pyroxene dolerite pegmatite
Plagioclase	36.1	36.9	18.2	18.3	33.2	35.7
Micropegmatite & orthoclase	8.1	16.6	20.7	24.9	15.6	18.7
Quartz	12.4	4.9	23.5	12.0	3.2	3.7
Hornblende & biotite	16.8	14.0	35.2	23.8	6.6	15.1
Pyroxene	24.0	5.7	0.4	17.9	40.2	22.4
Magnetite	2.9	2.0	2.0	3.1	1.1	4.3
% Anorthite	65	59	53	57	64	65

Chemical analyses (Table 17) show that whereas Na_2O is approximately the same as in the Mahalapye granite and pyroxenic dolerite-pegmatite, FeO increases sharply, and K_2O is intermediate between the two. Thus, the Mmamphaleng xenolith appears to have been basified, through an initial desilication of the granite together with a decrease in K_2O

and addition of Na_2O , FeO , TiO_2 , CaO , and MgO .

TABLE 17.

$\% \text{ BY WEIGHT}$	Hornblende- Dolerite - pegmatite	Pyroxene- dolerite - pegmatite	Add xenolith Rock	Add Xenolith Rock	Normal Mehalegys granite	Metamorphic red granite at base of sill.
FeO	3.79	8.20	8.30	10.51	0.48	0.84
Na_2O	2.93	3.27	3.20	3.27	3.41	3.34
K_2O	4.24	1.30	2.42	2.79	5.67	6.95

Further indications of the syntexis and anatexis in the sill are exemplified by some late-stage veins although the majority are probably magmatic.

Mountain (1935, 1937, and 1944) has shown that many quartz-felspar veins in the Karroo dolerites are syntectic and anatectic products of the intruded sediments. The initial mobilization, he maintains, could be explained by a decrease in pressure in the sill -(through contraction) combined with the extra pressure of the heated sedimentary floor. This was also assisted by the fluxing action of felspar on fusing - because the amount of pore fluid in such veins was characteristically small (Walker 1941).

In the Shoshong sill, therefore, some microgranitic veins, may be anatectic products of the Mahalapye granite, and in their relationship with the remaining vein types, three field localities are of immediate interest:

1. In the chilled roof section between Sung and Sunganen, small 1/16 inch thick amphibole and quartz-albite veins are continuous with a granitic xenolith 2 inches in diameter.
2. In the chilled floor section two miles north of Shoshong a prehnite vein is continuous with a microgranitic member, (Plate 16).
3. At the top of the Shoshong range thin white albite-aplite veins are common. Some of these, which are believed to be syntectic in origin, still retain some granitic texture, and in addition have micropegmatitic and myrmekitic intergrowths.

From these observations it appears that all four vein types were initially derived from the granite country rock.

51.

The first veins to be injected, were the microgranites. These reacted with their dolerite margins, uranitising the pyroxenes and leaching out $\text{Fe}(\text{OH})_3$, - (although some was almost immediately precipitated as magnetite). Subsequently, through continued permeation by solutions rich in K_2O and SiO_2 , plagioclase was replaced by micropegmatite, and the solutions, which were now enriched in CaO and FeSiO_3 , formed veins composed almost entirely of prehnite, clinozoisite and amphibole. Finally, after further diffusion of K_2O and SiO_2 , the plagioclases of the dolerite were sericitised, and the veins subsequently albitised by the liberated Na_2O .

The greater proportion of graphic intergrowth between quartz and felspar at upper levels of the sill may be explained by the higher temperatures existing in these regions and hence the longer time available for crystallization. A similar observation was also made by Mountain (1935) in syntectonic veins of the Coedmore dolerite near Durban.

Metamorphism of the Country rock.

This was briefly referred to on p. 21. Except for a slight increase in FeO (Table 17), these rocks are chemically the same as their unmetamorphosed equivalents.

Petrographically, the metamorphosed granite at the base of the sill is a coarse red variety composed of large red haematite-stained perthite crystals, sericitised basic oligoclase, quartz, green biotite, and accessory magnetite. (Plate 32). As in the micropegmatitic granodiorite of Slieve Gullion (Reynolds 1937), both oligoclase and perthite crystals are margined by dark rims of red orthoclase. Furthermore, the margins between contiguous perthite and quartz crystals show a slight crenulation due to an incipient intergrowth between them.

Similarly, in the pink metamorphosed roof granite, a close parallel is again found in the micropegmatitic granodiorite of Slieve Gullion (Reynolds 1937 p. 250). In the hand

specimen, this resembles a normal Mahalapye granite, but microscopically it consists of a number of basic oligoclase, perthite and quartz xenocrysts set in a more abundant granophyric matrix, while accessories include clinozoisite, green and brown biotite, and magnetite (Plate 33). Oligoclase phenocrysts (An 27-34) are either sericitised or replaced by a fine myrmekitic intergrowth, but nearly all are margined by a thin rim of perthite. With increasing distance from the contact, the degree of intergrowth decreases and the normal grey colour of the granite reappears.

C. Summary.

The 400 ft. thick Shoshong sill was formed by two successive influxes of magma, separated by only a short interval of time. Petrographically the sill is divided into four major horizons - a basal bronzite-phyric zone equivalent to the Hangnest dolerite; a thick intermediate zone equivalent to the Karroo Downes Mountain dolerite; and a relatively thin upper capping of dolerite-pegmatite. Late-stage veins are also common.

The mineralogical, chemical, and physical properties show a regular variation from top to bottom of the sill, thereby indicating a marked gravitational settling of magnesian pyroxenes, which was accompanied by an upward displacement of the lighter residuum and feldspars. Differentiation is well developed, and shows a marked tendency towards iron-enrichment.

A ten foot thick zone of fine rhythmic layering at the base of the second intrusive is developed above basin-shaped depressions in the floor. Its origin is believed to be the result of swirling currents of magma circulating within these, so that, by a combination of this, together with 'rhythmic differential settling' and filter pressing, these and the underlying laminated sections were produced.

The Shoshong magma does not show any great chemical activity towards its intruded country rocks. Included xenoliths however show considerable basification, but little or no albitization or potash metasomatism.

Contact metamorphism is significant in producing a coarse red granite beneath, and a pink porphyritic granophyre above the sill.

6.

THE MAKHWARE SILL.

A. PETROGRAPHY.

Two major rock types are distinguished in the Makhware sill, - a Basal Diorite and an Upper Red Rock -. Additional varieties, which are sometimes present as a capping to these, include granophyres and feldspathised quartzites.

Chilled Modifications.

Chilling at the roof contact is slight, but the basal phases (which range from 3 to 7 feet in thickness) are extremely fine-grained basaltic rocks with scattered phenocrysts of bronzite, bytownite, and augite. Texturally, they are intersertal with a dark brown glass (μ 1.553), but coarser varieties are intergranular with small crystals of labradorite (An 74), augite, magnetite and sometimes biotite (Plate 34). The bronzite phenocrysts (Fs 20-26) are occasionally rimmed by pigeonite with an extinction angle of 44° .

Basal Diorite.

The lower half of the Makhware sill consists of a dark grey basaltic rock which differs from most quartz-dolerites in its unusually high proportion of interstitial micropegmatite. (Plate 35). Dark green primary hornblende and large crystals of skeletal magnetite are common, while in addition a few phenocrysts of pyroxene and zoned bytownite are still discernible. Despite its relatively high normative anorthite content (An 52), this rock has been classed as a

granophyric diorite - chiefly on the basis of its high micro:
pegmatite content (Table 18).

TABLE 18.

Mode of Makhware Basal Diorite.

	%
Plagioclase	27.3
Orthoclase	10.2
Micropegmatite	23.3
Clinopyroxene	30.3
Hornblende	4.4
Biotite	1.5
Magnetite	3.0

Red Rock.

Approximately 100 feet above the floor of the sill the Basal Diorite grades into an 80 ft. thick zone of Red Rock, the main features of this being its pink colour and coarser texture. Microscopically, it is sub-ophitic, although pyroxenes tend to form individual twinned prismatic crystals with little or no ophitic relationship towards the plagioclase, (Plate 36).

The pyroxenes, have a well-developed basal parting, and are uralitised or altered to bowlingite. Intergrowths between quartz and the pink cloudy orthoclase ($Or_{63}Ab_{37}$) are coarse and patchy in distribution. Large crystals of hornblende, brown biotite, and magnetite are abundant, and the plagioclases are typically zoned with cores ranging from An 57 to An 45. The modes of two typical specimens are given in Table 19.

TABLE 19./

TABLE 19.Modes of Makhware Red Rock.

	<u>Tlakadeawa Hill</u>	<u>Kuchwe Hill.</u>
Plagioclase	36.2	21.5
Orthoclase	18.8	45.5
Quartz	9.7	6.0
Pyroxene	21.7	10.6
Hornblende & biotite	12.1	12.3
Magnetite	1.5	4.0

Acidified Red Rock.

In one locality a series of hydrothermally altered acid Red Rocks form a relatively thin capping to the normal Red Rock horizon. The plagioclase (An 45) is almost completely sericitised, and instead, zoisite and epidote are prominent constituents. Light green uralite hornblende, pink orthoclase, and quartz are abundant, but the degree of intergrowth between the latter is slight. Accessories include sphene, skeletal magnetite, ilmenite and brown tourmaline. (Table 20).

TABLE 20.Mode of Acidified Red Rock.

	<u>%.</u>
Plagioclase	30.4
Orthoclase	17.0
Quartz	3.8
Hornblende	38.7
Zoisite & epidote	9.4
Magnetite	0.7

A few veins of pink granophyre also occur in these rocks.

Granophyre.

Separating the Acidified Red Rocks from the quartzite roof at Tshuhung is a thin zone of red granophyre.

The lower most member of this is a typical hornblende - granophyre composed of small porphyroblastic crystals of reaction hornblende (Table 12), sericitised plagioclase (An 35) and skeletal magnetite set in a coarse micropegmatitic matrix, and accessories include epidote, zoisite, and apatite. (Plate 37). Above this is a more uniform, but slightly coarser granophyre with small crystals of accessory hornblende, epidote, zoisite, sphene, apatite, and magnetite, while in addition resorbed crystals of pink sericitised oligoclase and clastic quartz grains also occur. (Plate 38).

Felspathised Quartzite.

This rock, which comprises a 4 ft. thick zone above the granophyre at Tshuhung, differs from the normal Shoshong quartzite in possessing conspicuous pink or greenish patches scattered through the matrix. Microscopically these patches consist of cloudy pink feldspar - usually oligoclase (An 32) - or else small crystals of clinozoisite, epidote, chlorite and skeletal magnetite.

Graphic intergrowths between quartz, feldspar, and clinozoisite are typical - although poorly developed. As this is essentially a replacement product, the quartz grains are marginally invaded by stringers of feldspar (Plate 39), which by following two crystallographic planes, (one perpendicular, and the other parallel to the 'c' - axis) form a distinct 'network' or quartz - feldspar intergrowth.

The Normal Shoshong Quartzite.

This hard compact white quartzite is composed of sub-rounded quartz grains each with crenulate and interlocking margins, while very small amounts of a reddish isotropic substance, plus some chalcedonic material and magnetite also occur.

Late-stage veins.

As in the Shoshong sill, these veins include both

syntectic and late differentiated products alike. A good example of syntectic veining occurs in the Red Rock horizon south of Tshuhung, this being a thin vertical light-brown vein of irregular form and composed of a fine mesh of quartz, andesine (An 34), orthoclase, and large poikiloblastic crystals of magnetite. Especially significant are the presence of large rounded quartz xenocrysts with undulose extinction, and the streaking of magnetite grains parallel to the wall rocks, these features being indications of its syntectic origin from the Shoshong quartzite, (Plate 40).

A rather more doubtful case of syntexis, however, is the 18 inch thick dyke in the Red Rock near Tshuhung. This fine-grained rock with its small clumps of epidote and occasional large quartz crystals, is mineralogically similar to the feldspathised quartzites and granophyres described above, although texturally, it is microgranitic. Its main constituents are oligoclase (An 32-37), quartz, and orthoclase (Or 54-67 AbAn 46-53), but its extremely high Na_2O content might favour a late-stage differentiation origin equivalent to the albite-splite veins of Shoshong (Table 15).

True residual magmatic veins are, in fact, difficult to distinguish, but the thin pink ramifying forms in the chilled roof margins and the Red Rock zone do seem to belong. These, which are composed of orthoclase, oligoclase, (An 32), quartz, hornblende, biotite, clinozoisite, and magnetite, have few quartz-felspar intergrowths, but have a well-developed fluxion structure of feldspars parallel to the walls.

Pegmatitic Phases.

A few small pegmatitic phases occur in the Red Rock, these sometimes being associated with transfused xenoliths, as at Dtsokwan. Essentially they consist of long prismatic crystals of augite, pigeonite, and sericitised andesine, set in a matrix of coarse pink micropegmatite. Large crystals of

skeletal magnetite are conspicuous while hornblende and biotite are common accessories. The pyroxenes, which are occasionally sub-ophitic towards plagioclase, are basally striated, uranitized, and often altered to bowlingite.

B.

PETROLOGY.

Mineral variation from top to bottom of sill.

Mineral variation here is relatively slight, but as shown in Tables 18, 19 and 20, there is a marked increase in orthoclase and quartz with height, while, similarly, biotite and hornblende attain their highest proportions in the Red Rock horizon. Pyroxene decreases towards the top of the sill, but plagioclase shows no significant variation.

Contacts as a guide to the cooling history of the magma and the temperature of intrusion.

Unlike the Shoshong sill, the Makhware chilled phases are typically porphyritic with a predominance of pyroxene phenocrysts (Table 21). This feature also accounts for their unusually high pyroxene ratios compared with the remaining intrusions of this area.

This indicates (as also does Barth's f-norm calculations (1936; pp. 334-335), which here give a value of 124.5), that pyroxene was probably the first mineral phase to crystallize in the Makhware magma, - and that this was soon followed by plagioclase-.

The porphyritic nature of the Makhware chilled phases, also suggests that the initial temperature on intrusion was less than in the Shoshong sill, i.e. probably of the order of 1000 to 1050°C.

TABLE 21

Notes of Chilled Basal selvages in the Makhware sill.

Do 196	R2
<u>S. of Mmanloke</u>	<u>Tlakadeawa.</u>

Bytownite phenocrysts	4.3%	2.4%
Pyroxene "	6.2	3.9
Biotite "	3.6	
Matrix	<u>35.9</u>	<u>93.7</u>
Pyroxene ratio		
$\frac{P \times 100}{P + F}$	59%	62%

Metamorphism of the country rock.

In the Makhware sill contact metamorphism of the Mahalapye granite is slight. The metamorphosed roof zone, which consists of a granophyric granite with large rounded quartz, albite, and orthoclase crystals embedded in a fine granophyric matrix, is very similar in appearance to the syntectic veins described above. The rounded quartz crystals are typically strained, with undulose extinction and crenulate margins, while thin replacement rims of chlorite and clinozoisite are also evident. Oligoclase crystals, as in the Shoshong sill, are characteristically replaced by an extremely fine myremekitic intergrowth, besides which, both these and the perthite crystals are enveloped by later rims of pink cloudy orthoclase.

At the base of the sill the metamorphosed granite is a slightly coarser blood-red rock, which is mineralogically identical to the normal granite.

Similarly, although most of the Shoshong quartzites are only hardened through contact metamorphism, in one locality on top of Kuchwe hill a 10 ft. thick zone of magnetite-quartzite rock was discovered (Plate 21). This is an extremely pure rock composed of rounded quartz grains and conspicuous magnetite crystals, together with accessory biotite, chlorite, and hornblende. The magnetite is probably a recrystallization product of the abundant red-brown isotropic cement in the original quartzite.

TABLE 22.

	Do214	K7	K5	K4
FeO	7.49	5.56	2.26	0.68
Na ₂ O	3.73	2.71	2.67	1.82
K ₂ O	3.34	2.53	3.04	1.34
<u>K₂O × 100</u>				
<u>K₂O + Na₂O</u>				

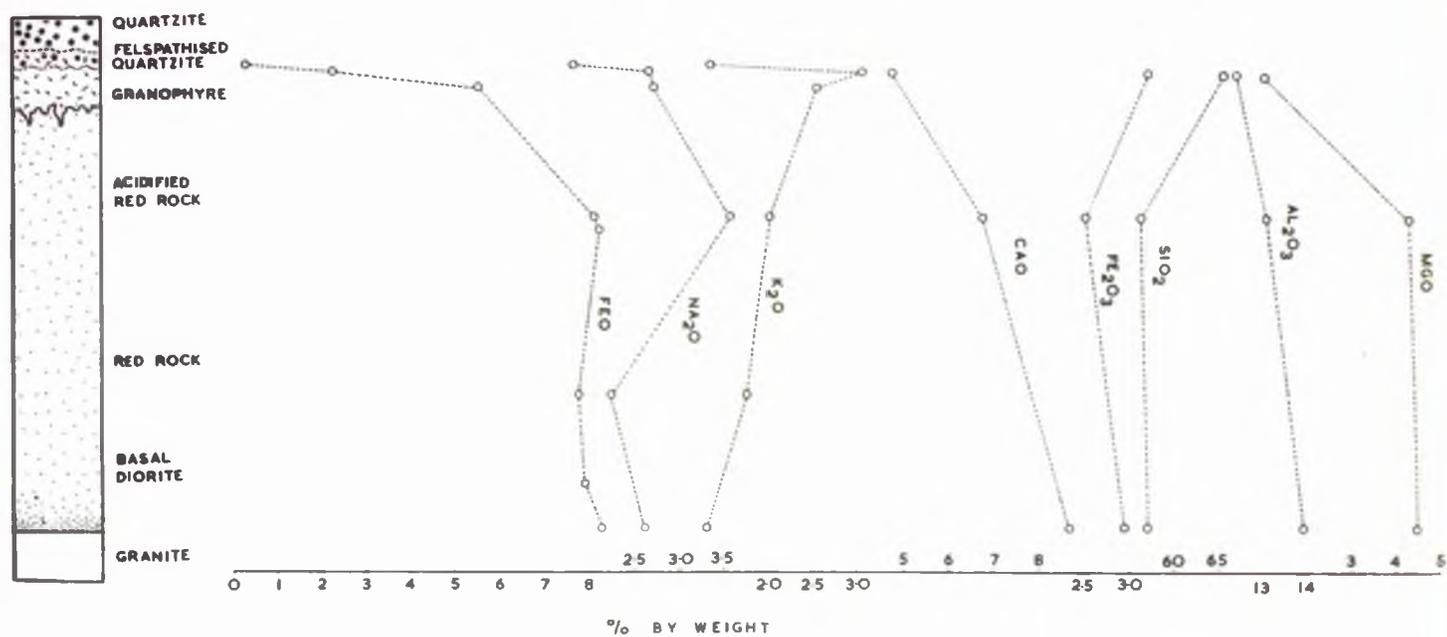
Do214	Metasomatised quartzite xenolith at Dtsokwan.
K7	Tshuhung hornblende-granophyre.
K5	Tshuhung red granophyre.
K4	Felspathised quartzite at Tshuhung.

Reaction of the magma with the Country rock.

From the numerous xenolithic clots and occasional felspathised roof sediments, the Makhware magma seems to have been far more reactive towards its country rock than was the Shoshong sill. In spite of this, one large xenolith is still preserved in the Red Rock one mile north-east of Kuchwe. This consists of remnant granite kernels up to 5 inches in diameter embedded in a pink granophyric matrix, which becomes darker and more doleritic with increasing distance from the xenolith core. In the initial stages of transfusion, the granite was replaced by fine micropegmatitic and myrmekitic intergrowths, which were subsequently blended to form an andesine-granophyre. Towards the margins of the xenolith, this rock became mottled with bright red patches of micropegmatite, and at the same time significant proportions of 'reaction' hornblende, skeletal magnetite, biotite, and pigeonite (2V.10°, optic plane perp. (010)) appeared. (The latter constituent has now mostly inverted to hypersthene (Fs50)).

Again on the southern slopes of Dtsokwan another large

FIG. 31. OXIDE PROFILES IN THE TSHUHUNG SECTION.



xenolith occurs, - although in this case it was probably a quartzite, which has now been completely transformed into a hornblende-granophyre. An analysis is given in Table 22.

The remaining xenoliths are generally small - although extremely numerous -. Thus in the chilled phases at Kuchwe, small hypersthene-micropegmatite patches up to 7 mm. long frequently occur. These consist of large quartz oikocrysts with chadocrysts of hypersthene (Fs50), labradorite (An52), magnetite, biotite, and hornblende. Similarly in the Red Rock horizon the basic xenolithic clots are legion, these being up to 3 inches long and composed of large ragged hornblende prisms, poikiloblastic quartz, biotite, plagioclase, epidote and skeletal magnetite, (Plates 16 and 41). It is probable that these were formerly granite xenoliths.

Only one outcrop of feldspathised roof quartzites was found, - this being on Tshuhung, where the Basal Diorite is successively overlain by Red Rock, granophyre, and feldspathised quartzites (Figs. 5 & 31, & Table 22). A study of the oxide profiles shows a relatively high FeO and low MgO content for the lower hornblende-granophyre, although both decrease steadily in the overlying quartzites. Alkalies reach a maximum of 9% in the uniform red granophyre, - K_2O being the most abundant, although in the feldspathised quartzite, Na_2O is proportionally higher, due to the greater content of albite. It seems therefore, that the chief metasomatic changes effected on the Sheshong quartzite were an initial desilication by geochemical culminations in FeO and Na_2O , and later, granitisation through culminations in K_2O and probably SiO_2 . Albitization was prominent during the initial transformation of the quartzite, and evidence of the corresponding iron-metasomatism is shown by the abundance of porphyroblastic iron-rich reaction hornblende. ($Mg_{37}FeTiMn_{63}$) in the more basic granophyre.

PETROGENESIS.

The association of acid and intermediate rocks with earlier basic varieties is a feature common to many hyperbyssal intrusions. The problem of their petrogenesis is a long-standing one, and is closely related to the fundamental origin of basaltic and granitic magmas. For this, many theories have been proposed, but for the most part these can be summarised under five main headings:-

1. Differentiation
2. Assimilation
3. Differentiation and Contamination
4. Metamorphism and Metasomatism
5. Hydrothermal alteration.

None of these theories however, can alone explain the many peculiar features of the Makhware sill - or, for that matter, of the Takane sheet - yet they all seem to have played some limited part.

As a result, the most relevant of these hypotheses are briefly discussed, and the author's own theory outlined.

Differentiation.

It is generally accepted that tholeiitic magmas by extreme differentiation can yield liquids of dacitic or rhyolitic composition (Walker, Mitchell, and Vincent, 1952); yet, these, at most, comprise only 5 to 15% of the total magma body (Nockolds 1936; Walker 1935; & Tomkeieff 1929). Edwards (1942), and later McDougall (1957), however, maintain that in subjacent bodies of batholithic proportions gravitational settling of pyroxenes and olivines have produced cappings of andesitic and/or rhyolitic composition in the upper levels of such magma bodies; - besides which, according to both Wager and Deer (1939), and Bowen (1919), this process was often enhanced by filter-press action through regional stresses during solidification, or else due to the shear weight of the overlying crystal mush.

Previously, when Nockolds (1934) had outlined a similar process of contrasted differentiation, Holmes replying, emphasised that even with a maximum of 15% acid residuum, it would be quite impossible to squeeze this out as a separate liquid fraction. Another complication also arises from Walker's observation (1957), that tholeiitic intrusions are seldom differentiated to the same degree as are alkali-basalt - types, and even the suggestion of Thomas and Bailey (1924, p. 330) cannot be entertained, as such a pause in the crystallization of a magma is unknown, (Penner, 1937).

An alternative hypothesis was outlined for the common Red Rock association of many N. American sills (Schwartz & Sandberg 1940; Grout, 1918; and Emmons 1927), this entailing a slow upward diffusion of volatiles, alkalic, and silicic components. In the Duluth lopolith, Grout (1918) maintains that these products are an immiscible product of the original basic magma, and being in a gaseous state and at high pressures, their upward diffusion was greatly facilitated. Hotz (1953) also emphasises the importance of pressure control in the diffusion of these late-stage residua, but makes no mention of their being in a gaseous state. A rather more suspect theory was outlined by Emmons for the Pigeon Point sill (1927), this involving a series of regional disturbances, which caused extensive fracturing in the stable crystal mush and brittle quartzite roof rocks. The resulting fractures became filled with the residual magma, which was then conducted into the upper levels of the sill.

More acceptable, however, is the "alkali-volatile diffusion-differentiation" hypothesis of Tomkeieff (1937), which entails the gravitational settling of olivine coupled with a slow upward diffusion of volatiles and alkalies - but not of silica -.

Finally, it has been suggested by several authors that the acid, intermediate, and basic rock associations of many composite intrusions arise primarily through differentiation in a subterranean magma body. In the Bushveld Complex, Lombard (1934), contrary to the proposals of Hall and du Toit (1923), envisages successive phases of crystal settling in a subterranean body, followed by refusion of these, and injection into the lopolith. These views are also shared by Strauss (1946) for the composite dolerite sill in the New Belgium Block, and by Krökstrom (1932, pp. 312-319) for the Breven dolerite dyke. Kennedy however, (1932) suggests that differentiation may have occurred as "the magma moved bodily up the throat of the volcano", for there is no evidence that the two fractions coexisted in some intercrustal basin".

Assimilation.

Many igneous-looking rocks have an assimilation origin (Hockolds 1931, 1934), - but there is still some uncertainty as to their quantitative value. Bain (1925, pp. 309-525), who estimated that the original Sudbury norite magma assimilated 63.34% of its own weight of sediments in order to produce the abundant micropegmatite horizon, was strongly criticised by both Phenister (1925, pp. 819-824) and Bowen (1925, pp. 825-829) for his complete lack of petrological and field evidence and general disregard of any metasomatic effects. Furthermore, as Walker (1957) has recently emphasised, the amount of assimilation by dolerite is small - even in deep-seated lopolithic masses -, although the (Karoo) bronzite-dolerites are far more reactive towards their country rock than the olivine-dolerites. Wager and Deer (1939), on the other hand, consider that this process deserves more careful consideration, because "The fact of a rock having a steady and correlated increase in iron-magnesium ratios and in the albite content of plagioclase does not preclude the possibility of extreme assimilation of material while differentiation was

in progress"; so that "assimilation did not radically effect the nature of the late stage differentiates but only the amount". In this, he is also supported by Krokstrom (1939). Mountain (1958), however, has a rather different view, for he finds no simple relationship between the acidified dolerites and transformed quartzites in the Coedmore sill near Durban.

It appears, therefore, that the regular variation trends in the Makhware sill (Figs. 36 & 5) provide no positive evidence against an assimilation origin, but, on the contrary, the high proportion of hornblende-biotite-clots within the Red Rock horizon indicates that there was probably an extensive assimilation of both granite and quartzite.

Assimilation and Differentiation.

Daly (1905, 1912, & 1917), realising that the ultimate origin of composite intrusions is unlikely to depend solely on differentiation or assimilation alone, suggested a combination of these instead, by which an acid syntectic magma, formed by assimilation and liquation, diffused upwards in the magma body, at the same time cleansing the gabbroic crystal mush of much interstitial residuum. This hypothesis, which accounts for the density stratification of intrusions, also eliminates the principal objection to assimilation, i.e. that chemical analyses show no genetic relation between the igneous rocks and the intruded formations.

Toens (1954) employed a similar explanation for some Bushveld diabase sills, as also did Coleman for the Sudbury norite (1907 pp. 759-782), - although in the latter meta-somatism was also effective. In the Duluth sills, however, Schwartz and Sandberg (1940) consider that this explanation is most improbable, due to the lack of xenoliths and the large amount of material which would have to be assimilated.

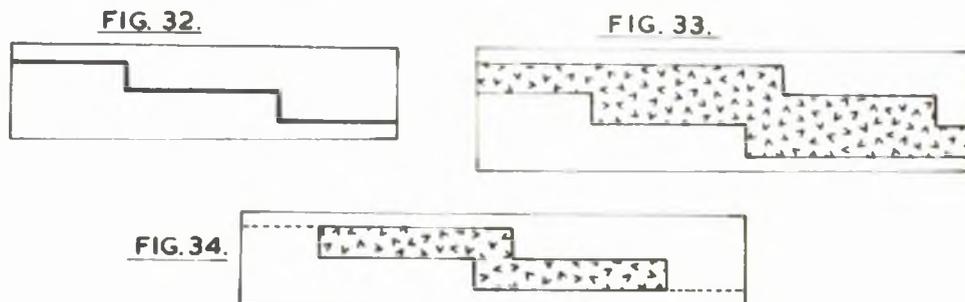
Nevertheless, in the Makiware sill this suggestion is worthy of a more careful consideration, as discussed later.

Metamorphism and Metasomatism.

Two S. African geologists in particular have been struck by the symbolic disappearance of large masses of sedimentary rock within the vicinity of certain "igneous intrusions", and by the seeming impracticability of explaining this by either stoping or assimilation. In the Bushveld Complex, van Biljon (1949) suggests that when the earth's crust was locally depressed, this caused a "sweating-out" of hot highly penetrative volatiles, which, during their initial migration, leached out certain constituents - in particular MgO and FeO -, but subsequently redepositing MgO in the zone of transformation, followed by FeO, and later, at higher levels, by Na₂O and K₂O. Previously, Ellis (1944) had outlined a similar hypothesis for the thick granophyre mass overlying the 'noritic-dabase' in the Far East Rand, - this being a syntectonic product of the shale roof "produced by heated emanations rising from the dolerite sill" (p. 150). In a later paper (1947), however, he believed the rather similar Marievale granophyre body to be a true metamorphic equivalent of the Main Reef and Jeppetown shales, which had been recrystallized through directed stress and plastic flow in the shales.

These proposals - especially those of van Biljon (1949) have been severely criticised. Some authors (Truter and Lombaard 1949, replies) suggest that this "missing sediment" dilemma is in fact the result of poor field interpretation, but (apparently unknown to them), Smythe (1930) had previously illustrated a most feasible explanation for this feature in the Whin sill (Clough 1876) (Figs. 32, 33, and 34). Petrologically, too, it was argued that the proportion of intermediate transformation products is too small, that the

FIGS. 32-34. DIAGRAMS ILLUSTRATING SMYTHE'S HYPOTHESIS FOR THE MISSING SEDIMENTS OF THE WHIN SILL.



chemical variation trend for 'metasomatites' differs from that of normal igneous rock suites, and that silica variation diagrams - particularly of highly siliceous rocks - are often misleading. Nevertheless, the experimental results of Tuttle and Bowen (1958) are especially significant, for they discovered that after heating a powdered sample of granite for a prolonged period in the presence of water, the composition of the charge was changed through the circulating water vapour abstracting alkalis silica and water vapour in the proportions of natural feldspar molecules. These results, which were confirmed by Mackenzie (1958), are further strengthened by the observation of Howe and Burnham (1957), that, as silica diffuses through the vapour following a concentration gradient, no actual movement of the latter is necessary.

Thus, although the Makhware sill as a whole is neither metasomatic nor metamorphic, (due to the prominent chilled phases, comparative scarcity of granophyre and feldspathised

quartzite, and non-felspathic nature of the original quartzite), these processes were still active - though on a more limited scale than described by Ellis (1944) -. Silica therefore, was added to the magma, and alkalis to the quartzite roof rocks following the existing concentration gradients.

Summary of preferred Hypothesis.

The present association and distribution of rock-types in the Makhware sill is the combined result of four major processes: crystal fractionation, differentiation, assimilation, and metasomatism.

Because this sill shows no degree of iron-enrichment comparable with the Shoshong dolerite, but instead trends essentially towards alkali-enrichment as in most calc-alkaline suites (Fig. 35), feldspar fractionation was predominant, and extreme quartzo-felspathic differentiates were produced.

FIG.35. DIFFERENTIATION TREND OF THE MAKHWARE SILL.

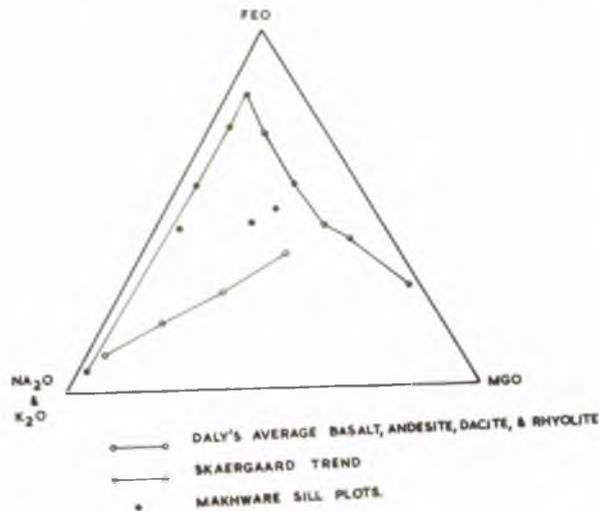


FIG.36. LARSEN VARIATION DIAGRAM FOR THE MAKHWARE SILL.

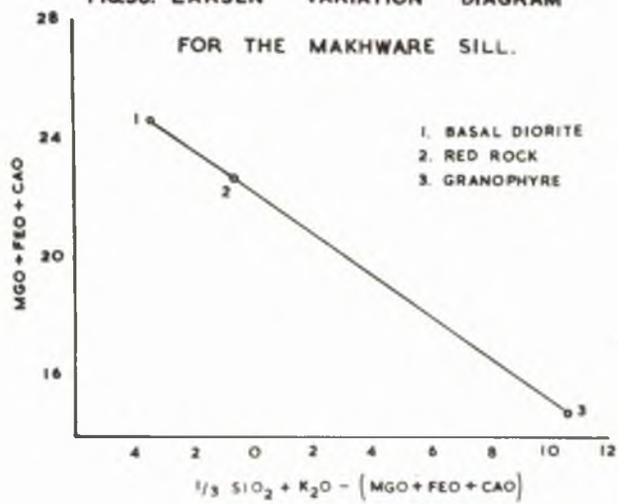
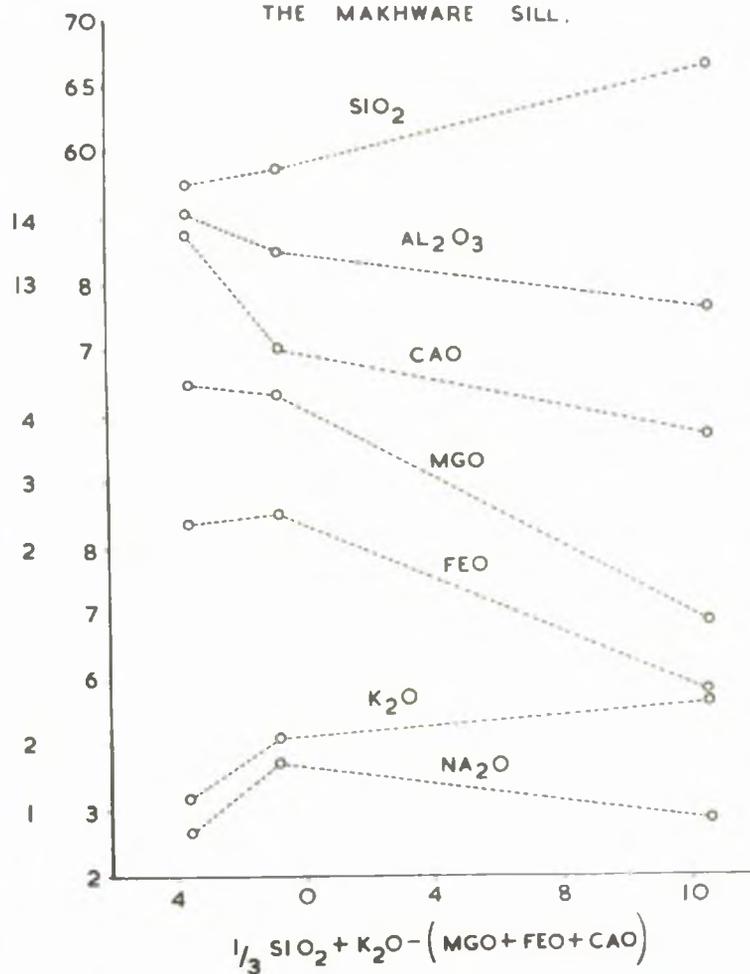


FIG.37. LARSEN VARIATION DIAGRAM FOR THE MAKHWARE SILL.



This hypothesis is also supported by the widespread zoning of individual plagioclase crystals and in their similarly wide compositional variation with height - both normatively and mineralogically (Figs. 5 & 31; Table 35).

Despite the lack of any significant crystal settling, an upward displacement of the abundant acid-alkaline residuum is strongly indicated, - especially as the granophyres and acid red rocks are invariably confined to the upper regions of the intrusion. However, as the chilled Basal Diorite (Table 35) has a higher proportion of normative quartz than the Red Rock, it is possible (in spite of a statement to the contrary by Tuttle and Bowen 1958) that the silica/felspar ratio of the residuum was lower than in the chilled basal phase. Thus, the ensuing differentiation process may have been analogous to that of Tomkeieff (1937), with the exception that the volatile-rich residuum was higher in alkalis, FeO, and Al_2O_3 .

The resulting increased concentration of residual magma beneath the sill roof caused further assimilation and metasomatism of the country rock, - particularly of the granite, which contributed in part to conspicuous colour of the Red Rock horizon. (Most of this reddish hue, however, probably resulted from the dissociation of the $KFeAlSi_3O_8$ molecule (Alling 1936)).

It is also possible that the high normative quartz content of the Basal diorite may be explained by the diffusion of silica from the quartzitic country rock, in which case the silica content of the residuum would probably have been high.

In the Larsen variation diagrams (Figs. 36 & 37) the three analyses of Basal Diorite, Red Rock, and granophyre all fall on the same straight line. This is often regarded as direct evidence of a crystallization-differentiation origin, but as Wager and Deer (1939) have pointed out, a similar arrangement is also shown by some hybrid assimilation products (see p.313). Consequently

it/

seems that at least some of the Tshuhung hornblende-granophyres are hybrid products formed through contamination of the late residuum by felspathised quartzites, - especially as they have the conspicuous reaction hornblende as the sole ferromagnesian constituent. Such a process would be similar to the differentiation-assimilation hypothesis of Daly (1905).

D.

SUMMARY.

The 200 ft. thick Makhware sill forms a composite diorite sheet, the lower portion of which is a grey porphyritic Basal Diorite and the upper section an acid Red Rock. Mineral variation is slight, but shows a general increase in micro: pegmatite and orthoclase with height, while, hornblende replaces pyroxene as the predominant ferromagnesian mineral in the Red Rock horizon. Plagioclase become increasingly more sodic with height, while, at the same time, bytownite phenocrysts show a more complicated oscillatory and progressive zoning.

Due to the high concentration of volatiles in the upper levels of the sill, the assimilation of granite (& quartzite) xenoliths was pronounced, although felspathisation of the quartzite roof was relatively slight - due to its impervious- and non-felspathic nature. All three phases of transformation are distinguishable i.e. iron-metasomatism (as indicated by reaction hornblende in the granophyre), albitisation, and granitisation.

Contact metamorphism has produced a general hardening of the Shoshong quartzites, while at Kuchwe a quartz-magnetite hornfels has been formed. As in the Shoshong sill, the granite is converted to a coarse red floor variety and a granophyric roof type.

The primary mechanism in the differentiation of this sill entails feldspar fractionation coupled with the upward migration of some volatile-rich residuum plus alkalis, FeO, and Al_2O_3 into the Red Rock zone, and subsequently into the feldspathised quartzites and granophyres. Assimilation of granite is believed to have resulted in more acid rock-types, and also in the numerous small hornblende-biotite clots of the Red Rock zone.

THE TAKANE, MAPAIJA, & MAIYABANE SHEETS.

The petrology and field relations of the Takane, Mapaija, and Maiyabane sheets are so similar that formerly they may have been interconnected, or else off-shoots of some larger sheet. Their basic rock type is a quartz-dolerite, but in the Takane sill this grades up into normal quartz-diorites, quartz-hornblende-diorites, granitic rocks, and feldspathised shales and siltstones (Fig. 38).

A. PETROGRAPHY.

Chilled Modifications.

Although the upper and lower chilled margins are preserved only in the Takane sill, basal selvages of this, - like those of Mapaija - generally are fresh, fine-grained porphyritic rocks with phenocrysts of bytownite (An_{71-80}) and bronzite (Fe_{22}) set in an intergranular matrix of labradorite (An_{56}), augite, micropegmatite, magnetite, biotite, and hornblende, (Table 23).

TABLE 23. Mode of Chilled Quartz-dolerite Selvages.

Plagioclase	38.8 %
Micropegmatite	23.4
Pyroxene	29.6
Hornblende & biotite	5.1
Magnetite	3.2

The chilled roof phases, on the other hand, have a variolitic groundmass and carry comparatively few phenocrysts of labradorite and bronzite. They are far more altered, (the pyroxene being completely unaltered and the plagioclase extensively sericitised), but texturally they are similar to chilled roof phases of the Ben Hiant quartz-dolerite boss, described by Thomas (1930, pp. 171-172).

quartz-dolerites.

Although variable in appearance, the typical quartz-dolerite is coarse-grained subophitic, and gray to pinkish in colour. It is composed essentially of zoned plagioclase laths (An_{64-54}), augite, pigeonite, bronzite (Fs_{22-25}), micropegmatite, and accessory magnetite, biotite, hornblende, and olivine. Of these, olivine (Fa_{62}) is a comparatively rare constituent, occurring only as resorbed cores to larger bronzite crystals, while the latter is particularly common near the base of the Mapija sheet. This is often the sole remaining pyroxene in hydrothermally altered rocks, because due to the marked assimilation of aluminous sediments, all the available CaO would have combined with the Al_2O_3 to form anorthite (Kuno 1950; Read 1955; Wilson 1952).

Representative modes of these rocks are given in Table 24

TABLE 24. Modes of quartz-dolerites.

	<u>Do 19.</u>	<u>Do 17.</u>	<u>Do 25.</u>	<u>Do 21.</u>	<u>Do 48.</u>	<u>Do 165.</u>
Plagioclase	29.2	27.7	43.6	26.8	34.9	35.6
Micropegmatite } Quartz } Orthoclase }	11.5	18.6	24.05	21.7	8.14	29.7
Orthopyroxene	11.6	7.5	-	8.7	15.9	-
Clinopyroxene	9.8	8.3	24.55	7.1	24.8	25.6
Hornblende	33.3	33.8	4.86	33.2	4.42	4.4
Biotite	-	1.3	-	-	-	1.8
Magnetite	4.6	2.8	3.07	2.6	2.16	3.0

EXPLANATION LIST TO INDEX NUMBERS IN TABLE 24.

Do 19	} Normal Takane Quartz-dolerite
Do 17	
Do 25	
Do 21	
Do 48	Mapaija quartz-dolerite. High in orthopyroxene having been collected from the base of the sill.
Do 165	Maiyabane quartz dolerite.

TABLE 25. Modes of Takane Quartz-diorites.

	<u>Do 285</u>	<u>Do 286</u>	<u>Do 287</u>	<u>Do 18</u>
Alagioclase	34.5	35.4	28.8	34.1
Micropegmatite } Orthoclase	17.4	14.9	23.1	7.2
Quartz	4.9	10.4	10.2	7.1
Pyroxene	22.3	23.7	19.7	-
Corundum	15.9	11.7	14.6	43.9
Magnetite	3.5	3.9	2.0	3.2
Accessories	1.7	-	1.6	0.7

Takane Quartz-diorite.

In the Takane sill, a poorly defined zone of quartz-diorite overlies the former quartz-dolerite horizon. These diorites are still sub-ophitic, but differ from the dolerites in having more micropegmatite and less pyroxene. The latter, (most of which appears to be a late pigeonite), is frequently pseudomorphed by bowlingite. Individual crystals of both quartz and orthoclase are common, but show poor crystal form. See Table 25 for modes.

Quartz-hornblende-diorites.

Immediately beneath the siltstone roof of the Takane sill is a series of coarse - acid rocks of variable composition and patchy distribution. These are composed of quartz, orthoclase, reaction hornblende, sericitised andesine, chlorite, biotite, and magnetite, - though with little or no pyroxene. Texturally, they are not unlike the Marievale granophyre, and may therefore be termed 'granophyric', although true quartz-felspar intergrowths are rare. Poikiloblastic structures, are not uncommon, as shown by the frequent occurrence of magnetite-riddled reaction-hornblende crystals (Plate 43).

The more acid members of this group constitute a thin zone of pink granitic rocks between the siltstone roof and normal quartz-hornblende-diorites. These, they have veined and brecciated to such an extent, that "intrusion breccias" were formed with fragments of diorite and siltstone embedded in a pink quartzo-felspathic matrix (Plates 2, 20 & 42). Essentially, they are composed of quartz, pink orthoclase, oligoclase, and reaction hornblende, (Plate 44).

Dolerite-Pegmatites.

Within the Takane & Napaija sheets numerous patches and schlieren of dolerite-pegmatite occur. These consist of large hornblende and andesine crystals, together with accessory magnetite and clinozoisite, set in a pink to white micropegmatitic matrix.

A partial analysis of this rock is given in Table 15.

Syntectic Siltstone Veins.

Thin white syntectic veins are common in the chilled roof margins of the Takane sill. Both petrologically and chemically, they resemble the granitic quartz-hornblende-diorites

above, although a single vein may change from a variety, which is identical with the former, to another, in which both hornblende and micropegmatite have been replaced by larger crystals of biotite, quartz, and orthoclase (Plate 45). Generally however, the thinner veins are composed almost entirely of micropegmatite and "chess-board" albite.

Syntectic Sandstones.

Two outcrops of a pink felspathised quartzites were discovered in the Takane area. The best of these, is exposed in a native well, where it forms part of a gently inclined 5 ft. thick mass within the hornfelsed Shoshong shales. It is fine-grained, poorly jointed, and composed mainly of clastic quartz grains marginally replaced by a clouded pink feldspar. Other constituents include sericitised andesine laths (An 36), clusters of cassiterite magnetite and pyrite grains, large poikiloblastic crystals of schorlite, chlorite, clinozoisite, and muscovite. The quartz and pink feldspars show a crude graphic intergrowth, which, apparently is a replacement product.

The Unaltered Shoshong Siltstone.

This rock, which is described as a 'flagstone' by Green (1950), Poldervaart (1952), & Cullen (1957/1958), is light-brown to grey in colour with a slightly coarser bedding than the normal shale. Microscopically, it is composed of small sub-rounded quartz grains set in a brown to grey micaceous matrix. A representative mode is given in Table 26, and a partial analysis in Table 28.

Following Pettijohn's classification (1949, pp. 255-257), - primarily on the basis of mineral composition, this rock may be termed a subgreywacke, but it is doubtful whether

its tectonic association would confirm with such a terminology.

Table 26.

Mode of Shoshong Siltstone.

Quartz	41.7
Muscovite	39.0
Biotite	1.8
Brown Matrix	11.8
Magnetite	3.9
Felspar	1.8

The Metasomatised Siltstones.

At least three stages of metasomatised siltstone are recognised in the Takane sill, these being best seen at Site A. (Plate 2).

Stage 1. The most striking changes here are the growth of larger muscovite and chlorite crystals within the original micaceous matrix; the appearance of large poikiloblastic crystals of pink cloudy felspar (Plate 46); and an increase in the proportion of magnetite. The sedimentary texture of the rock is unchanged however.

Stage 2. In this phase the rock has been coarsened. The enlarged quartz grains adopt a sieve texture by enclosing small pällagonite flakes, silliminite needles, cordierite prisms and magnetite, while interstitially, larger poikiloblastic crystals of chlorite, muscovite, and brown tourmaline appear.

Stage 3. Here the changes of stage 2 are still further accentuated and the chlorite has inverted to biotite, while cordierite is now completely altered to pinnite and the

elongated pällagonite flakes marginally replaced by oligoclase. Furthermore the pink feldspars are also more enlarged, and the sillimanite needles have become grouped as distinct felted masses (Plate 47).

These rocks eventually grade into the more granitic rocks of the Takane sill through the replacement of chlorite and biotite by reaction hornblende, and recrystallization of the pink feldspars to form distinct crystals, or graphic intergrowths with quartz.

As the contacts between these three metasomatised phases are often sharp, there may well have been some plastic flow between them.

B.

PETROLOGY.

Mineral variation from top to bottom of the sill.

Due to the complex nature of the Takane sill, modal variations are somewhat irregular, yet there is a steady decrease in both plagioclase and pyroxene, with height, together with a corresponding increase in quartz, orthoclase, micropegmatite, and hornblende (Fig. 38). Furthermore, at the top of the quartz-hornblende-diorite horizon there is the reciprocal relationship between hornblende on the one hand, and epidote, chlorite, and clinozoisite on the other. This feature may be attributed to the replacement of chlorite and biotite by reaction hornblende in the last stages of metasomatism.

Contacts as a guide to the temperature of intrusion and cooling history of the magma.

The modes of representative porphyritic chilled selvages are given in Table 28.

FIG. 38. COMPOSITE GRAPH OF SITE 'A' IN THE TAKANE SILL.

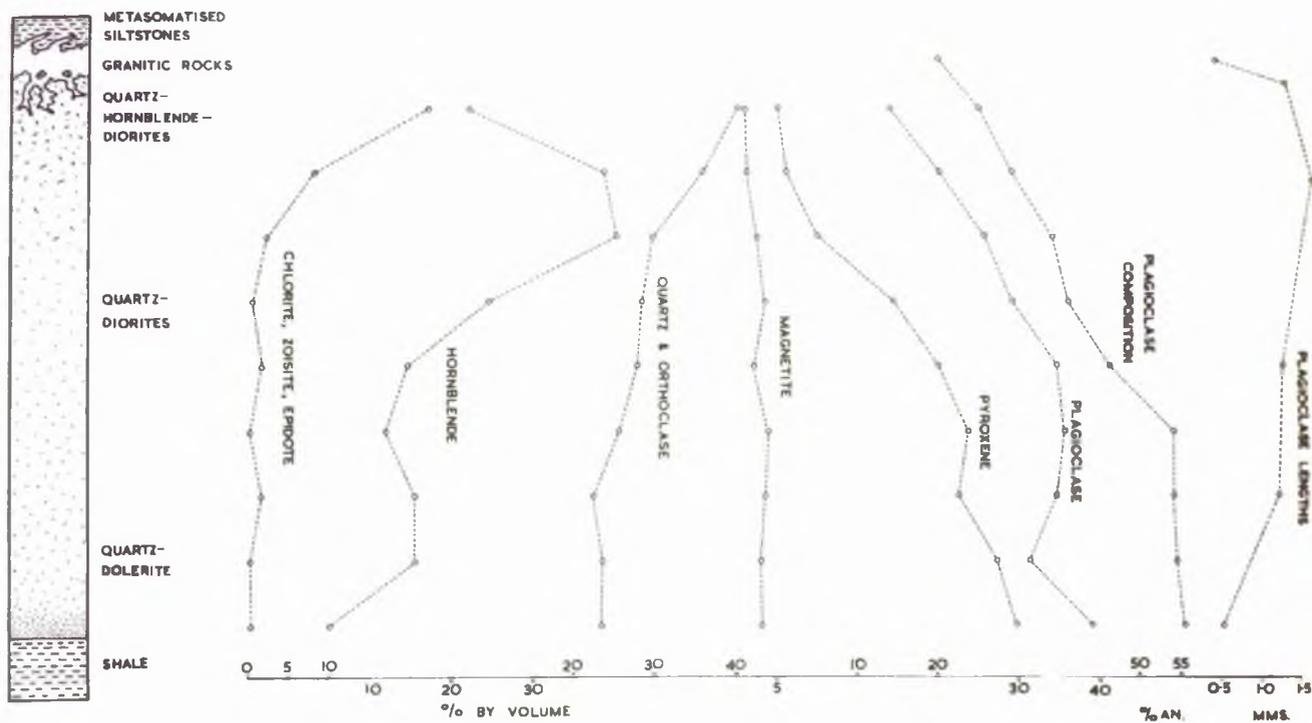


TABLE 27.

Mode of chilled basal selvages.

	<u>Takane</u>	<u>Mapaija</u>
Plagioclase phenocrysts	3.3 %	4.7 %
Orthopyroxene "	0.6	1.2
Clinopyroxene "	1.6	
Matrix	94.5	94.6
Ratio $\frac{P \times 100}{P + f}$	40%	20.4 %

The pyroxene ratios here are normal for most tholeiitic rocks (Walker 1957), and are intermediate between those of the Shoshong and Makhware sills. The initial temperature of the Takane magma was therefore probably between 1070°C and 1080°C, and crystallization began with the separation of plagioclase, followed by augite and finally hypersthene. No conclusion can be made as to the crystallization period of olivine, but as it is enclosed by orthopyroxenes, it probably formed soon after the first plagioclase.

Metamorphism and reaction with the country rock.

Contact metamorphism within the vicinity of these intrusives is slight, and the Shoshong shales are now tough hornfelses with small quartz grains set in a partially re-crystallised micaceous matrix. A few poikiloblastic crystals of schorlite are also present, and small inclusion-riddled cordierite crystals may be observed. They are seldom feldspathised, as are their more psammitic siltstone equivalents.

Similarly, the quartzites are little changed, -
(beyond a slight hardening through the closer interlocking of

quartz grains); yet, in one locality the contact rock is a friable purplish variety composed of arborescent magnetite crystals, interstitial quartz, albite, and orthoclase. Spencer (1908, p. 10-16) suggested that similar Pennsylvanian deposits were produced by iron-rich emanations from the diabase magma metasomatising the country rock. Such an explanation could also apply here - except that such features are more common in limestones-.

The siltstones on the other hand, show a slightly higher grade of metamorphism through the occurrence of sericitised cordierite prisms and felted masses of sillimanite needles (Plate 47). In addition, they are also extensively feldspathised, - this being assisted by localised folding and brecciation during intrusion; for as Blignaut (1952, p. 21) has stated: "Lateral pressure, if present, tends to produce local folding in strata adjacent to an inclined intrusion". "Intrusion breccias" with their pink quartzo-feldspathic matrices (Plate 49) are therefore conspicuous at the immediate contact of the sill rocks and the transformed siltstones.

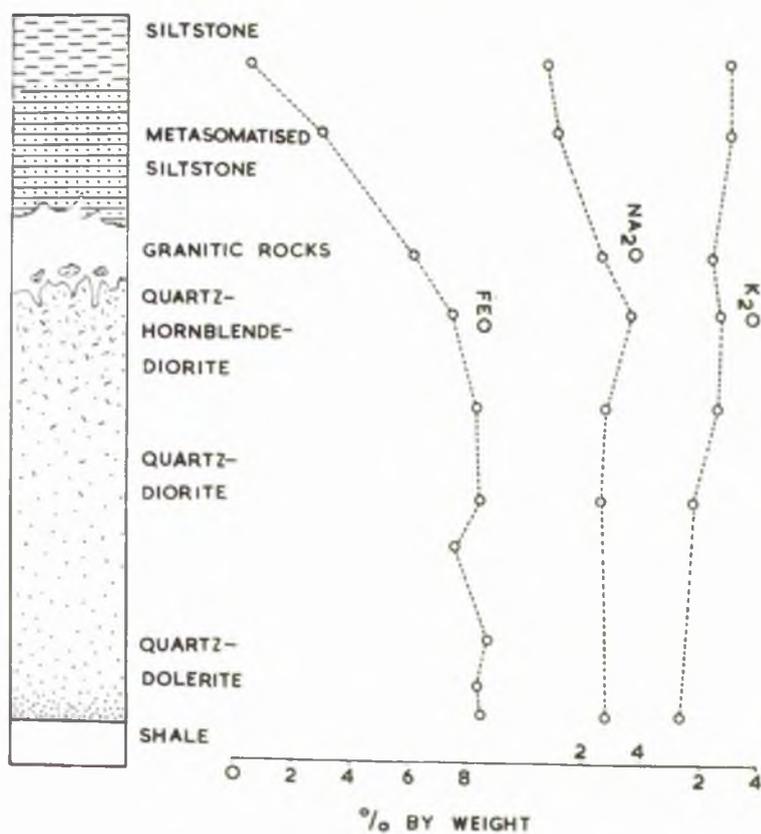
Within the chilled margins, numerous small quartzo-feldspathic patches with tiny prisms of orthopyroxene occur (Plate 22). These retain no clue as to their origin, but probably they are small siltstone xenoliths, which had been caught up by the dolerite magma from the brecciated contact zones. Furthermore, as the syntectic siltstone veins, described above, occur only within the immediate vicinity of such brecciated zones, their mobilization was apparently enhanced by the aquiescence of volatiles and assisted by the comminution of siltstones into small fragments.

PETROGENESIS.

As neither the Mapaija nor the Maiyabane sheets show any significant variation in the field, the ensuing discussion

deals almost entirely with the Takane Sill. The oxide profiles through this sill (Fig. 39) are remarkably similar to those

FIG. 39. OXIDE PROFILES FOR SITE 'A' IN THE TAKANE SILL.



at Tshuhung, (Fig. 31) - despite the metasomatic effects of the former being far more widespread-. Petrologically too, they are similar, for both have a basal zone of quartz-dolerite or -diorite, which grades up into more acid contaminated rocks and felspathised roof sediments.

On this account, it seems that both sills had a similar mode of origin i.e. feldspar fractionation, assimilation, and an upward diffusion of volatiles, alkalies, and FeO. In the

Takane sill, however, these processes were made even more effective by the contemporaneous folding and brecciation of country rock, for, by this the characteristic "intrusion breccias" and syntectic granite rocks were produced.

TABLE 28.

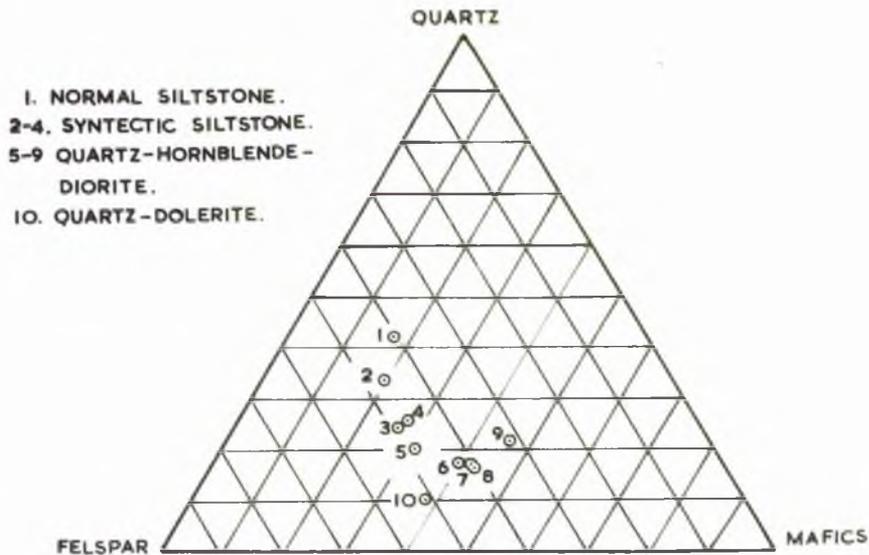
Partial analyses of Transfused Siltstones.

	Unaltered Siltstone	Metasomatised siltstone stage 3.	Syntectic siltstone vein	Acid quartz- hornblende- diorite
FeO	1.62	2.95	4.30	6.13
Na ₂ O	0.70	1.13	2.78	2.51
K ₂ O	2.88	3.11	2.88	2.41

In the overlying siltstones all three transformation phases can be distinguished i.e. basification, albitisation, and granitisation, but as their K₂O; Na₂O ratio was already high, a large introduction of Na₂O was necessary for their transformation (Fig. 39). Thus, in spite of the fact that their replacement was not uniform (but restricted to certain 'channels'), Cullen's suggestion that the feldspathised rocks formed by "recrystallization or preferential segregation of potassic material from the shale under the stimulus of contact metamorphism" is unconvincing (1957/58).

By use of von Wolff's triangular diagrams, however, a further attempt is made to illustrate the effects of these transformation processes, but as no complete chemical analyses are available, plots were made on the basis of modal analyses, instead of the conventional normative values, (Fig. 40).

FIG. 40. VON WOLFF DIAGRAM OF THE TAKANE SILL.



The resulting trends show a distinct desilication of the siltstones followed by basification. The divergence of these trends from those of Reynolds (1946, p. 409) may be explained by the more basic composition of the initial Takane magma.

A final point here concerns the remarkable compositional similarity between the syntectic siltstone vein and the granitic quartz-hornblende-diorite (Table 27), for both have a similar syntectic origin.

SUMMARY.

Three related quartz-dolerite sheets are intruded into the sediments of the Shoshong series, the largest of these being the composite sill of Takane. By slow upward diffusion of the late acid residuum, this has differentiated into a basal zone of quartz-dolerite, similar to the Shoshong sill, together with an overlying zone of quartz-diorite. Above this is an irregular horizon of quartz-hornblende-diorite and felspathised siltstones, which are believed to have

originated through the basification, albitisation, and granitisation of the former siltstone roof rocks by the late acid dolerite residuum. Felspathization was enhanced by contemporaneous folding and brecciation of the siltstones on intrusion, while syntectic veins of this penetrate the dolerite and the more basic quartz-hornblende-diorites.

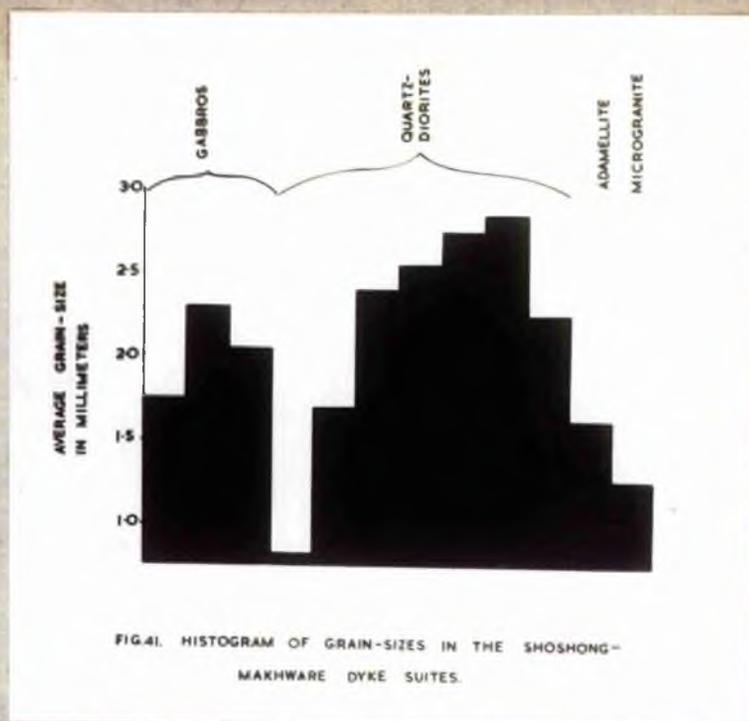
Evidence from the chilled porphyritic selvages indicates that the temperature of the magma on intrusion was about 1070°C . to 1080°C .

SECTION 8. THE SHOSHONG-MAKHWARE DYKE SUITES.GENERAL DESCRIPTION.

Earlier in this paper, reference was made to the occurrence of two prominent Post-Loskop dyke suites in the Shoshong-Makhware area. Briefly, (Plate 1), these follow two major N.W. and E.N.E. fault trends, and are represented by dioritic and microgranitic rocks respectively. A re-examination of certain critical sections which were mapped by Green (1950) as showing dioritic dykes transecting earlier microgranitic members, has failed to confirm any evidence for the younger age of the former, - indeed the reverse seems to be the case.

In several localities beneath the Shoshong sill, outcrops of dolerite feeder dykes exist, but apart from the fact that they have the same general East-West trend of the large dolerite dyke 10 miles south of Shoshong, extensive weathering has prevented any more detailed investigations.

Five petrological varieties are represented by the dykes of this area:- the Shoshong sill feeder dykes are all dolerites, the E.N.E.-W.S.W. set microgranites, and the N.W.-S.E. set gabbros, quartz-diorites and adamellite. These are distinct both petrologically and, in their average grain-size, - the quartz-diorites being coarser - and the microgranites finer-grained, as shown in fig. 41.



PETROGRAPHY.

Dolerite Dykes.

In the Shoshong sill, these are fine-grained basaltic rocks with a sub-ophitic texture and occasional phenocrysts of plagioclase (An 77) and hypersthene (Fs 20).

In some dykes, small dark-green basic clots, similar to those of the Makhware Red Rock, appear, but, as the dyke rocks are entirely confined to the Mahalapye granite, it seems that they must in fact be transfused granite xenoliths.

In the Makhware area, dolerite feeder dykes are very poorly exposed, but one dyke on the eastern slopes of Tlakadeawa contained phenocrysts of sericitised plagioclase and elongated prisms of pigeonite ($2V 15^\circ$ with the optic plane parallel to (010)).

Modal analyses of these rocks are given in Table 29, but as there is no direct relationship between these and the

main basic dyke suite, any future reference made to "the basic dyke suite" will not include the dolerite dykes.

The Dioritic Suite.

Although primarily a coarse undersaturated gabbro, the rocks of this suite (due to extensive assimilation and hydrothermal alteration), now comprise a variable group, the predominant variety of which is a coarse pink quartz-diorite.

The majority of these dykes are confined to the area between the Shoshong and Makhware ranges, but on one hillock named Phate hill 5 miles east of Kuchwi, a small boss of quartz-diorite was found. This body, which has a distinct chilled roof margin (Fig. 42), is up to 60 yards wide and 100 yards long, while the dykes are 7 to 170 yards wide and up to 24 miles long (Plate 50).

Gabbros.

The only true gabbro dyke in the area occurs approximately 2 miles south of Kalamare following a W.N.W. trend. Although evidence of its belonging to the main dioritic suite is scanty, this is indicated by its similarities in texture, grain-size, and geographical trend.

In thin section the Kalamare gabbro is a coarse dark greenish rock with large labradorite laths (An 63), augite (α 1.693, β 1.723, $2V$ 39° , & $c^{\wedge}z$ 47° , abundant serpentine pseudomorphs after olivine and orthopyroxene, large skeletal titan-magnetite crystals, and accessory biotite, apatite, hornblende, epidote, and calcite, (Plate 48). A few unaltered remnants of bronzite are still discernible (Fs 20 & $2V$ 74°), while interstitial quartz (probably of late hydrothermal origin) becomes increasingly more abundant towards the margins.

The more typical 'gabbros' of this suite comprise a series of highly altered light green-grey rocks, which differ both chemically and mineralogically from the Kalamare gabbro. Still, assuming that they are the more altered equivalents of the gabbro, the most striking changes incurred are: the replacement of serpentine by scattered needles and patches of tremolitic amphibole ($\delta' 1.662 \text{ \AA}$ $c \wedge z 18^\circ$) and talc; albitisation epidotization and sericitisation of the plagioclases; partial uralitisation of augite by light green uralite horn; blende and chlorite; and an increase in the proportion of quartz, orthoclase, epidote, and clinozoisite.

The gabbroic rocks of Phate, although compositionally similar to the above, differ in being finer grained and having less tremolitic amphibole. Instead, they have more quartz and orthoclase, while numerous magnetite grains riddle the uralitised pyroxenes.

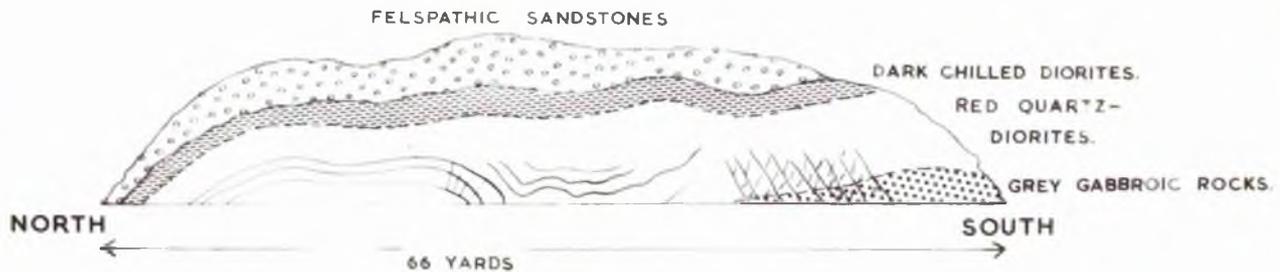
Representative modes of these rocks are given in Table 30.

Quartz-Diorites.

These are typically coarse pink rocks, which differ from the gabbros in having more pink orthoclase and quartz. The pyroxenes are all uralitised, and the plagioclases are sodic, pink, and completely sericitised. Clinozoisite and chlorite are abundant (Plate 55), but the gabbroic texture is still retained, and occasionally even remnants of the (001) augite exsolution lamellae in orthopyroxene.

In the only two intrusions where the 'gabbro' and quartz-diorite are associated, (the Phate hill boss and a large dyke cut by the Mahalapshwe River 8 miles north of Mahalapye), - the quartz-diorite member generally overlies the 'gabbro'.

FIG. 42. SECTION OF THE PHATE HILL BOSS EXPOSED
IN THE KUCHWE RIVER CUTTING.



An admirable example of this was found on the Southern slopes of Phate hill (Fig. 42). Here, the dark grey 'gabbro' grades up into a lighter pink variety, which has large needles of magnetite, increased proportions of quartz and orthoclase, and a few elongated prisms of orthopyroxene (Ps 37) and plagioclase (Plate 51). Above this, the rocks, which are even more acid, contain small quartz xenocrysts, each enveloped by a thin rim of pink orthoclase (Plate 52), but near the top of the hill, large prisms of hornblende appear, (Plate 53). The thin zone of chilled rocks overlying these, however, is relatively inconspicuous containing numerous patches of pink micropegmatite, sericitised plagioclase (An 32-48), abundant amphibole (frequently as pseudomorphs after pyroxene phenocrysts), and needles of magnetite, (Plate 54).

In the composite Mahalapshwe dyke these relations are poorly shown. The transitional zone between the underlying grey gabbro and the upper quartz-diorite is only about six feet in width, and there is no evidence of any assimilation.

About 5 miles south-west of Kuchwe Gorge, a relatively thin quartz-diorite dyke with approximately the same N.W.-S.E. trend was discovered. Although a relatively fine-grained acidified variety, this has a well preserved porphyritic chilled margin with phenocrysts of labradorite (An 56) and augite (γ 1.712, & $2V$ 49°), while the main dyke rock is not unlike the chilled quartz-diorites of Phate hill.

Finally, beside the Mahalapye-Tsethong road eleven miles from Mahalapye, a dark-grey dioritic rock (Di 41) was observed. This has a conspicuous flow structure and is composed essentially of plagioclase, pyroxene, quartz, orthoclase, and accessories. In neither its mineralogical composition, texture, nor chemical composition does it show any resemblance to the main dioritic suite, but field exposures are too poor to permit any clarification of this.

Adamellites.

The single representative of this which is exposed in the bank of the Mahalapshwe River about 7 miles north of Mahalapye, shows no apparent variation in the field. It is essentially a medium grained red rock with red orthoclase, pink sericitised andesine (An 33), quartz, and accessory sphene, magnetite, chlorite, hornblende, and epidote. The rock has a typical granitic texture, and is thus similar in appearance to the microgranites.

The Microgranite Suite.

The rocks of this suite are more uniform in nature being typically pink and grey varieties composed of sericitised oligoclase, orthoclase, quartz, occasional pink phenocrysts of perthite, and accessory chlorite, epidote, hornblende, sphene, magnetite, and biotite. Sometimes, as in the thin microgranite dykes intruded within the contorted garnetiferous Mahalapye granite $1\frac{1}{2}$ miles north of Kalamare, small clusters of pink

almandine garnet are observed.

About four miles east of Mmamphaleng hill a peculiar small dyke of pink quartz-porphyry was discovered. This has phenocrysts of quartz, microcline, and perthite set in a fine-grained 'felsitic' matrix of quartz and orthoclase, plus accessory chlorite, epidote, and magnetite.

C. PETROLOGY.

METAMORPHISM.

Evidence of contact metamorphism is poor generally, and the only example was found in a river cutting of the composite Mahalapshwe dyke, where blocks of well-jointed granite have become marginally reddened. This reddening effect, which was also recognised by Green (1950), may be due to the introduction of late hydrothermal solutions rich in $\text{Fe}(\text{OH})_2$, reprecipitating some iron as hematite dust in the granite.

CHEMISTRY.

The most striking feature of these analyses is the unusually high alkali content of the basic dykes, - the sole exceptions to this being the anomalous pyroxene-diorite (Di 41) and the Kalamare gabbro (Table 31). Thus, as the silica content of the Mahalapshwe dyke is low, (Table 32) these two factors have combined to produce high normative contents of nepheline, olivine, and albite. The alkali content however, was checked three times with an Eel flame photometer, so that an experimental error is improbable, - besides which, as the titania is also low, the presence of normative nepheline cannot be due to the substitution of SiO_2 in the pyroxene by titania, as suggested by Nockolds (1954, p. 1009) and Searle (1960, p. 29). Still, after comparing the Kalamare gabbro

with its more altered equivalents at Phate hill and in the Mahalapshwe dyke, it seems reasonable to assume a fairly high degree of albitisation of these basic dykes after they had solidified.

Although the contrast in composition between the gabbros and the pink quartz-diorites is here relatively slight, full analyses would undoubtedly show some significant differences. The greatest variation in these oxides occurs in the hybrid quartz-diorite zone of the Phate hill boss (Table 35). Here the total alkali content is 8.88%, as compared with 7.24% in the underlying gabbros. In general therefore, the quartz-diorite members are more alkali-rich than the 'gabbros'.

CONCLUSION.

With the relatively meagre evidence available no detailed discussion on the petrogenesis of these rocks can be presented; but it appears that the pink quartz-diorites are hydrothermally altered and contaminated equivalents of the earlier gabbros. Consequently, it is assumed that two different magma types existed during the emplacement of these dyke suites, - an undersaturated gabbroic variety and an oversaturated granitic counterpart. Various intermediate types were subsequently produced through contamination of the gabbroic variety by included granitic material and later hydrothermal alteration.

D.

SUMMARY.

Within the Shoshong-Makhware area are two prominent dyke systems - a N.W.-S.E. dioritic suite and a later E.N.E.-W.S.W. microgranitic member. Whereas the latter is fairly

uniform in composition, the dioritic suite, (although basically an undersaturated gabbroic magma), includes a variety of hybrid pink quartz-diorites with occasional xenoliths of granite.

The extensive sericitisation and uralitisation of plagioclases and pyroxenes together with the high alkali content indicated by the chemical analyses, suggest that these rocks were subjected to extensive hydrothermal alteration and albitisation.

A number of dolerite feeder dykes also occur within the area, these being petrologically similar to the corresponding Shoshong and Makhware sills.

TABLE 29.

MODAL ANALYSES OF DOLERITE FEEDER DYKES.

	<u>Co 2</u>	<u>Co 6</u>	<u>Dy 13</u>
Plagioclase	37.6	36.4	31.3
Micropegmatite } Quartz & Orthoclase	13.5	13.4	26.3
Orthopyroxene	4.9	21.7	6.2
Clinopyroxene	31.9	24.7	25.4
Hornblende & } biotite	7.9	8.7	6.5
Magnetite	4.3	1.6	4.3

- Co 2 - Margin of large dolerite dyke in the Sekgwaape hills which 'feeds' the Shoshong sill.
- Co 6 - Core of the above same dyke.
- Dy 13 - Thin dolerite dyke $1\frac{1}{2}$ miles north of Kalamare.

TABLE 30.

	<u>Dyke 1.</u>		<u>Dyke 2.</u>		<u>Dyke 3.</u>		<u>Dyke 4.</u>
	<u>Sy 1</u>	<u>Sy 2</u>	<u>J 412</u>	<u>D1 38</u>	<u>D1 32</u>	<u>D1 3</u>	<u>D1 41</u>
Plagioclase	25.93	24.00	41.2	49.1	47.2	47.2	27.6
K-Felspar	41.60	23.50	10.7	5.9	11.4	12.9	10.8
Quartz & Micropegmatite	1.09	19.30	5.4	1.9	12.5	10.6	21.6
Hornblende	21.67	25.60	34.9	20.4	14.5	12.6	10.4
Magnetite	5.24	2.6	3.9	3.9	3.0	2.1	-
Accessories	5.15	5.20	4.9	11.8	11.1	14.8	3.3
Pyroxene	-	-	-	8.0	0.3	-	25.9
An %	(30-50)	(30-50)	(28-32)	(24-50)	(31-44)	(30)	(37-52)
	<u>Dyke 5</u>	<u>Dyke 6</u>	<u>Dyke 7</u>				
	<u>D1 37</u>	<u>D1 34</u>	<u>MGM 8</u>	<u>MGM 8w</u>			
Plagioclase	38.8	32.8	34.22	36.3			
K-Felspar	6.5	9.6	12.35	3.1			
Quartz & Micropegmatite	7.4	17.5					
Hornblende	21.5	32.0	1.96	16.1			
Magnetite	3.3	5.1	5.98	10.6			
Accessories	9.3	3.0	20.68	1.2			
Pyroxene	13.2	-	22.83	30.50			
An %	(33-38)	(31-57)	(63)				

Explanation list of index numbers given in metal
analyses.

- Sy 1 Light pink quartz-diorite from isolated dyke
outcrop about 4½ miles E.N.E. of Kalamare.
- Sy 2 Slightly darker pink variety.
- Di 33 Red quartz-diorite from Mahalapshwe dyke 3 miles
north of Mahalapye.
- Di 37 Green-grey gabbro beside track 6 miles north of
Mahalapye.
- Di 34 Fine-grained quartz-diorite dyke 5 miles south-
east of Kuehwe Gorge.
- J 412 Major dioritic dyke 4 miles north of Kalamare.
- Di 41 Grey dioritic dyke beside Mahalapye-Taethong road
10 miles north of Mahalapye.
- HGM 8 } Kalamare Gabbro dyke 4 miles south of Kalamare.
HGM 9 }

MODAL ANALYSES OF REPRESENTATIVE SPECIMENS FROM PHATE.

	Di 11	Di 12	Di 6	Di 13
Plagioclase	16.9	11.77	19.7	46.0
Orthoclase	31.9	35.20	13.7	12.9
Quartz	15.0	13.43	12.7	7.1
Hornblende	17.2	32.43	39.6	24.1
Magnetite	5.6	6.1	14.1	7.8
Accessories	14.4	1.1	0.4	0.2
% An	(32-48)	(28-33)		(28-38)

	Typical Microgranite	Adamellite
Plagioclase	33.4	29.4
Orthoclase	23.2	26.1
Quartz	27.3	31.0
Hornblende		4.3
Chlorite	3.3	4.8
Sphene		2.6
Magnetite	2.2	1.8
% An	(14-26)	(33)

Index numbers the same as in analyses (Table 31) except for:-

- Di 11 - Chilled roof margin. (Phate hill).
- Di 12 - Pink quartz-diorite above Phate gabbro.
- Di 6 - Coarse pink contaminated diorite at Phate.

TABLE 31.PARTIAL ANALYSES OF ROCKS FROM THE DIORITIC SUITE.

	D1 41	D1 38	D1 31	MGM 8 _w	D1 3	J 412.
FeO	6.32	7.00	8.97	8.92	7.74	7.18
Na ₂ O	3.07	4.32	3.81	2.63	5.40	3.65
K ₂ O	0.69	2.29	3.35	0.67	2.43	1.37
<u>K₂O x 100</u>	18.4	34.7	46.8	20.3	31.1	
<u>K₂O + Na₂O</u>						

J 412 - The largest dioritic dyke 5 miles north of Kalamare.

D1 38 - "Gabbro" of the Mahalapshwe dyke.

D1 31 - Fine-grained quartz-diorite dyke 5 miles S.E. of Kuchwe.

MGM 8_w - Kalamare gabbro dyke 2 miles south of Kalamare.

D1 3 - Quartz-Diorite of Mahalapshwe dyke.

TABLE 33.PARTIAL ANALYSES OF THE PHATE HILL BOSS.

	D1 13	D1 15	D1 20	D1 26
FeO	6.29	8.69	7.30	7.62
Na ₂ O	4.42	3.75	5.39	5.58
K ₂ O	2.82	2.34	3.49	1.30
<u>K₂O x 100</u>	38.9	38.5	39.3	18.9
<u>K₂O + Na₂O</u>				

D1 13 - 'Gabbro' at base of Phate hill.

D1 15 - Light pink quartz-diorite above the latter.

D1 20 - Red quartz-diorite with small quartz xenocrysts.

D1 26 - Chilled roof diorite.

TABLE 52.

ANALYSIS AND NORM OF GABBRO FROM MAHALAPSEWE DYKE.

	<u>Σ</u>
SiO ₂	49.84
Al ₂ O ₃	16.22
Fe ₂ O ₃	1.95
FeO	7.00
MgO	7.51
CaO	8.53
Na ₂ O	4.32
K ₂ O	2.29
H ₂ O ⁺	1.16
H ₂ O ⁻	1.29
TiO ₂	0.86
Total	<u>100.77</u>

Orthoclase		13.34
Albite		20.96
Nepheline		8.24
Anorthite		18.35
Magnetite		3.02
Ilmenite		1.67
Diopside	{ En	6.20
	{ Fs	3.17
	{ Wo	9.78
Olivine	{ Fa	5.00
	{ Fo	8.49
Water		<u>2.45</u>
Total		<u>100.67</u>

COMPARISONS AND SUMMARY OF PETROLOGICAL SEQUENCE

The petrology of each large intrusive in the Shoshong-Yakware area has been described, but the fundamental relationship between these and the magmatic cycles of the Union has still to be explained. The foregoing discussion purports to fill that gap.

Summary of Field Relations and Relative ages of Intrusions

As the absolute dating and correlation of these intrusions is greatly hampered by the paucity of stratigraphic horizons of known age, the maximum use has been made of their intrusive relations and general tectonic trends. This was greatly facilitated by further correspondence with the Geological Survey with respect to certain critical sections.

The resulting sequence of intrusion is summarised in Table 34. It is almost certain that the Shoshong sill, being confined entirely to the Mahalapye granite, is the oldest, but deductions as to the relative ages of the remaining sheets, which intrude the Shoshong sediments, are more controversial. As field data give no further indications here, the problem is essentially a petrological one, but by correlation of the tectonic trends in the area, it appears that the dyke suites are younger than any of the above intrusives, and that the microgranitic suite are later than the basic dyke suite.

Comparison of the petrology of the Basic Intrusives.

The petrology of these intrusives is uniform; they have similar reaction and metamorphic effects, and are composed

of primary mineral phases of approximately the same composition. Thus primary orthopyroxenes range between Fs 20 to Fs 26, augite is generally sub-calcic and plagioclase acid labradorite. These show a definite sequence of crystallization i.e. bytownite, (An₇₃₋₈₅), augite, orthopyroxene, magnetite, and micropegmatite, while the pyroxene ratios of their chilled selvages show a general increase from 13.3% in the Shoshong sill to 62% in the Makhware sill (Table 34). This also indicates a corresponding decrease in temperature of the initial magmas of each sheet according to its time of emplacement (Table 34).

TABLE 34.

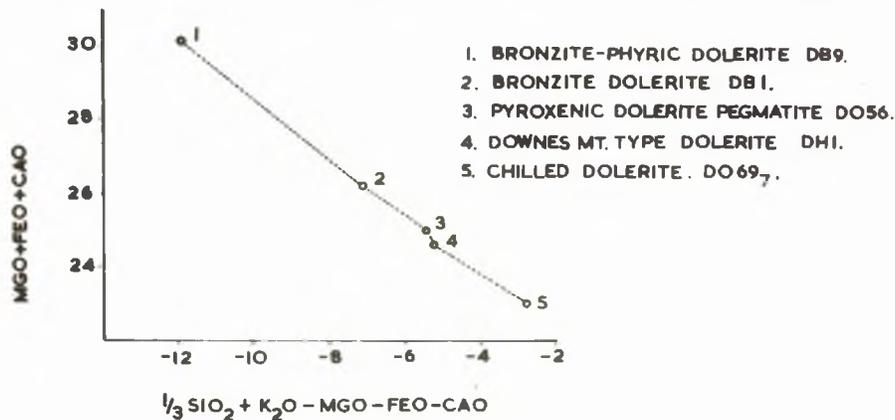
<u>% by volume</u>	Shoshong Sill	Mapaija	Takane	Makhware	Kuchwe dyke
Plagioclase	2.6	4.7	3.3	2.4	6.3
Pyroxene	0.4	1.2	2.2	3.9	2.1
Matrix	97.0	94.6	94.5	93.7	91.6
<u>P x 100</u>					
P + F	13.3%	20.4%	40.0%	62.0%	25.0%
Estimated temp. of magma	1100°C	1080°C	1070°C	1000-1050°C	1078°C
Total % by vol. of phenocrysts.	3.0	5.9	5.5	6.3	8.4

Conclusions of Petrological Sequence

The Shoshong sill is the largest, and most basic of these intrusives, and although all are differentiated to some degree, its basal sections have by far the highest proportion of orthopyroxene, and hence MgO, (Figs. 28 & 35, Tables 24 & 35). It should be mentioned however that in these sheets the axiomatic assumption that the chilled phases of an intrusion represent the initial magma composition does not seem to hold, and instead, a method based on comparisons and deductions through Larsen

variation diagrams must be used (Fig. 43). By this, the composition of the Shoshong magma appears to have been equivalent to that of the bronzite-phyric dolerite 220 ft. above the sill floor at Malebadi, i.e. specimen DB 1 (Table 35).

FIG. 43. LARSEN VARIATION DIAGRAM FOR THE SHOSHONG SILL.



Magmatic activity therefore, was initiated by the emplacement of the extensive Shoshong sill in two successive influxes, but although the first phase was almost completely aphyric (except for a few small plagioclase phenocrysts (An_{84}), the second had a number of intratelluric orthopyroxene phenocrysts, and it was during this phase, that the Mapaija sheet was emplaced, (this being closely followed by that of Takane, and subsequently after a slightly longer interval, by the Makhware sill). A comparatively long period then elapsed while these solidified and were subsequently faulted. The cycle was terminated by the emplacement of the large gabbroic, dioritic and microgranitic dykes within the Mahalapye Granite.

The gabbroic members of these dykes are especially interesting, for in spite of their high alkali content, they are remarkably similar to the 'undifferentiated' Shoshong magma, the essential differences being explained by leaching of FeSiO_3 ,

and the addition of alkalis through hydrothermal liquids, (Table 32 & 35).

On this account it seems possible that two different magmatic cycles existed here during post-Transvaal and Pre-Karoo times. The first of these gave rise to the basic differentiated sills of Shoshong, Mapaija, Takane, Maiyabane and Makhware, while the second cycle is represented by the two prominent dyke suites.

The rocks of both cycles are tholeiitic and range from basic dolerites and gabbros to acid granophyres and microgranites.

Although the primary magma of both cycles had approximately the same initial composition, the first was a normatively over-saturated hypersthene-dolerite with very little olivine, and the second a normatively undersaturated olivine-hypersthene-gabbro (Tables 32 & 35).

In deriving the primary magmas of the first cycle, the present author envisages a mechanism analogous to that of Larsen (1940 pp. 921-946). He showed that in Central Montana, these were derived from a magma equivalent to the primary olivine-basalt of Kennedy (1933) by the removal of hypersthene and bytownite under deep-seated conditions. The derived magmas, which represent liquids tapped from different levels of an differentiated subterraneous magma chamber, were injected into their present environments, where they continued to differentiate, - though modified by special conditions of assimilation and crystallization. By this means, the wide variety of calc-alkaline rock-types were produced.

Although the Shoshong-Makhware intrusives are by no means so spectacular, the later Makhware magma is lower in Al_2O_3 , CaO, and MgO, but higher in SiO_2 , FeO, Na_2O , K_2O , and Fe_2O_3 , - and this would correspond with lower normative

TABLE 35.

	R 1.	Do 56.	DB 1	DB 9	K 7	K 13	R	
SiO ₂	57.01	54.71	53.90	52.21	64.34	SiO ₂	55.31	
Al ₂ O ₃	13.92	15.23	15.40	13.18	12.18	Al ₂ O ₃	12.87	
Fe ₂ O ₃	2.95	3.71	1.50	2.97	3.17	Fe ₂ O ₃	2.49	R 1 - Chilled basal phase of Malheur Sill Analyt: W.H. Herdman & P.L.C. Grubb.
FeO	8.28	8.20	7.10	7.60	5.56	FeO	8.12	
MgO	4.42	4.23	8.40	9.12	0.83	MgO	4.13	Do 56 - Fyromio dolerite-pegmatite of Shoshong Sill. Analyt: W.H. Herdman & P.L.C. Grubb.
CaO	8.68	8.84	9.60	10.36	4.59	CaO	6.66	
Na ₂ O	2.61	3.27	2.00	1.96	2.71	Na ₂ O	3.55	
K ₂ O	1.30	1.30	0.80	0.80	2.53	K ₂ O	2.00	
H ₂ O ⁻ 105°C	0.20	0.56	n.d.	0.07	0.91	H ₂ O ⁻	1.39	DB 9 - Bronzite-phyric dolerite of banded section, Shoshong sill. Analyt: W.H. Herdman.
H ₂ O ⁺ 105°C	n.d.	n.d.	n.d.	0.60	n.d.	H ₂ O ⁺	0.23	
TFiO ₂	n.d.	n.d.	n.d.	0.65	n.d.	TFiO ₂	1.01	
MnO	n.d.	n.d.	n.d.	0.07	n.d.	MnO	n.d.	
CO ₂	n.d.	n.d.	n.d.	0.06	n.d.	CO ₂	n.d.	DB 1 - Top of Bronzite-phyric dolerite horizon of Shoshong Sill. An estimate based on mineralogical compositions and proportions.
P ₂ O ₅	n.d.	n.d.	n.d.	0.21	n.d.	P ₂ O ₅	n.d.	
Quartz	8.16	2.28		-	25.86	Quartz	3.96	
Orthoclase	7.78	7.78		5.00	15.01	Orthoclase	11.68	
Albite	22.01	27.77		16.77	23.06	Albite	29.87	
Anorthite	22.24	22.80		24.46	13.34	Anorthite	13.34	
Dioptside	4.50	4.60		7.40	1.00	Dioptside	4.40	
	3.96	3.96		2.64	3.04		3.56	
	8.70	8.82		10.90	3.94		8.24	
Hyperssthene	10.11	9.40		18.60	1.60	Hyperssthene	9.20	
	8.84	8.05		6.47	4.49		7.52	
Magnetite	4.18	7.66		4.41	4.64	Magnetite	3.71	
Ilmenite	-	-		1.37	-	Ilmenite	1.98	
Apatite	-	-		0.34	-	Apatite	n.d.	
Water	-	-		0.59	-	Water	1.62	
Oil vlns	-	-		5.74	-			
	-	-		2.24	-			
	101.48	100.52		106.93	96.08		98.16	

K 13 - Malheur Red Rock from Tahuhung.
Analyt: W.H. Herdman and P.L.C. Grubb.

contents of anorthite and hypersthene. This is also reflected in the similar composition of the Makhware chilled phase and the Shoshong pyroxenic dolerite-pegmatite, for both show the same degree of iron-enrichment and have similar normative contents of anorthite and hypersthene (Tables 35 and Figs. 29 & 35). Consequently, as differentiation in the Shoshong sill was mainly restricted to the gravitative settling of hypersthene together with the slight separation of calcic-plagioclase, it seems logical that the composition of the late stage differentiates of the Shoshong sill should be similar to that of the hypothetical subterranean magma body, - assuming that this mechanism was also active in the latter body.

In conclusion, the author envisages the formation of a large subterranean body of tholeiitic magma, equivalent in composition to the Shoshong dolerite specimen DB 1. While this was still in a completely molten state, a large volume was drawn off and emplaced as the extensive Shoshong sill. When this had solidified to a weak crystal mesh, renewed supplies of magma from the same underlying chamber were injected immediately above the earlier phase. At this stage, the primary magma of the chamber had begun to crystallise with the separation of bytownite, hypersthene, and augite crystals. As the upper regions of the chamber became relatively impoverished in the above constituents, the future primary magmas of Takane, Mapaija, Maiyabane, and Makhware became more dioritic in composition. The phenocrysts, which were caught up in these magmas and are now preserved within the chilled phases, were more abundant in the later intrusions, at which stage crystallisation of the underlying chamber was more advanced (Table 34).

While deductions as to the petrological sequence of magmas responsible for the major dyke suites are even more suspect, the similarities of primary magmas in both cycles is

noteworthy. Due to the wide diversity of rock types encountered in these dykes, it appears that conditions of differentiation were not quite the same as those in the first cycle, so that although gravitative settling of orthopyroxenes and calcic-plagioclases probably occurred, the quiescent conditions and greater amount of time available here favoured an upward concentration of felsic constituents, with the formation of alkali-rich diorites and microgranites, - this being assisted by some assimilation of the granitic country rock.

In Central Montana Larsen (1940) rejects an origin of the potassic and alkalic provinces by assimilation, but instead, he maintains that the special conditions necessary for slow differentiation of the magma are admirably illustrated by the tectonic history of the area; so that the various magmas of these subprovinces were derived from a common deep-seated layered magma body. Still, he admits, that after they had been intruded, these magmas were modified through the assimilation of country rock, which increased the relative proportions of their more felsic end-members.

A different emphasis on this problematic association of rock-types was advanced by Chapman and Williams (1935, pp. 519-528) for the White Mountain district. By applying Stokes Law and using the viscosities given by Daly (1933, p. 193) for moderate depths in the earth, they calculated that the rate of settling of an olivine crystal 0.5 mm. in diameter at depths of 30-40 miles in the crust is practically negligible in the time available. Consequently, they envisage the invasion of the crust by a vast body of basaltic magma assisted by stoping, assimilation, and pure melting of the country rock. At higher levels, due to the slightly lower temperatures of the magma, fractional crystallisation of the basaltic and syntectic magmas predominated, while different stages of the fractionating liquids were 'tapped' and subsequently intruded

into their present positions. A complete sequence of rocks therefore, starting with undifferentiated gabbroic types and ending with syenites and granites was formed, although they emphasise that no further differentiation occurred after the final emplacement.

SUMMARY AND RELATIONSHIPS OF DOLERITES IN THE
EASTERN PROTECTORATE

Several dolerite intrusions have been recorded and mapped within the Eastern Protectorate, but details of these are still scanty. The first comprehensive survey was made by Du Toit (1939 p. 195) in which he proposed that the extensive Shoshong and Molepolole sills were of post-Waterberg age (Plate 6). In 1952 however, when more details were available, a further survey of the dolerites in the Eastern Protectorate was attempted by Poldervaart. While admitting that 'Some difficulties were experienced in determining the relations of dolerites of the Eastern part of the Protectorate, especially in distinguishing between Karroo and the so-called Waterberg dolerites' (p. 126) Poldervaart concluded that the petrological similarities of the Romoutsa-Molepolole dolerites with the Karroo sheets at Semarule, renders it more likely that the intrusions are all of Karroo age'. Similarly, the Molepolole sheet, which intrudes Waterberg sediments and consists of fresh picrite-dolerite, Poldervaart claims 'can be matched by similar rocks of Karroo age in the Karroo basin proper.' (p.126). Recently, Boocock (1959) has shown that neither the Semarule alkaline complex nor the associated dolerites are of Karroo age, so that true Karroo dolerites are rare in the Eastern Protectorate. In dealing with the Shoshong sheet, Poldervaart (1952) states that this consists of a 'rather altered, quartz-rich dolerite identical with specimens obtained from sheets in Karroo beds which encircle the Shoshong granite

area to the west; in fact it seems highly probable that these sheets are off-shoots of the main Shoshong intrusion.' The above statement is surprising. His brief description of the 'Shoshong dolerite' would hardly apply to any representative specimen from the sill as a whole, this being characteristically a fresh rock with little hydrothermal alteration. Furthermore, the Takane, Mapaija, and Kaiyabane sheets are petrologically distinct from the main Shoshong sill, so that the possibility of their being direct off-shoots of the latter is remote.

Cursory examination of dolerite outcrops at Naka-la-Phala and Bonopitsa, showed a distinct resemblance between these and the Shoshong 'off-shoots', besides which, as nearly all are intruded within the same sedimentary horizon, they are probably of the same relative age - post-Transvaal and pre-Waterberg. It is also interesting that similar rock associations are recorded in these sheets. Thus at Naka-la-Phala and Maipithlwane, Poldervaart notes the association of dolerite and pink quartz-syenite; - the latter being a transfusion product of the associated cherty Transvaal dolomite. Again in dolerite sheets near Matlha-Banelo, Cullen has observed examples of pink 'monsonite' or 'syenodiorite' produced by the transfusion of included blocks of arkosic Shoshong flagstones (personal communication). Finally, Cullen (1957/58) briefly described the igneous intrusions in the Shoshong series as consisting of "related dolerite and syenodiorite, with subordinate masses of syenite and ultrabasic rocks". The localised ultrabasics, which are associated with dolerite and syenodiorite, consist predominantly of olivine and pyroxene and hence may be regarded as "local differentiates from a basic magma" (1958, p.6). The 'syenodiorites', he finds have "a restricted distribution being confined to the contact zone between dolerite and sediments of the Shoshong

series". This is remarkably similar to the situation encountered in the Makhware and Takane sills.

For the 'group of dolerites intrusive in Waterberg sediments in the area south of Palla Camp' (this including the Debeeti hill 'diorite'), Poldervaart again suggests a Karroo age. While the present author makes no claim as to the age of the latter intrusion, it is interesting that a specimen collected from a large outcrop beside the main road has little resemblance to the average Shoshong dolerite. See Table 36.

TABLE 36.

	<u>Mode of Debeeti 'diorite'</u>	<u>Average Shoshong Dolerite DB 1.</u>
Plagioclase	44.8%	47.4
Micropegmatite	23.0%	14.3
Orthopyroxene	6.8%	14.1
Clinopyroxene	7.1%	20.5
Hornblende	10.7%	2.6
Biotite	4.9%	
Magnetite	<u>2.7%</u>	<u>1.1</u>
	<u>100.0%</u>	<u>100.0</u>

Although both rocks are hypersthene-bearing quartz-dolerites, the Debeeti specimen differs in being non-porphyrific with less pyroxene and more micropegmatite, hornblende and biotite. On this account it is termed a 'hypersthene-diorite' by the Geological Survey.

The Khale dolerite sheet, which occurs in red granite just north of Gaberones, has been described by Poldervaart (1952) and Hales (1959). They emphasise its close petrological resemblance to the normal Downes Mountain-type dolerite of the Union, for which reason they maintain that it is Karroo in age. Boocock (1959) disagrees however, pointing out that

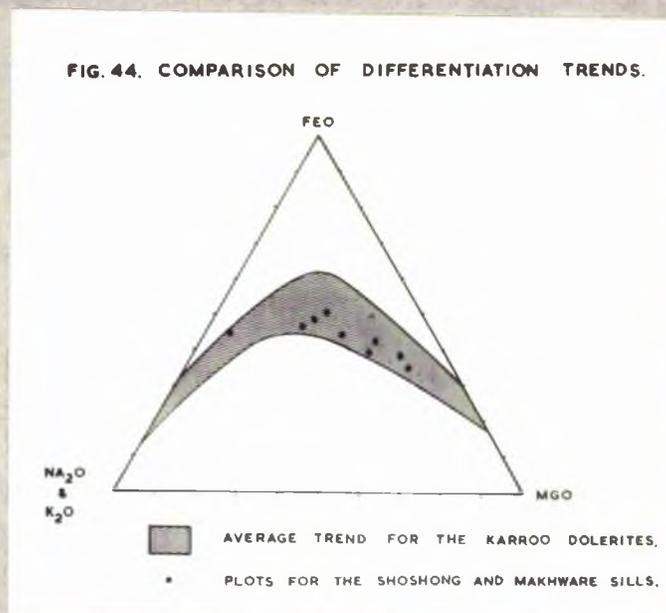
Post-Waterberg - Pre-Karoo dolerites are particularly common in the Eastern Protectorate, and that no field evidence for a Karroo age of the Khale sheet exists. Chemically too, it shows little resemblance to the Downes Mountain-type dolerite of the Shoshong sill, as it is higher in FeO and TiO_2 but lower in MgO and CaO.

Finally, in dealing with dioritic dyke suite of the Shoshong-Makhware area, both Green and Poldervaart again assume a Karroo age, and Poldervaart states further that 'Preferred strike directions of the dykes are W.N.W. and N.N.E.' while 'the W.N.W. dyke swarm appears to be the dominant set'. Field evidence as to the age of these dykes is admittedly difficult to obtain, but the author can find no petrological resemblance between these and the average Kentani type of established Karroo age (Walker and Poldervaart 1949) (1950), because the true Kentani dolerite is normatively oversaturated and also has less MgO, - not to mention the differences in the textures and general appearance.

In conclusion therefore, it appears that, whereas dolerites in the Eastern Protectorate are of different ages, the majority of those found within the extensive Mahalapye-Shoshong area were Post-Transvaal Pre-Karoo in time.

POSSIBLE RELATIONSHIP TO THE KARROO MAGMATIC PROVINCE.

The possible consanguinity of the Shoshong-Makware intrusives with the Karroo dolerite province was discussed by Poldervaart (1952), and commented on by the present author, but despite strong evidence against this, certain petrological affinities between these do exist. Poldervaart (1952) was the first to recognise that the Shoshong sill is composed of two dolerite types, which are petrologically similar to the Downes Mountain - and Hangnest-type dolerites of the main Karroo Province. These only differ from types Karroo specimens in being darker with less plagioclase, and Al_2O_3 , but more MgO and Na_2O (Fig. 44 & Table 35). In this respect, the Khale sheet is far closer to the type Downes Mountain dolerite (Eales 1959).



An even more formidable obstacle is encountered, when attempting a petrological correlation of the Takane, Mapaija, Maiyabane, and Makware sheets with type Karroo dolerites; - still, these have one particular feature in common with the true Downes mountain and Hangnest

types, for they all have porphyritic chilled selvages. It is also possible that the great similarity between these sheets and the quartz-mica-diorites near Klip Fontein (du Toit, 1906 pp. 66-67) would lend support to the argument for a Karroo age.

COMPARISON OF THE SHOSHONG MAKHWARE INTRUSIVES WITH THE BUSHVELDIGNEOUS CYCLE.

Many analogies and comparisons have been made between the Shoshong-Makhowe intrusives and those of the Bushveld complex in the Union. The petrological resemblance of the former intrusives towards the Bushveld sequence is far greater than it is to any other province or sub-province in Southern Africa.

Besides the extensive norite zone of this lopolith, a second phase of basic magmatic activity, which resulted in the emplacement of a series of differentiated diabase dykes and sills, is recognised. Although the relative age of these is controversial, - Daly maintaining that they precede the main norite mass, and Hall and du Toit (1924 & 1932) arguing that they are of the same or slightly later age, - their similarity to the sills of the Shoshong-Makhowe area is significant.

In dealing with the relationship of these hypabyssals to the main norite zone, du Toit, Daly, and Hall are all agreed. Daly (1924 p. 31) states that these "sills may represent the main Bushveld magma in its chemical state just before the differentiation of felsite and norite". Thus, if the Shoshong sill was contemporaneous with the Bushveld cycle, its average composition would correspond with that of the norite - and this, Table 37 confirms.

Similarly, the late salic differentiates of the Bushveld lopolith form a well-defined compositional group, which corresponds closely with that of the Makhowe hornblende-granophyre (Fig. 45), so that their compositional trends, are remarkably similar -, although the Bushveld lopolith shows a higher degree of fractionation, due to its greater bulk and longer period of solidification.

Lombaard (1934) found that the norite-diabase periphery, which is comparable with the Mull Plateau magma (Table 37, No. 1; & Table 38, No. c), was formed by fractional crystallisation - either together with the tholeiitic diabase from some unknown magma, or from the tholeiitic diabase magma itself. This factor is particularly important in view of the striking similarity between the norite-diabase periphery and the Shoshong bronzite-phyric dolerite (Tables 35, 37 & 38). The main complication however, arises in the method by which Lombaard distinguishes between Pre-Karoo "diabases" and Post-Karoo "dolerites". He maintains that the pyroxenes of all Bushveld diabases are represented only by hypersthene and diopside-hedenbergite, while those of the Post-Karoo dolerites include pigeonite. He agrees with Tsuboi (1932), that pyroxenes crystallising in a more effusive state are often pigeonitic, but the present author does not regard this as a satisfactory criterion for such a distinction, because as the Shoshong-Makware intrusives had only a relatively thin cover of country rock, it is possible that such "effusive" conditions existed here too. In the Transvaal, on the other hand, the pressure due to the vast bulk of the Bushveld lopolith was probably sufficient to inhibit the crystallisation of pigeonite. It appears accordingly that the basic intrusives of the Shoshong-Makware area which also intrude Transvaal sediments are of Bushveld age, and therefore, probably outlying satellites of that great complex.

TABLE 37.

COMPARISON OF ANALYSES OF BUSHVELD NORITE
AND THE SHOSHONG DOLERITE.

	1.	2.	3.	4.
SiO ₂	50.80	51.80	53.90	52.21
Al ₂ O ₃	16.41	17.95	15.40	13.18
TiO ₂	1.38	.27	n.d.	.65
Fe ₂ O ₃	.20	.46	1.50	2.97
FeO	10.79	7.85	8.18	7.60
MnO	.47	.35	n.d.	.07
MgO	5.84	7.91	8.40	9.12
CaO	10.69	11.16	9.60	10.36
Na ₂ O	1.91	1.70	2.00	1.96
K ₂ O	.42	.27	.80	.80
H ₂ O ⁺	1.07	.49	n.d.	.60
H ₂ O ⁻	.10	.14	n.d.	.07
P ₂ O ₅	.16	.11	n.d.	.21
CO ₂	-	-	n.d.	.06

1. Abnormal diabase sill in Mahaliesberg shale. De Grootse Boom 214 Farm.

E.G. Radley, analyst.

2. Average analysis of the main Bushveld norite quoted from Daly 1928,

EGSA. V. 39, Table XVI. No. 4. p. 741.

3. Average deduced analysis of Shoshong dolerite. DB 1.

4. Hypersthene-rich dolerite from banded section of Shoshong sill.

Malebadi hill. W.H. Herdsman, analyst.

TABLE 38.

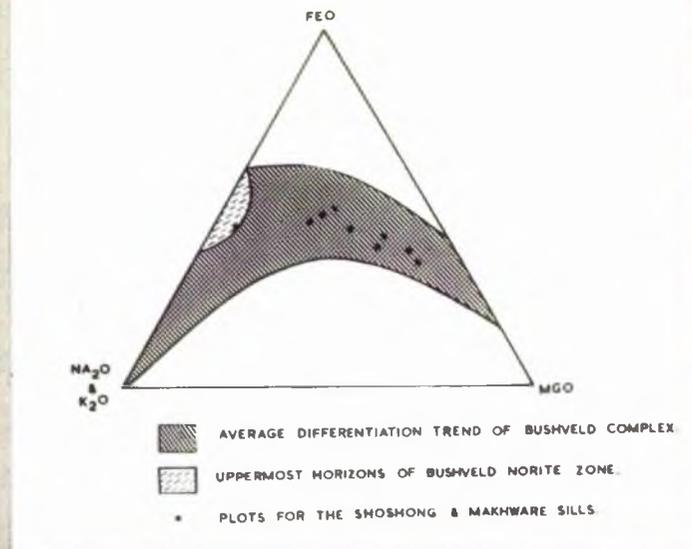
	<u>a.</u>	<u>b.</u>	<u>c.</u>
SiO ₂	54.00	53.95	52.00
TiO ₂	0.48	0.90	0.44
Al ₂ O ₃	10.30	9.55	13.96
Fe ₂ O ₃	4.85	0.80	4.54
FeO	8.75	11.40	6.75
MnO	0.20	0.15	n.d.
MgO	9.90	9.45	9.30
CaO	7.65	8.50	9.40
Na ₂ O	1.50	0.95	1.90
K ₂ O	1.04	1.50	0.44
P ₂ O ₅	0.10	0.15	0.06
H ₂ O ⁺	1.60	2.30	0.60
H ₂ O ⁻	<u>0.10</u>	<u>0.15</u>	<u>0.12</u>
	<u>100.47</u>	<u>99.75</u>	<u>99.51</u>
Quartz	9.24	7.26	5.70
Orthoclase	6.12	8.90	2.22
Albite	12.58	7.86	16.24
Anorthite	18.35	17.51	28.36
Diopside	{ CaSiO ₃ 7.89	9.78	7.66
	{ MgSiO ₃ 5.00	5.38	5.30
	{ FeSiO ₃ 2.38	4.36	1.72
Hypersthene	{ MgSiO ₃ 19.70	18.30	17.90
	{ FeSiO ₃ 9.37	14.65	6.20
Ilmenite	0.91	1.67	0.76
Magnetite	6.96	1.16	6.73
Apatite	0.34	0.34	-
H ₂ O	<u>1.70</u>	<u>2.45</u>	<u>0.78</u>
	<u>100.54</u>	<u>99.54</u>	<u>99.57</u>

a. Diabase (fine-grained). Waterval. No. 40. Lydenburg district. Analyst: B. Lombaard.

b. Diabase (fine-grained typical) Lydenburg station. Analyst: H.G. Weall.

c. Diabase, adjoining norite, De Kafferskraal. No. 359. Lydenburg district. Analyst: B. Lombaard.
(The typical "Norite-d diabase" of Lombaard (1934)).

FIG. 45. COMPARISON OF DIFFERENTIATION TRENDS.



STRUCTURE OF THE AREA AND MECHANISM OF INTERUSION.

The structural history of the Shoshong-Makware area is not well known, for although Green (1950) and Cullen (1958) recorded several large-scale folds and faults, they completely ignored minor structures, such as joints and shearing. Nevertheless, by a statistical analysis the present author suggests a possible structural interpretation for the area - although still fully aware of the comparatively small size of his area and meagreness of the available data.

RESULTS OF PREVIOUS WORK.

Green (1950) was the first to recognise any foliation in the Mahalapye granite, and this he claimed was the roof zone of a more extensive granite pluton. He also described a "synclinal structure" in the Takane hills, and the "drag effects" on this produced by the major east-west Mosulutsane fault.

Later, Cullen (1958) gave a brief account of the general structure of the entire area:-

"The dominant structure of the Shoshong area is a broad, low, westerly-pitching anticline which affects rocks of the Basement Complex and the Shoshong series, and associated intrusive suites. Dips rarely exceed 10° to 12° . The pre-Karoo age of the anticlinal folding is demonstrated by the overstep of Ecca Series grits and conglomerates on to the Basement Complex at Mosulutsane, Leselinte and east of Boyo.

The anticline has been affected by extensive, complex faulting. The major faults trend in a general WNW - ESE direction, but often deviate to E - W or NW - SE, and the downthrow is almost invariably on the north".

Although Cullen here refers to True North, in the ensuing context the Magnetic North is adopted by the present author.

GENERAL DESCRIPTION OF STRUCTURES IN THE SHOSHONG-
MAKHWARE AREA.

Prior to the publication of the above report by Cullen (1958), the present author had already held similar views of the structural relations here.

All observed faults and folds in the Shoshong-Makhware area were measured and recorded, and particular attention was paid to jointing in the granite, quartzites, and basic intrusives. These joints were plotted stereographically and then superimposed on an outline map of the area, on which the most important structures are shown (Plate 1). This is considered to be the most satisfactory method of combining all the observed structural features within the minimum amount of space.

Folding.

Although few folds occur in this area, (these being confined to the Mosulutsane, Tlakadeawa, and Kalamare regions), the entire area is itself part of a large anticlinal structure, that plunges gently in a westerly direction. In the northern Makhware region, therefore, the Shoshong sediments dip in a northerly direction at 5 to 25 degrees, while further south in the Shoshong area, the granite foliation dips more steeply in a south- to westerly direction at 10° to 42° . In the Mosulutsane region, the Shoshong sediments and associated intrusives dip in a westerly to north-westerly direction at 5° to 35° .

while further north in the Maiyabane area, dips vary between 5° and 15° towards the west.

This anticlinal structure has also produced a series of intense local folds parallel to its fold axis and, with the sole exception of those near the Mosulutsane fault - their fold axes are all remarkably similar in trend, although plunges vary considerably.

Faulting.

It is unfortunate that due to the very poor exposures in this area, some faults may have been completely overlooked, while others were virtually unmeasurable.

The largest fault, which now forms the picturesque Kuchwe Gorge (Plate 8) has, like most N.-S. faults, a downthrow on the eastern side with a nett displacement of about 100 ft. Its less striking counterparts, on the other hand, have lateral NNE - E displacements, and sometimes, WNW - NW (as recorded by the Geological Survey south of the Mahalapye-Shoshong area).

The major fault trends of the Mahalapye-Shoshong area between Artesia and Naka-la-Phala, are plotted in a rosette diagram (Fig. 46).

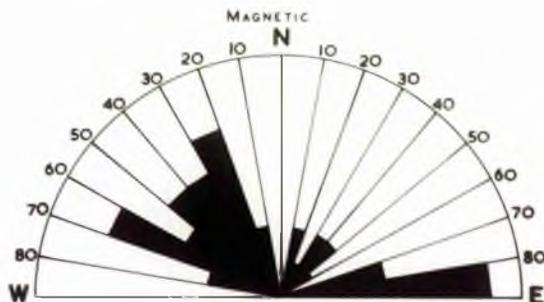


FIG.46. DIAGRAM SHOWING GENERAL DIRECTION OF FAULT TRENDS BETWEEN LATITUDES $22^{\circ}30'S$ & $24^{\circ}S$ AND LONGITUDES 26° & $27^{\circ}W$ IN THE BAMANGWATO RESERVE.

Three distinct maxima are shown, - one corresponding to the WNW normal faults, and the other two to the lateral NWN and E-W wrench faults, while finally, a minor concentration of normal faults shows a general NE-SW trend.

Jointing.

When stereographically plotted, jointing conforms to a fairly regular pattern (Plate 1), so that if Nevin (1936), Weiss (1954), and Turner and Verhoogen (1951) are correct in assuming that tensional-joints are more common than shear joints in regionally deformed rocks such as dolerites, then both cross 'ac' - and longitudinal 'bc'-joints predominate in the Shoshong-Makware area. In addition, a few (Ok1) and (hk0-) joints also exist, while shear zones parallel to the ENE cross-joints frequently occur in the Mahalapye granite.

PROPOSED INTERPRETATION OF THE STRUCTURAL HISTORY OF THE SHOSHONG-MAKWARE

AREA.

The ideal pattern of structural features, produced by a stress system of directional compression, has long been understood. This was described in detail by Anderson (1951), who used a number of regions, including the South Wales coal field, the Midland areas, and Scotland, as examples: The sequence is initiated by folding and thrust faulting perpendicular to the greatest stress direction (σ^1). Subsequently, the strain ellipsoid becomes rotated 90° about σ^1 until the least stress (σ^3) is in the horizontal plane. Two pairs of wrench faults (Sinistrals and Dextrals) then form at an acute angle to σ^1 , and these are soon followed by tension-release normal faults parallel to σ^1 . The sequence is then terminated by the relaxation of

compression and the formation of normal faults perpendicular to the former direction of 'a'.

Thus, in the Shoshong-Makware area, regional deformation was initiated by the formation of the large anticlinal structure with minor folding and occasional brecciation, (as in the area north of Kalamare (Plate 1)). This was accompanied by faulting in the Mathla-Banselo-Molelemans area.

Through a slight decrease in pressure parallel to the 'b' fabric axis, caused by the extension of the anticlinal structure in this direction, two sets of dextral and sinistral faults were formed. The first of these are well developed with an approximately $E 10^{\circ} N$ trend, while the second, being $N 25^{\circ} W$ trending sinistrals, are found only in the area to the south-east of that described.

After all movement along these faults had ceased, a period ensued, when the main north-south compressional force was reduced, and a number of prominent $W 25^{\circ} N$ normal faults were produced such as the Mosulutsane fault. These were generally oblique (as observed from the slickensides on Mmamphalang hill) and had a downthrow on the northern side.

This sequence of events was terminated by a further elongation of the anticlinal structure with the formation of several large $N 30^{\circ} E$ normal faults, which cut across the earlier structures. At this stage too, the prominent cross and longitudinal joint sets were formed.

MECHANICS OF INTUSION.

Sills.

One of the most useful accounts of the mechanics of sill formation was compiled by Anderson (1951). By simple graphical means he convincingly

elucidated the relationship between the various stress systems and the resulting intrusion forms (p. 52). From this, he concluded that the optimum stress conditions for sill-formation are that the two larger forces should act in a horizontal direction, while the minimum stress remains vertical.

Although the total thickness of the Shoshong series is estimated by Cullen (1958) to be approximately 1260 feet, (together with an additional 600 feet of Mahalapye granite above the Shoshong sill), - the hydrostatic pressure existing in this area at the time of sill emplacement must have been considerably less than that in the Karroo Tasmanian and Palisadan provinces. Thus Anderson's theory of sill-emplacment receives adequate support in Bechuanaland.

du Toit (1920) in his study of the Karroo dolerite Province, has observed a general confinement of sills to the base of thick argillaceous bands overlying more closely-jointed Quartzite horizons. His explanation of this is that the latter with their more prominent vertical jointing offer better potential feeder channels than the shales.

In the Cape Peninsular a rather different situation is described by Walker (1956). Here dolerite dykes, after traversing the Cape Granite and Basal Shales, end "bluntly and abruptly" against the widely-jointed base of the Table Mountain quartzite, which lies immediately above the shale horizon.

In the Ermelo district, however, Krige (1929) observed horizontal dolerite sills intruding the massive Basement granite. These, he suggests, resulted from the tangential pressure produced by the heating effects of overlying intrusions, - this causing a decrease of pressure in the lower levels of the crust.

Recently (1957), Carey gave a summary of the intrusion mechanics of sills, lopoliths, and lava flows, with particular reference to the development of conical dolerite sheets, which are often encountered in the Karroo, Palisadan, and Tasmanian Provinces. While emphasising the scarcity of normal sills in the Basement Shield or in previously folded and compacted sediments, he suggests "a compromise between this tendency to intrude laterally as sills and to rise as a steep cone sheet through the sediments" (p. 167), so that "the resulting intrusion tends to be a much flatter cone sheet which becomes even flatter as it rises" (p. 167). This closely fits the description of the Eureka Cone Sheet near Zeehan (Spry, 1957 Dolerite Symposium).

In the Karroo and Palisadan provinces dolerite sheets are more basin-shaped with dips decreasing inwards (du Toit, 1920; Hotz, 1953). Lombaard (1952) therefore, suggests an origin similar to that of normal cone sheets, but Hotz (1953) states that "the mechanism ----- is not clearly understood" (p. 386). Still, he admits that in the absence of any fractures, the magma could have made its own way by wedging (p. 387).

With the above factors and arguments in mind, an explanation of the intrusive behaviour of the Shoshong-Makhware sills is greatly facilitated.

Reference to Plates 2 and 3 shows a remarkable conformity between the attitude of the Shoshong sill and that of the granite foliation. The latter is often accompanied by an increased development of fractures and joints parallel to the 's'-plane, - this being admirably demonstrated by the joint diagram between the Tauklo and Dekokong hills (Plate 1)-.

Despite this uniformity, the above pattern is broken in the most northerly part of the Western Shoshong range by the sheet adopting a conical form with inward dips of 12° to 35° (Plate 2). Outcrops of this are found only in the southern part, - the northern half apparently, still being

concealed by its granite overburden -. A smaller and less striking example of this conical form is found on the hill due west of Mmamlekeleabe. Here, the margins dip inwards at 30° , though increasing towards the centre.

Hence, although vertical feeder dykes are common in the massive core of the Mahalapye granite pluton, the initial basic magma, on reaching the more impervious foliated granite roof zone, was deflected laterally as an extensive sill-like body (the Shoshong sill); while the remaining sheets were concordantly intruded into the overlying Shoshong sediments.

The contrast in behaviour between the Makhware sill and the dolerite dykes in the Cape Peninsula, - both of which have intruded similar geological horizons, - can be explained by one of two alternatives:-

1. The hydrostatic pressure due to the overlying rock burden was less in the Makhware region than in the Peninsular at the time of intrusion.

2. The hydrostatic pressure of the intruding magma was greater in the Makhware region.

For reasons already mentioned (p.134), the author favours the first of the alternatives. Besides, although both du Toit (1920) and Krige (1929) observe that the younger Karroo dolerite sills in the Union are injected beneath their older members, this situation does not seem to apply to the Shoshong-Makhware area, - despite the fact that the Shoshong sill is the heaviest and most basic in composition (Krige 1929, p. 58; du Toit, 1920, p. 33)

Dykes.

The emplacement of the two prominent dyke suites followed closely upon the regional deformation of the area. Upon relaxation of the major north-south compression, a series of WNW tension-release normal faults were formed, and along these the basic magma of the earlier dioritic suite was

emplaced. Subsequently, with further compression release, the E 10° N dextral faults were intruded by the acid magma of the microgranitic suite.

14.

ASPECTS OF WEATHERING AND SOIL FORMATION IN THE
SHOSHONG - MAKHWARE INTRUSIVES.

A. INTRODUCTION.

Two different weathered products are recognised in this area, - a black soil derived from the Shoshong dolerite, and a red-brown soil from the later dioritic intrusives -.

B. GENERAL DESCRIPTION.

The Shoshong sill.

The resistant Shoshong dolerite forms a steep mesa-like range 200 to 400 feet above the pediment. On top of this there are a series of shallow basins filled with a derived black soil (or Mukutwane) and other decomposition products.

In the weathering of this dolerite both pigeonite and orthopyroxene are replaced by bowlingite, while the plagioclases are sericitised, but as this pseudomorphism of pyroxene involves both hydration and removal of FeSiO_3 , the optic axial angle is enlarged (as in the pigeonite of Malebadi, which changes from 27° to 30°). Besides, due to the greater replacement along basal partings, pigeonite is generally more altered than orthopyroxene.

The Black Soil or 'Mukutwane'. This fine dark-grey powdery soil consists essentially of a brown or colourless montmorillonoid clay mineral ($\alpha 1.522$), a few clouded feldspar grains, rounded quartz granules, magnetite, calcium carbonate pellets, and small angular fragments of hornblende. The soil is relatively alkaline in nature having a pH of 7.89, while the organic content is only 0.968% to 1.050% by weight. Furthermore, it has a high moisture absorption capacity and supports a more dense vegetation cover than the corresponding Red-brown soils. When dry, it has a cloddy appearance with an abundant development of mud cracks.

Identical soils are also associated with the Bushveld norite zone and the dolerite intrusions of Tasmania. In both cases they are restricted to regions of poor drainage and relatively low rainfall, - this accounting for their general increase in alkalinity with depth and crude zonal differentiation into A and B horizons. Because of their low organic content, they are quite distinct from the black soils, which constitute the intrazonal horizons of the High Veld, E. Province, and Natal Coastal Belts. It is probably to the latter variety, however, that Walker and Bolderwaard (1949) refer, when they state that, the colour of the soil depends "chiefly on the degree of oxidation and amount of humus present" (p. 692).

The Makhware and Takane Sills.

These rocks, - particularly the hydrothermally altered varieties -, are even more susceptible to weathering, for three inches beneath the surface plagioclases may be extensively sericitised and pyroxenes replaced by bowlingite.

The Red-brown Soil.

This soil, which varies from a dark-red sand rich in heavy minerals, to a fine red 'clay', also has a high proportion

of unaltered mineral fragments. The above sands, which consist of rounded quartz grains, pink feldspars, green hornblende, abundant magnetite octahedra, a little ilmenite and pyrite, and a few larger quartzite and diorite fragments, were derived by effective washing and erosion during periods of heavy rainfall.

The fine Red-brown soil, on the other hand, consists predominantly of an abundant red montmorillonite clay mineral ($\alpha 1.622$), various magnetite grains, rounded quartz granules, and a few altered fragments of pyroxene, feldspar, and hornblende. It is slightly acid in nature having a pH of 6.20, although the organic content is only 0.55% to 0.76% by weight. Its water absorption capacity is slightly lower than that of the 'Mukutwane'.

C. ORIGIN OF THE MUKUTWANE AND RED-BROWN SOILS.

The origin of these two different soils from similar rocks and under identical climatic conditions is problematic.

Contrary to Reiche's calculated order of weathering potentials (1943, pp. 58-68), Shima found that acid rocks are more susceptible to weathering than basic types. Similarly, Tyrrell (1909, p. 308) and Smythe (1932, pp. 45-46) find that acid quartz-dolerites are more easily decomposed due to the dissolution of apatite and alkali feldspar through leaching, and resultant disintegration of the micropegmatitic matrix.

It appears, therefore, that there are two important factors in the weathering of any rock: internal drainage and initial rock composition. The black doleritic soils, which are regarded as immature products, were thus formed from basic rocks with high $\text{FeO}:\text{Fe}_2\text{O}_3$ ratios, because these, on weathering, produce an active montmorillonoid colloid with a high volume expansion, and this preserves the ferromagnesian in a low state of oxidation. Conversely, in better drained regions, or where

there are significant proportions of magnetite or sand granules, the red soils are predominant, (Lombaard 1934; van der Merwe 1941; Nicholls 1957).

The above conclusions compare favourably with the situation in the Shoshong-Makware area, for here, the Shoshong sill is confined entirely to the impervious Mahalapye granite, and has a higher $\text{FeO}:\text{Fe}_2\text{O}_3$ ratio than the remaining intrusives.

Finally with regard to the Mukutwane-filled basins of the Shoshong range, - Enslin (1943), has observed that "local basins of decomposition may be formed where ground water is dammed by dolerite intrusions, and weathering may extend deeply in such places". It appears, therefore, that these were initiated in a manner analogous to the development of large-scale swallow- or sink-holes in limestone terrain, for, due to the impervious nature of the underlying granite floor, water was dammed up and decomposition continued to thereby accentuate their peculiar morphological features.

-----oOo-----

A P P E N D I X.METAMORPHISM AND RHEOMORPHISM.

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The object of this section is to provide a feasible explanation for the contrasted behaviour of the roof and floor granite in the Shoshong sill.

A Distribution of temperature.

Jaeger (1957 & 1959) calculated that the highest contact temperatures of a normal dolerite sill are between 600°C and 700°C, - and, if his basic equations are reliable, this would also apply to the Shoshong sill. Yet, Walker (personal communication) points out that high temperature minerals eg. tridymite, are common in such contact metamorphosed rocks, and none of Jaeger's explanations for this are entirely convincing.

It seems more probable, therefore, that contact temperatures in the Shoshong sill were in the region of about 700°C.

B Estimated hydrostatic pressures.

The total pressures at the top and bottom of the Shoshong sill are estimated to have been 149 Kg/cm², and 188 Kg/cm² respectively, yet these figures are undoubtedly low. Walker (1953, p. 54) points out that "Sills in which dolerite-pegmatite is found do not seem to be over 500 metres thick and the depth of cover was probably in the order of 1 km. to 5 km.", besides which, sheets less than 500 ft. thick are seldom differentiated, and even in those of more than 1000 ft. thick, rhythmic layering does not occur. All the same, the calculated difference in pressure between the roof and floor of the sill is appreciable.

C Quartz - Felspar melting relations.

Some confusion still appears to exist as to the exact

crystallization behaviour between quartz and felspars, but the recent work of Tuttle and Bowen (1958) has shown that whereas the minimum melting point of granites under anhydrous conditions is 960°C , this may be decreased to 640°C in charges with more water.

D. Suggested Hypothesis.

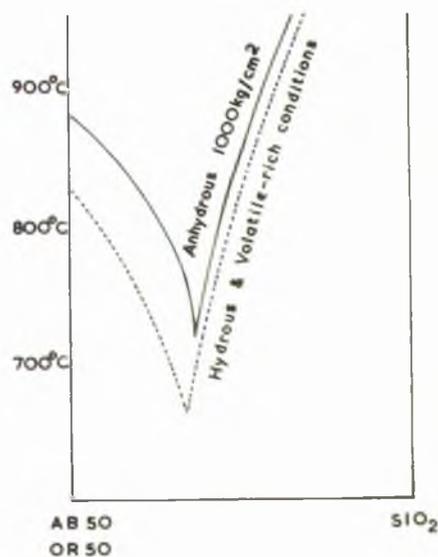
One possible explanation for the contrasted behaviour of the floor and roof granites in this sill might be dependent on pressure; for as Birch, Schairer, and Spicer (1942, pp. 196-202) have pointed out: the effect of increasing pressure on a eutectic system is to raise the temperature of melting of the two components, and to enrich the melt in that component whose melting point is least affected by pressure. Assuming, therefore that the pressure acting on the floor was considerably greater than that experienced by the roof, the former might have been sufficient to raise the quartz - felspar eutectic curves above the maximum temperatures induced at the lower contact, and thereby permit only a slow recrystallization of the floor granite to a coarser-grained variety (Plate 32). On the other hand, the lower temperatures experienced by the roof granites led to anatexis, - and hence the formation of the typical granophyric roof granites (Plate 33). Subsequently, when cooling cracks, or similar planes of weakness, formed within the chilled selvages, hydrostatic pressures were locally decreased, so that with the corresponding drop in eutectic melting temperatures, anatexis, and the injection of melts as quartz-felspathic veins occurred.

This hypothesis, however, fails in the initial assumption that the minimum melting point of the quartz-felspar

eutectic is increased by pressure, for, as Vogt (1921) first pointed out: "the melting point of alkali feldspar and quartz is only very little displaced by pressure". Later, Tuttle and Bowen (1958) confirmed this statement.

In this case therefore, an alternative hypothesis based on the variations of water and volatiles might prove to be more relevant: In the upper levels of the Shoshong sill, the persistent "dolerite - pegmatite" horizon (Plate 2) strongly indicates a marked upward concentration of volatiles. These would lower the minimum melting temperatures of the granite roof rocks, so that at the existing contact temperatures partial anatexis would result (Fig. 47). At the lower contact, however, more anhydrous conditions predominated, so that only a slight recrystallization of the granite occurred.

FIG. 47. DIAGRAM ILLUSTRATING THE EFFECT OF VOLATILES ON THE QUARTZ-FELSPAR EUTECTIC SYSTEM.



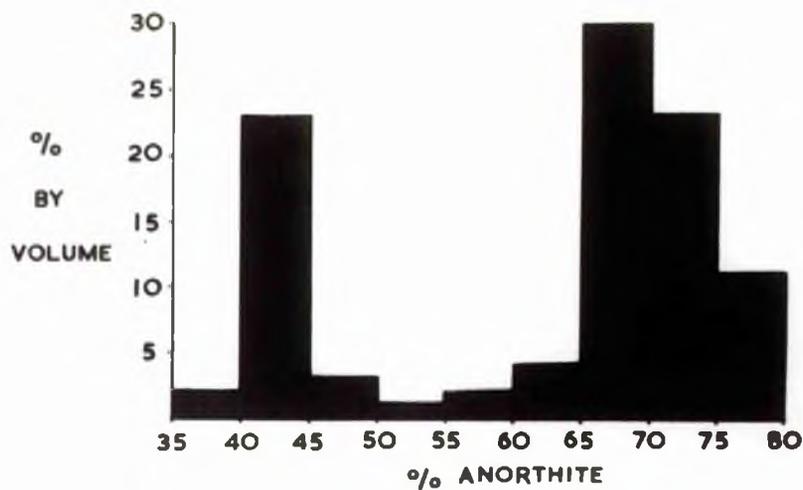
DATA FOR ANHYDROUS CONDITIONS TAKEN FROM TUTTLE & BOWEN (1958).

A NOTE ON THE COMPOSITIONAL VARIATION IN PLAGIOCLASES.

In every rock there is some compositional variation of the plagioclases, and for this reason the accuracy of standard determinative techniques should be tested:-

A single section of the banded bronzite-phyric dolerite from Malebadi was examined. The compositional zones of several plagioclase crystals were measured and determined by the Universal Stage method (Tröger, 1952). Each crystal was then drawn to scale on squared graph paper and the areas of different compositional zones measured. From this, the accompanying histogram was plotted, (Fig. 48).

FIG. 48. COMPOSITIONAL RANGE OF PLAGIOCLASE IN A SINGLE SPECIMEN OF BRONZITE-PHYRIC DOLERITE.



Two distinct peaks are evident, the larger of these (An_{55-80}) corresponding to the main plagioclase precipitate, while the second (An_{35-50}) probably represents the more sodic rims formed by the late acid residuum. The lack of intermediate compositions is significant, as this is possibly due to incomplete fractionation

of felsic constituents during crystallization of the magma, for in most gravity layered intrusions, the interprecipitate magma may cause strong marginal zoning of the primary plagioclases (Wager 1953). Hess (1938) suggests that this zoning depends primarily on the rate of crystal settling, because, when rapid, diffusion between the interprecipitate liquid and the overlying magma was short, and since the interstitial liquid was richer in "soda than the settled crystals", extreme marginal zoning of the plagioclases resulted.

Still, it is reassuring that there is fairly close agreement between the average composition determined by immersion methods, (An_{63}) and that of the histogram (Fig. 48). Similarly the normative composition is not far removed, being An_{59} .

17.
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THE RELATIONSHIPS OF HIGH AND LOW PLAGIOCLASES IN
THE SHOSHONG SILL.

During the past few years, the distribution and origin of high and low plagioclases has been a subject of several detailed investigations. van der Kaaden (1951) found that the optical orientation of plagioclases (An_{35-70}) in volcanic rocks differs from those of plutonic and metamorphic rocks, and that the distinction becomes less with increasing anorthite until, as Tersch (1942) discovered, they become indistinguishable between An_{70} and An_{100} .

In their experimental studies, Tuttle and Bowen (1950) found that, although high-albite is easily synthesised from low-albite, the reverse invariably met with failure. Reynolds (1952) concluded from this that some other factor, besides temperature, is responsible for the distribution of high and low plagioclases. Hence, she concludes that low plagioclases are metamorphic in origin, while high plagioclase is more characteristic of a volcanic environment. Muir (1955), however, found that both forms exist in dolerite.

Following the example of Muir (1955), therefore, an investigation into the distribution and relationships of high and low plagioclases in the Shoshong sill showed that with only a few exceptions, these follow a fairly regular patterns: In the chilled selvages and lower 100 feet of the sill, high-plagioclases predominate, while between the 100 and 300 ft. levels, low-plagioclases are more common. (Fig. 6).

Similarly, in the Kosulutsane xenolith (Fig. 30), the relations of these plagioclases are significant. Here the original low plagioclase of the granite ($An_{27}-An_{32}$) were transformed into high andesine ($An_{27}-An_{42}$), while in the enclosing dolerite, low labradorite predominates. Thus it

appears that low-oligoclase was transformed into high plagioclase by the influence of heat from the enclosing dolerite.

18.
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THE CRYSTALLIZATION OF PYROXENES IN THE SHOSHONG SILL.
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A. SEQUENCE OF CRYSTALLIZATION.

In the Shoshong dolerite, augite and pigeonite were the first pyroxenes to crystallise. The latter, which has now almost entirely inverted to orthopyroxene (Of 16), has irregular (001) augite exsolution lamellae. This was soon followed by subophitic exsolved crystals of orthopyroxene (Of 26), which became larger and more idiomorphic with height, until at the 50 ft. level, they formed conspicuous unexsolved prisms up to 3 mm. long. At this stage, pigeonite ($2V = 14^\circ$; optic plane perpendicular to (010)) reappeared, - either as discrete twinned prismatic crystals, or as thin optically discontinuous rims to the orthopyroxenes -; but during the ensuing period of crystallization, they inverted to orthopyroxene and exsolved augite along the (001) and (100) planes. At the same time, the orthopyroxenes became marginally exsolved, until eventually in the Downes Mountain-type horizon two sets of exsolution lamellae parallel to (001) and (100) were conspicuous, (Plate 58). The prismatic twinned augite crystals, however, show little variation in form or composition, and have no apparent exsolution phenomena, - except for a more conspicuous development of sahlite striations in the upper levels of the sill -.

The compositional variation of the three main pyroxene groups is slight compared with those of the Skaergaard or Bushveld intrusives, because of the more rapid cooling and lower degree of fractionation of the Shoshong magma (Fig. 7).

B. THE ORTHOPYROXENE - PIGEONITE RELATIONSHIPS AND THEIR
EXOLUTION PHENOMENA.

The fundamental stability relations between orthopyroxene and pigeonite have been disputed for some years. Hess (1941) maintained that pigeonite is a high temperature, rapidly cooled, calcium-poor pyroxene, while orthopyroxene formed under more plutonic conditions with slower cooling. In support of this, he observed that pigeonite is virtually unknown in most plutonic masses. Recently, however Brown (1957) found an inverted variety in the chilled margins of the Skaergaard complex, but unlike Walker (1940), who emphasises the importance of volatiles, he modified Hess' pigeonite-orthopyroxene, diagram (1941; fig. 9) to a normal continuous reaction series with both solidus and liquidus curves (1957; fig. 5). In so doing, the inverted pigeonites would probably be calcium-poor pyroxenes which crystallised above the inversion and subsequently inverted with cooling. The orthopyroxenes, on the other hand, continued to form with slow cooling becoming more ferrosilite-rich, until eventually the intersection of the solidus and inversion curves was reached at $En_{70}Fs_{30}$. From here on pigeonite crystallised instead of orthopyroxene, but beyond the two-pyroxene boundary, only ferroaugite was formed. As the igneous body continued to cool, these pigeonites threw out their excess calcium as (001) augite lamellae, and on reaching the inversion curve, inverted to orthopyroxene. In this respect, Brown points out that the more the solidus and inversion curves diverge from each other, the more time there will be for a more ordered exsolution of the augite lamellae.

Still, it is interesting that Bowen and Gay (1960) find that pigeonite often "experiences difficulty in accomplishing the energetically desirable transformation to orthopyroxene on

cooling" (p. 387).

In conclusion, however, Hess (1960) maintains that the calcium-content of orthopyroxenes is a direct function of their magma temperature.

C. Exsolution and Inversion characteristics in the Shoshong Sill.

Although the general characteristics of exsolution and inversion in orthopyroxenes and pigeonites are well-known, a detailed study of these in the Shoshong sill has revealed some additional features of interest.

One of the most important of these is the origin of marginal zoning. The latter is admirably demonstrated in the bronzite-phyric dolerite from Malebadi hill, where it is caused by the exsolution of inverted pigeonite rims to orthopyroxene phenocrysts.

Four stages in the development of this form of exsolution are discussed and illustrated here. In the first of these the pigeonite rim is still retained (Plate 56), but small exsolution blebs of augite can be seen in the margins between the two members.

In the second stage, the pigeonite rim has inverted and exsolved fine augite lamellae parallel to (001), but these are often difficult to distinguish due to their relatively high birefringence (Plate 57).

In the third stage, the (001) lamellae are now well developed, and (100) lamellae have begun to appear (Plate 58). The latter sometimes form fine conspicuous lamellae which traverse the entire rim and even penetrate the orthopyroxene member. The inverted pigeonite usually has the same crystallographic orientation as the primary orthopyroxene, but differs optically. (Plate 60).

In the fourth stage, the fine (100) lamellae are well developed extending through the larger part of the crystal, so that only a small core remains unexsolved, (Plate 59). Furthermore, the exsolution lamellae of the two members are now indistinguishable.

D. Retention of Crystallographic Axes upon Inversion.

Poldervaart and Hess (1951) maintain that when pigeonite inverts to orthopyroxene both the 'b' and 'c' axial directions are retained.

Brown (1957), like Bowen and Gay (1960), denies this in the Skaergaard Complex, for in only one instance did they find any retention of the 'b' and 'c' axes.

In the Shoshong sill, although no X-ray data are available, microscopic evidence tends to confirm the deductions of Brown, Bowen and Gay, for an inverted pigeonite will often adopt a completely different set of (110) cleavages from those of the original crystal (Plate 60).

E. Other Exsolution Phenomena.

In some large bronzite phenocrysts a form of mottled or patchy extinction occurs (Plate 61) (Poldervaart 1947). This was described by Walker as "graphic intergrowth on a submicroscopic scale", but, as it is particularly evident in the immediate vicinity of larger exsolution lamellae, the possibility of its being due to some form of strain, as a result of the exsolution process, might also be considered.

In other crystals too, there are a series of irregular cross-fractures which are filled with a highly birefringent exsolved material, probably augite (Plate 62).

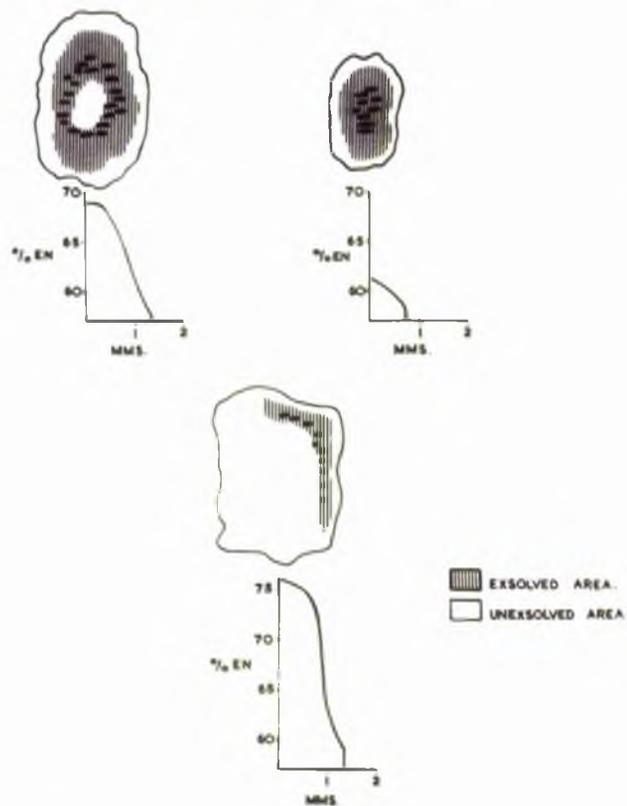
Zoning and Anomalous Behaviour of Exsolution.

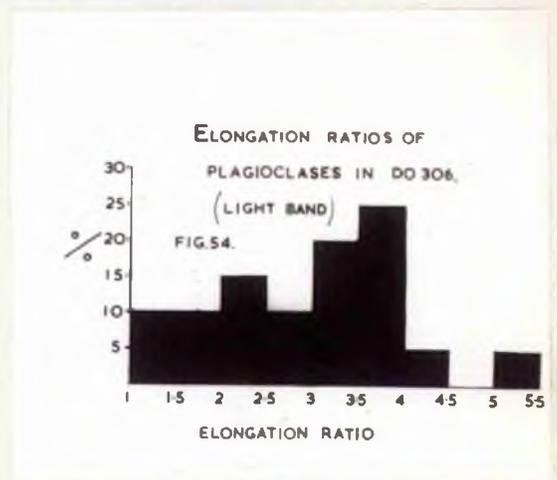
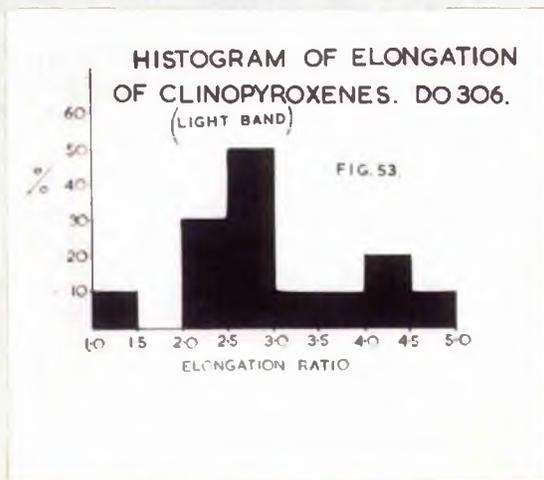
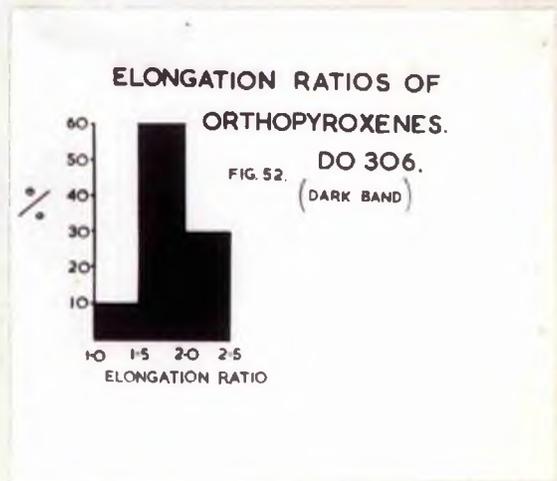
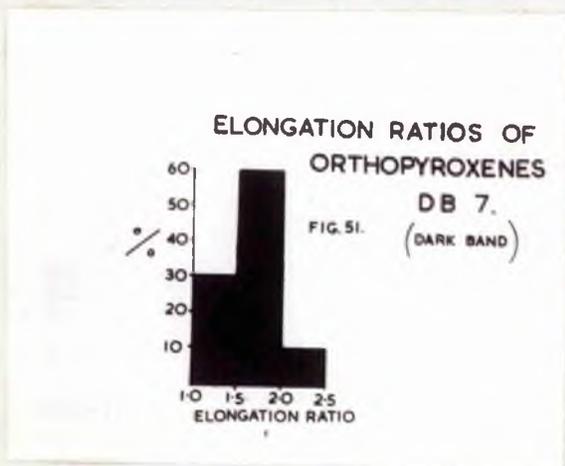
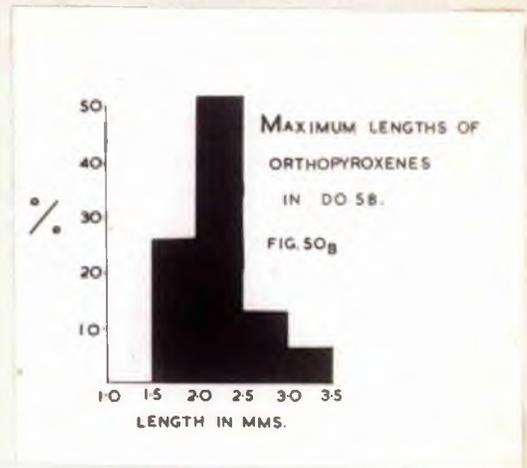
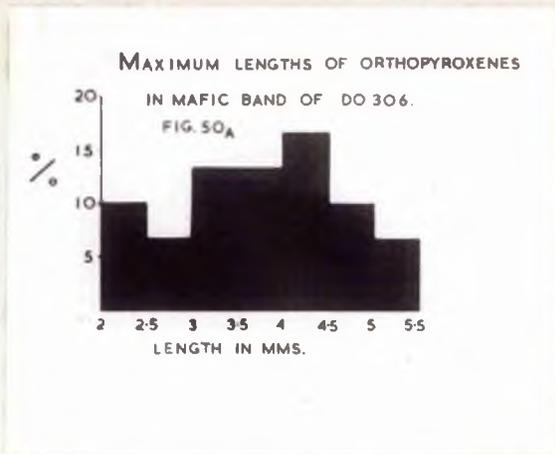
Theoretically, all orthopyroxenes crystallizing from basaltic magmas with $MgSiO_3 - FeSiO_3$ ratios greater than 70 : 30 should show exsolution phenomena (Hess 1941; Brown 1957). - yet this generalization does not always hold.

Walker (1943) finds that, due to the low volatile content, "the early hypersthene of the relatively inactive Scottish dolerites, though considerably richer in iron, is quite free from exsolved plates or blebs". Similarly, Brown observes that "it is not uncommon to see orthopyroxene free from coarse exsolution lamellae forming narrow extensions to the variety rich in blebs and lamellae, thought to be inverted pigeonite", (although both have the same composition). Brown (Personal Communication) points out that this is particularly common in pigeonite with Mg:Fe ratios close to 70 : 30, so that "exsolution began at the centre, the exsolved material from the rim migrating there and leaving the extension free from exsolution lamellae" (1957; p. 521). On the other hand, where this feature is observed in primary orthopyroxenes, the exsolved rim may be due to crystallization from a late residual magma after the temperature had dropped below the inversion.

As this feature is fairly common in the Shoshong dolerite, the compositional variations were determined for several crystals, (Fig. 49). In each case, the narrow unexsolved margin is more iron-rich than the corresponding exsolved portion. As the Shoshong magma cooled fairly rapidly, this phenomenon could be due to crystallization below the inversion level.

FIG.49. ZONED ORTHOPYROXENES
IN THE SHOSHONG SILL.





RHYTHMIC LAYERING IN THE SHOSHONG SILL.

In this section the special features of rhythmic layering are described in more detail, and current hypothesis of its origin briefly reviewed.

A Micrometric data.

Primary orthopyroxene, being the chief cumulus mineral responsible for banding in the Shoshong dolerite, attains the largest crystallographic dimensions, but, - due to its tabular form -, has the lowest elongation ratio (width/length). These features are summarised in Figs. 50, 51, 52, 53, & 54, and Table 7.

B Specific Gravities.

The specific gravities of alternate light and dark bands are listed in Table 39. Their wide fluctuation in density is largely due to the proportion of orthopyroxene present, for this, having the highest specific gravity and smallest elongation ratio, would have settled more rapidly than any other mineral present.

<u>TABLE 39.</u>	<u>Specimen Number.</u>	<u>Specific Gravity</u>
Near top of banded section.	Do 58	2.980.
Coarser banding	DB 9	Light band 3.006
	DB 10	Dark band 3.043
Fine - scale banding.	FB	Light band 3.022
		Light band 3.050
		Dark band 3.113
Basal laminated section.	Do 306	3.044
	Do 65	3.063

ORIENTATION OF PLAGIOCLASES IN LIGHT BAND.
DO 306. HORIZONTAL SECTION.

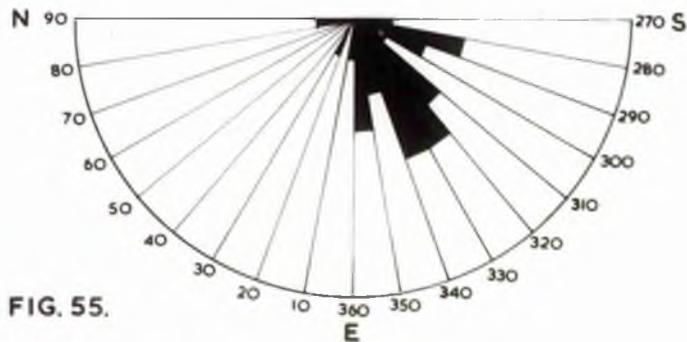


FIG. 55.

ORIENTATION OF PLAGIOCLASES IN DARK BAND.
HORIZONTAL SECTION DO 306.

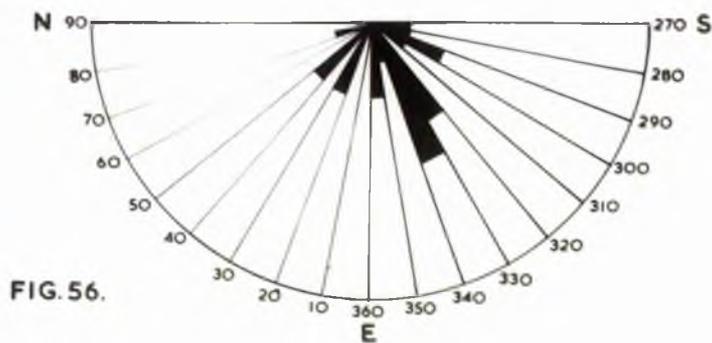


FIG. 56.

C Petrofabric Data.

Orientation of Plagioclase.

Except for the small anorthositic bands, which have planar- or laminar-flow structures (Plates 28 & 29), there are few signs of any directional orientation of the plagioclase laths. This may be due to their

ORIENTATION OF PLAGIOCLASES IN DO 65.
HORIZONTAL SECTION.

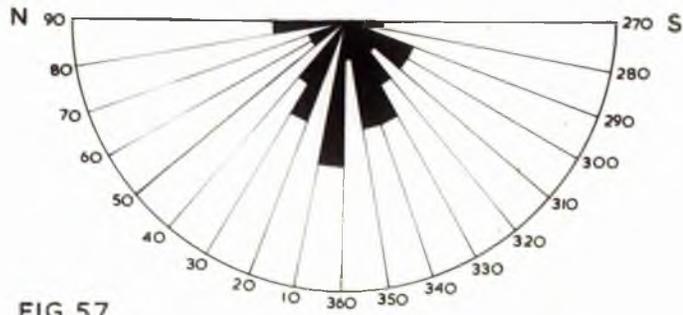


FIG. 57.

ORIENTATION OF PLAGIOCLASES IN DO 65.
VERTICAL SECTION.

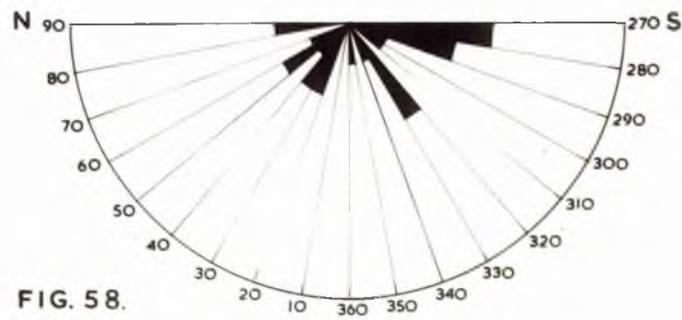


FIG. 58.

ORIENTATION OF ELONGATION FOR
CLINOPYROXENES. DO 306. VERTICAL SECTION.

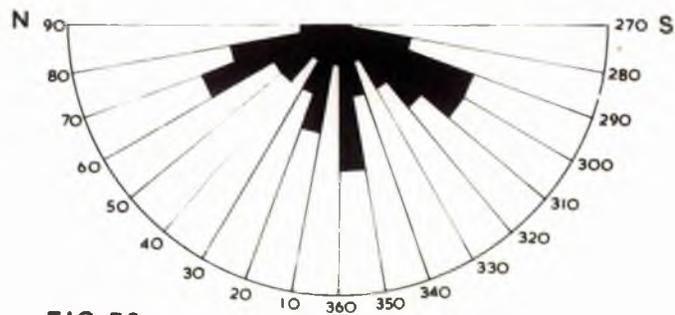


FIG. 59.

wide range of crystal dimensions, their prismatic form, or to the viscous nature of the magma. Still, in the basal laminated sections of the sill a weak orientation can sometimes be distinguished as shown in Figs. 55, 56, 57, and from these it appears that the greater concentrations are parallel to δ -axes of orthopyroxenes, in the same rock (Figs. 22 & 23).

Orientation of Clinopyroxene.

Although their degree of elongation is intermediate between that of orthopyroxene and plagioclase, clinopyroxenes show no directional orientation (Fig. 59).

Orientation of Orthopyroxenes.

Oriented specimens were collected in the manner described by Haff, Fairbairn, and Billings (1938, 1942, & 1942), and thin sections cut in two or three perpendicular directions. The relative orientations of indicatrix axes were measured on a Universal stage and plotted stereographically, following the procedure of Haff (1938), but in the final contouring, Turner's method (1942) was adopted.

Location of Specimens examined.

- Do 306 - Laminated section 70 ft. above the base of Mmamlekeleabe hill.
- Do 65 - Laminated section 60 ft. above the base on Lesetwene hill.
- Do 271 - Finely banded section 60 ft. above the base west of Marutwe.
- Do 58 - Coarser banding 80 ft. above the base on Sung hill.

In each of these petrofabric diagrams (Figs. 16-27) there is a tendency for orthopyroxenes to lie with their δ - axes in the plane of banding and in direction of flow, but with their α - axes perpendicular to these, - although in the same plane. The β - axes, are perpendicular to the latter, and hence parallel to the 'c' fabric axis. These characteristics are almost identical to those observed in the banded sections of the Bon Accord gabbro (van den Berg; 1946), the Merensky Reef at Rustenberg (Schmidt; 1952), and the fluxion norite in the Nygård pluton (Larsson; 1934). Orthopyroxenes in the highest sections of the Shoshong banded zone (specimen Do 58), show little orientation, but as Larsson (1934) has shown, this scattering of plots is often due to the varying angle (\angle) between the face (Ok1) and the 'c' crystallographic axis.

D Origins of Rhythmic Layering.

Since Grout (1918) first discussed the merits and demerits of various suggested hypotheses for the origin of banding, many new theories and facts have been recorded, yet his schematic summary of these still provides a useful guide to early geological thought in this field:-

1. Partial assimilation of inclusions forming schlieren.
2. Lit-par-lit injection, or fluidal gneiss.
3. Deformation just after solidification.
4. Deformation during solidification.
5. Streaked differentiation, with reference to rhythmic cooling and intrusive action.
6. Successive intrusions:-
 - a. Cooling separately and successively.
 - b. Cooling later and all together.

7. Heterogeneous intrusion.
8. Convection during crystallization differentiation.

To these the following may now be added:-

9. Repeated variations in temperature and pressure.
10. Slumping of unconsolidated material and turbulent currents.
11. Disturbance during crystallization.
12. Rhythmic differential settling.
13. Rhythmic crystallization due to variable volatile content.
14. Repeated variations in water vapour pressure.
15. Nucleation and alternate super-saturation of the magma with respect to the larger mineral groups.
16. Undercooling and crystallization in the oversaturated region, combined with periodic disturbances.
17. Diffusion.

Assimilation and Lit-par-lit injection.

Due to the almost complete lack of any chemical relationship between the primary igneous bands and country rock, such hypotheses are quite untenable in the majority of cases (Grout, 1918; & Balk, 1927). Besides, as Balk has pointed out in the Peekskill norite: the thickness of the norite bands shows no relation to the more finely banded gneiss which it intrudes, and even where inclusions of the latter do occur within the fluxion norite, their lamination planes are oriented at high angles to that of the norite (1927, p. 262, figs. 5 & 6), so that their lineations are nowhere parallel.

Deformation during or just after solidification.

Bowen (1919 & 1920) suggests that in most banded intrusions, gravitative settling and deformation of the crystal mesh went hand-in-hand. If this were repetitive, a form of banding would be developed with fluxion structures through the reorientation of detached crystals.

Similarly, in the Bushveld Complex Daly (1928), suggests that the "continued deepening of the basin during crystallisation could not fail to cause centripetal and oblique downward shearing of layer against layer in the hot plastic mass". Such a mechanism would also explain the origin of flow structures in the norite, but Grout doubts whether this could explain the banding.

The present author regards that for this hypothesis some other evidence of deformation is necessary, and for that reason the Shoshong Sill may be excepted.

Successive Intrusions.

Such a mechanism, which involves a series of magmatic influxes of differing composition, (Brown, 1956; Lombaard 1934; Worst, 1958; Richey 1930; and Balk, 1927), can hardly apply to the fine-scale banding of the Shoshong sill. The complete lack of chilling, the gradational contacts between all bands, and the fact that no bands are observed to transgress others, would clearly dismiss this as a possible explanation.

Heterogeneous Intrusion.

This mechanism, which was advocated by Harker (1904 pp. 138-140) for banding in the Cuillins gabbro, was summarily dismissed by Grout (1918); his reasons being that in such bodies stirring and additional disturbances

would destroy any banding effects or regular crystal settling.

In the Whin and Fair Head sills, however, Tomkeieff (1929 & 1960) postulates a liquation process of the magma into "wet" and "dry" fractions, followed by the "streaking out" of these on emplacement.

Although the banding described by Tomkeieff is quite distinct from that of Shoshong, it appears that the second influx of magma, which contained a fairly high proportion of intratelluric crystalline phases, could also have been streaked out in the plane of banding.

Streaked Differentiation.

Despite Grout's statement that "none of the theories of differentiation outline a process that will result in a combination of gravitative arrangement, parallel banding, and parallelism of grain" (1918, p. 453), this hypothesis received considerable support in the Peekskill norite and the Nygård pluton (Balk, 1927, pp. 249-302; Larsson, 1934, pp. 14-132). In both cases, banding is essentially parallel to the wall rocks, and as the magmas contained regular dispersions of intratelluric pyroxene and plagioclase crystals on emplacement, a well-developed lineation has resulted. Balk (1948) maintains that these are common features of most plutonic masses, but that the actual segregation of bands occurred in situ, - these being further widened by successive injections of the more felspathic norite magma into the darker and more stable portion -.

In the Nygård pluton, however, Larsson (1934, p. 56, fig. 21) noticed that near the contact, the foliation of the gneissic country rock is conformable with that of the fluxion norite. From this he concluded that with the upward force of magmatic flow, the more viscous "nebangesteins" and the fluid norite behaved in a manner analogous to competent and incompetent rocks

during dynamic metamorphism. This mechanism, he maintains, can explain the origin of bands with both gradational and sharp contacts. Still it has no apparent relation to the Shoshong sill.

Convection during crystallization differentiation.

In the Skaergaard intrusion Wager and Deer (1939) claim that conditions were ideal for convection, and that alternate light and dark layers were formed by a pulsatory variation in the velocity of convection currents" (1953). Hess (1960), also finds evidence for this in the Stillwater Complex, but as Daly (1912, p. 772) points out, these currents were probably only very feeble and short-lived. Besides, Bowen (1919, p. 411-413) found that they are confined to hexagonal columnar cells, and this would have tended to upset any regular crystal settling.

Earlier Grout (1918) had formulated a two-phase convection hypothesis, by which both gaseous and crystalline phases separated simultaneously from the magma, but this was summarily denied by Wager and Deer (1939) for the Skaergaard intrusion, as no gaseous phase could possibly exist at such depths.

Walker (1957) maintains that if convection did ever exist in dolerite intrusions, it was quite different from that in plutons and leopoliths, this also seems to apply to the Shoshong sill - especially as the viscosity factor was appreciable.

Repeated variations in temperature and pressure.

The main problem here concerns the ultimate cause of such 'variations'. Daly suggests that a slow basining, of a magma chamber can produce slight rhythmic changes in temperature and pressure with intermittent

showers of crystals. Later, Yoder (1954) proposed that a rhythmic variation in water vapour pressure is often effective. In the present situation, however, evidence for any such variations is too scanty although this seems rather unlikely.

Slumping of unconsolidated material and Turbidity currents.

In the Bushveld norite, (Hall 1932) suggests that rhythmic precipitations of specific minerals formed local accumulations, which, through differential movement and slumping, developed into fine - scale rhythmic layering.

At the top of the Rhum layered series Brown (1956) found thin peridotitic layers with slump structures similar to those figured by Jones (1937, & 1939), Kuszen (1948) and Carr (1954). This he maintained, was due to the abundant interprecipitate liquid imparting the necessary mobility to the unconsolidated material.

These structures however, are quite distinct from any observed in the Shoshong dolerite, and it is most improbable that any preferred orientation of minerals could have originated by such a process, although the turbulent currents, which are assumed to have been responsible for the trough-banding in the Skaergaard complex, might prove to be the exception.

Disturbance after crystallization.

In his earlier work Hess (1938) believed that rhythmic layering was caused by a series of local disturbances during the crystallization of a magma. Later, after detailed investigations in the Stillwater Complex,

(1960), he modified this hypothesis to include only certain persistent zones, which had obvious signs of slumping and drag folding.

In the Shoshong sill however, evidence for slumping is too poor and the requirements of this hypothesis too great to be of any pertinent value.

Rhythmic differential settling.

This mechanism (Coats 1936, pp. 412-414), was briefly discussed in conjunction with the author's own hypothesis, but considered alone, it fails to explain the preferred orientation of mineral grains, or the more persistent banded units. The same arguments apply to van Zyl's hypothesis of "mutual interference" between heavy crystals, which are sinking, and the lighter plagioclases, which are trying to rise (1950, p. 72). It is possible however, that it may have been effective in the formation of the thin gradational bands, such as those encountered near the top of the Shoshong section.

Repeated variations in water vapour pressure.

Yoder (1954) has found that if the water vapour pressure in a basaltic magma is increased, the temperature of the minimum melting point is reduced, and the melt becomes more enriched in the anorthite member, so that "By varying the water vapour pressure over a critical range, it would be possible to shift the eutectic so that alternatively a pyroxene or a basic plagioclase could crystallize and separate out". Such a mechanism may account for the rhythmic layering in the Stillwater, Bushveld and Belhelvie complexes, - provided that there was a cyclic fracturing of the roof to release the water vapour.

Brown (1956) instead of cyclic roof fracturing, suggests a periodic volcanicity connected with the Rhum Complex, but, like Poldervaart and Taubeneck (1959) he doubts whether this could also be applied to the large-scale banding of plutonic masses.

Thus, as both Wager (1959) and Brown (1956) indicate, it is doubtful whether this method, which requires such a critical magma composition and elaborate repetition of events, would be a practicable explanation for banding.

Nucleation and supersaturation of the magma.

As an alternative to convection sorting, Wager (1959) has suggested an hypothesis based on the different nucleation powers of minerals. A magma on cooling becomes supersaturated, and the mineral group with the greatest nucleation power and simplest structure, precipitates out. The heat of crystallization will then elevate the temperature of the magma to its former peak, and after a slight mixing by convection the same sequence is repeated for the next mineral group.

Weedon (1960), on the other hand, maintains that this cannot apply to the Gars Rheine sill, which has a high volatile content and little or no convectional movement. Besides, an important objection is, that due to the compositional identity of the chief mineral phases in successive banded units, the temperature must have repeatedly oscillated-though always returning to the same maximum-. Still, it is possible that this difficulty may be overcome after the recent work of Wyllie (1960) on the $\text{CaO.MgO.FeO.SiO}_2 - \text{CaO.MgO.Al}_2\text{O}_3 . \text{SiO}_2$ system.

Undercooling and crystallization within the supersaturated region.

This is a comparatively recent hypothesis, which is thought by Poldervaart and Taubeneck (1959) to have been responsible for their Willow Lake-type bandings; but recently

van Zyl (1959) gave a more detailed account of this in the Kapalagulu Complex. A magma is undercooled without any crystallization taking place until its temperature intersects the solidus curve. At this stage rapid crystallization will ensue with the release of much heat of crystallization so that the temperature of the magma will be increased - though not to its former maximum -, and the rate of crystallization reduced. Thereafter, only a minute temperature fluctuation will be necessary to produce another large shower of crystals. This hypothesis is closely allied to that of nucleation, for a condition of metastability is necessary in both.

That this mechanism was not effective in the Shoshong sill is evident from the lack of reversed zoning here.

Diffusion.

This mechanism, which is inseparable from crystal nucleation, undercooling, and gravity settling, requires the initial formation of an unconsolidated precipitate, so that once thin films of material have been deposited around each crystal, diffusion will occur between the liquid and solid, following a compositional gradient.

Rhythmic crystallisation due to variable volatile content.

Recently, in the Gars-Bheinn sill, Weedon (1960) has postulated that banding originated by upward migration of the volatile-rich residuum, so that the fine-grained (olivine-rich) bands developed slowly while the coarser (felspathic) bands formed rapidly under more volatile-rich conditions. Good indications of this process, he maintains, lie in the extreme zoning of both feldspars and pyroxenes, and in the transgressive nature of some felspathic bands. The present author has observed similar relations of felspathic bands in the hypersthene-gabbro at Sanna Bay, Ardnamurchan, but no indications of this

are known in the Shoshong dolerite. It is possible however, that some of the extreme zoning of plagioclases in the latter may have originated by upward migration of the late residuum from the underlying magmatic unit.

Analogous examples of fine-scale Shoshong banding.

Fine-scale banding is a common feature of many large intrusions like the Skaergaard, Bushveld, Rhum, and Stillwater. Thus in the Bay of Islands complex, Cooper (1936) describes fine-scale banding caused by varying proportions of augite crystals, - although these show no directional orientation. For this he favours an origin by normal gravitative settling, assisted by disturbances set up by successively larger influxes of magma.

In the Belhelvie complex, Stewart (1946 p. 489) observed an analogous type of layering produced by varying proportions of hypersthene crystals, which, he maintains, show some directional orientation within the plane of banding. Very similar occurrences are also described by Peoples (1933) & Hess (1960) in the Stillwater complex, by Hall (1932) in the Bushveld norite, by Walker in the southern extension of the Palisades sill, by Larsson in the Nygård pluton (1934), by Balk in the Peekskill norite, and by Buddington (1933) in the N.W. Adirondacks.

The fine-scale Shoshong-type banding thus appears to be a common feature of many basic intrusions, and is quite distinct both in form and origin from the Willow-Lake- or Skaergaard - type banding (Poldervaart & Taubeneck (1959)).

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PLATE 7. Eastern Shoshong Range
from Khudubeaku.



PLATE 8. Kuchwe Gorge in
the Makhware hills.

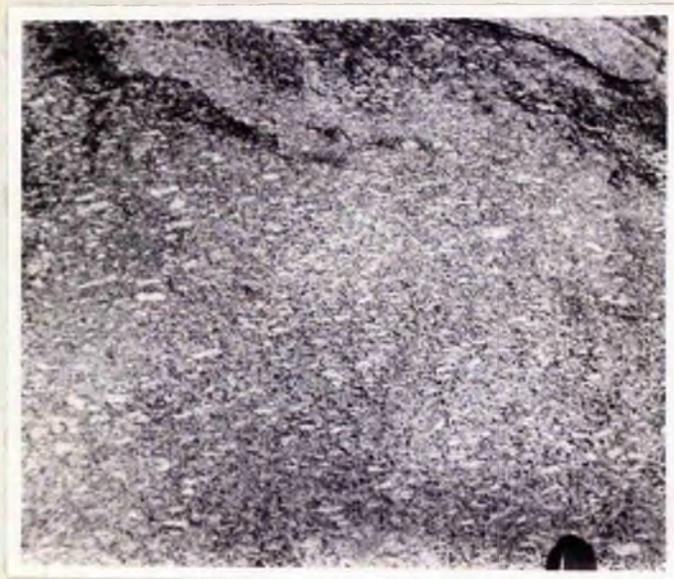


PLATE 9. Platy-flow structure
of felspars in the Mahalapye
Granite. Dekokong Hills.



PLATE 10. Foliated Mahalapye
Granite at Khudubeaku.

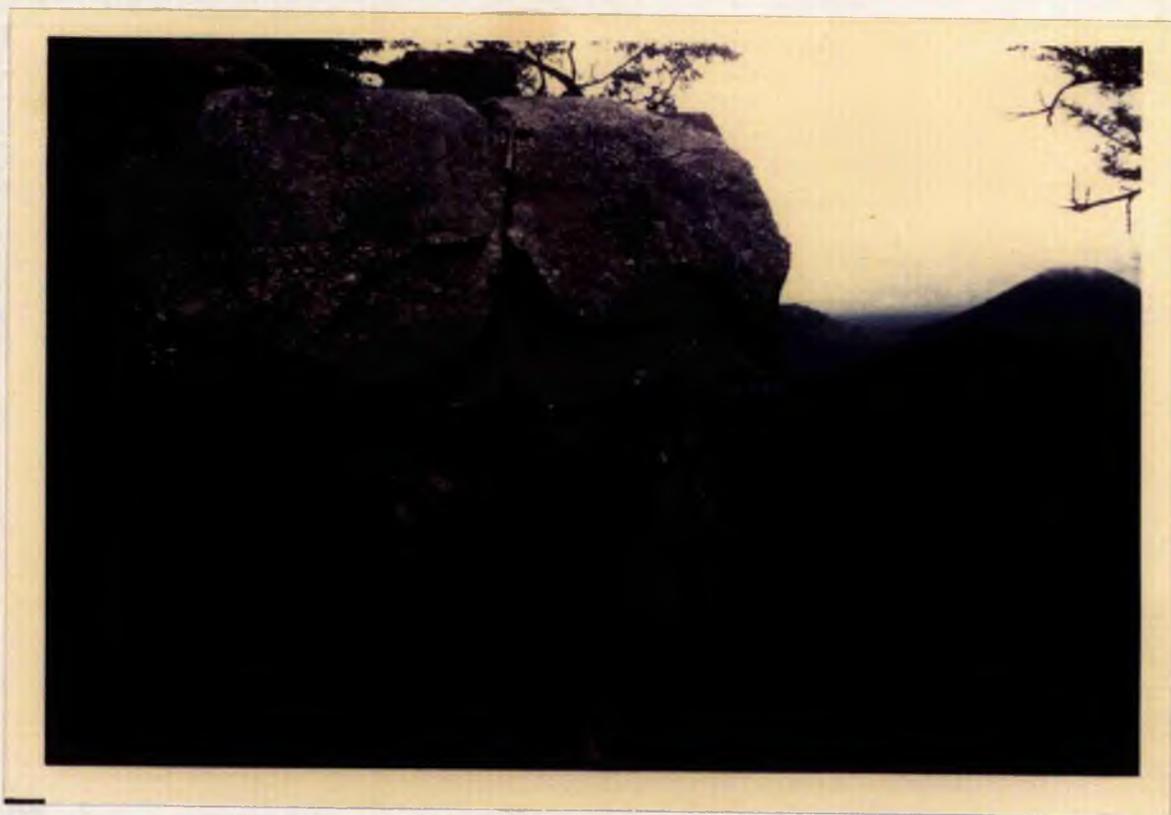


PLATE II. Loskop-Waterberg conglomerates overlying sheared Shoshong quartzites.

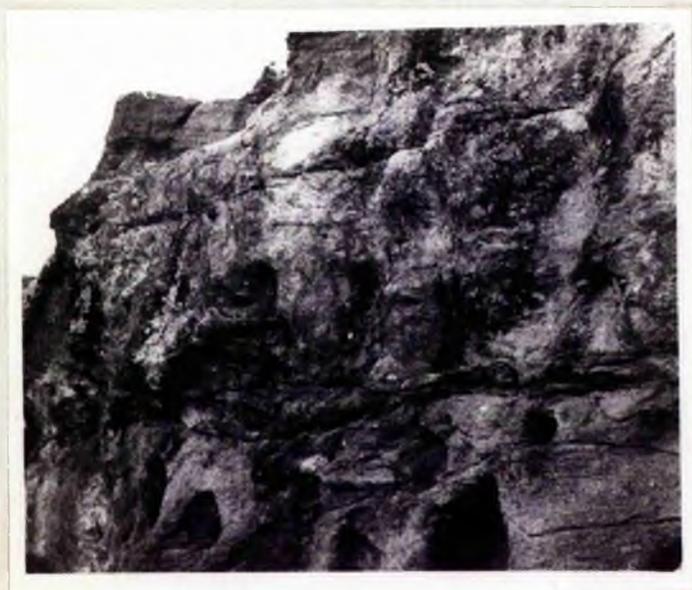


PLATE I2. Feldspathic Ecca Sediments north of Tholoane.



PLATE I3. Weathering features of Silcrete.

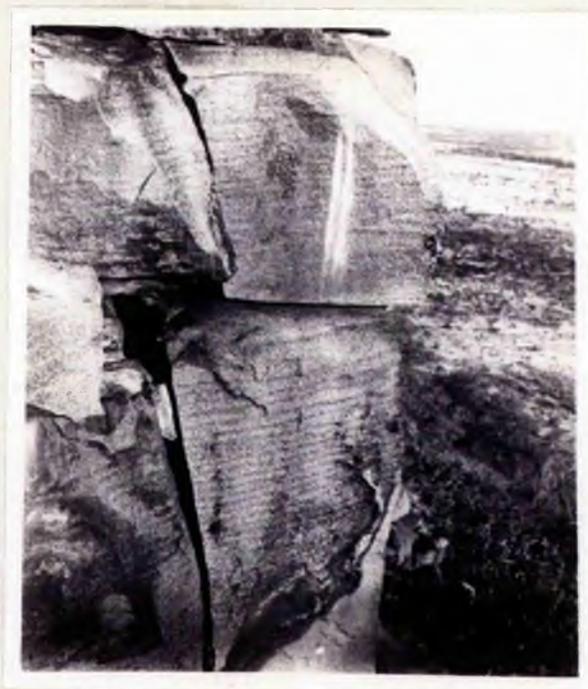


PLATE 14. Rhythmic layering in the Shoshong Sill
at Maraletsane.

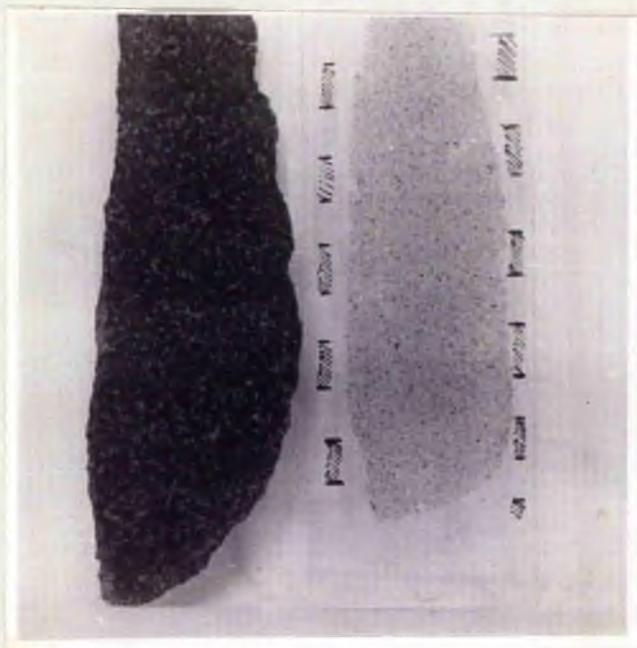


PLATE 15. Comparison of a polished
specimen and thin section of the
banded Shoshong dolerite from
near Marutwe.

Half natural size.



PLATE 16. Flow structure in
the Makhware Red Rock
horizon.



PLATE 17. Dolerite-pegmatite body in the Shoshong Sill
near Mutlene.

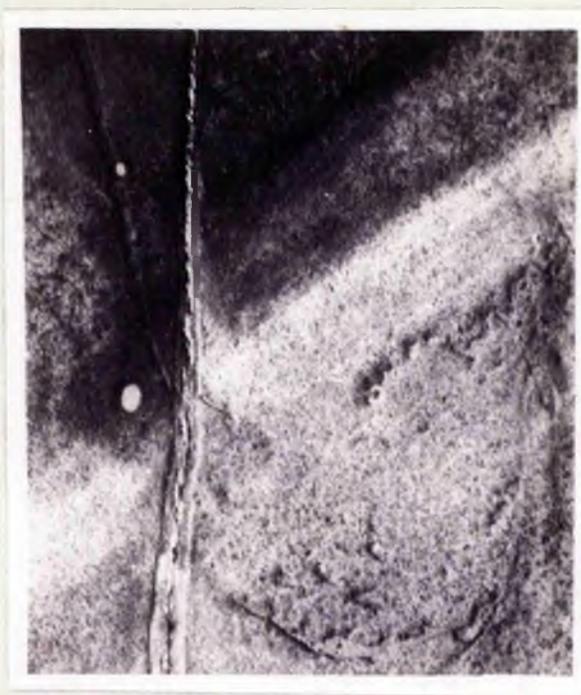


PLATE 18. Microgranite and
prehnite veins in the
Shoshong dolerite.

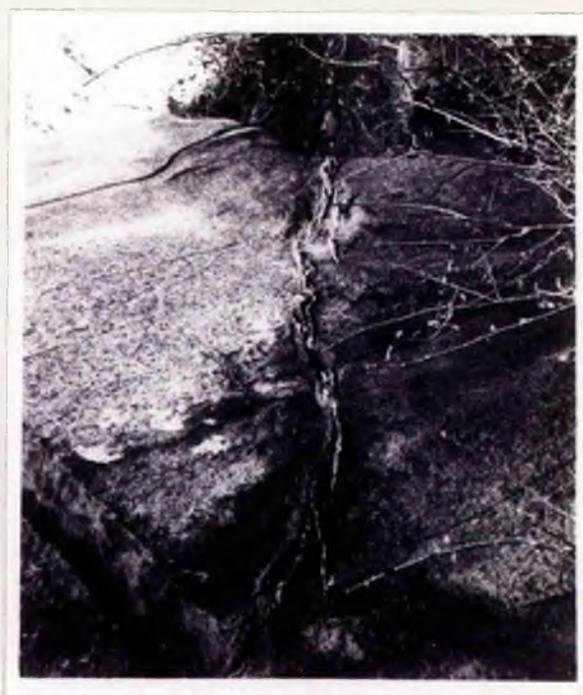


PLATE 19. Albite-aplite vein
in the Shoshong sill.



PLATE 20. Syntectic 'granite' veins in earlier quartz-hornblende-diorites at Site 'A' in the Takane area.

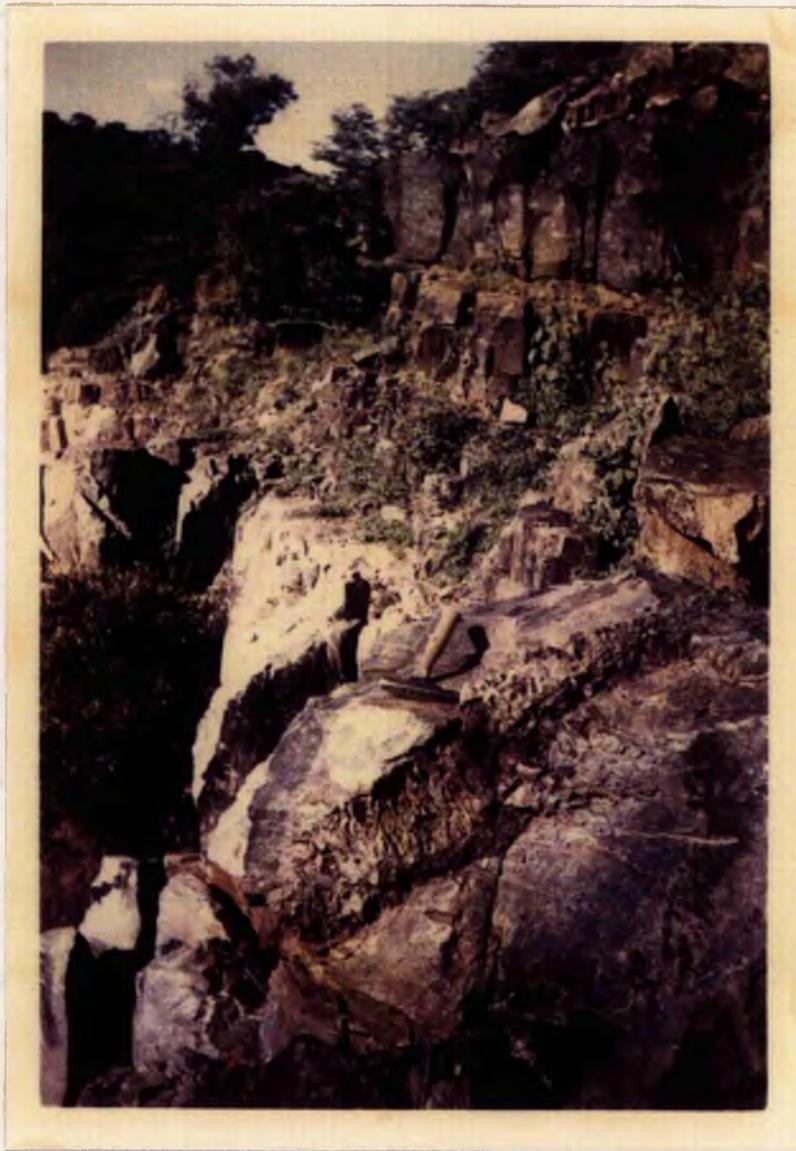


PLATE 21. Lower contact of the Makhware Sill showing the ten foot thick zone of quartz-magnetite-hornfels immediately beneath the sill.

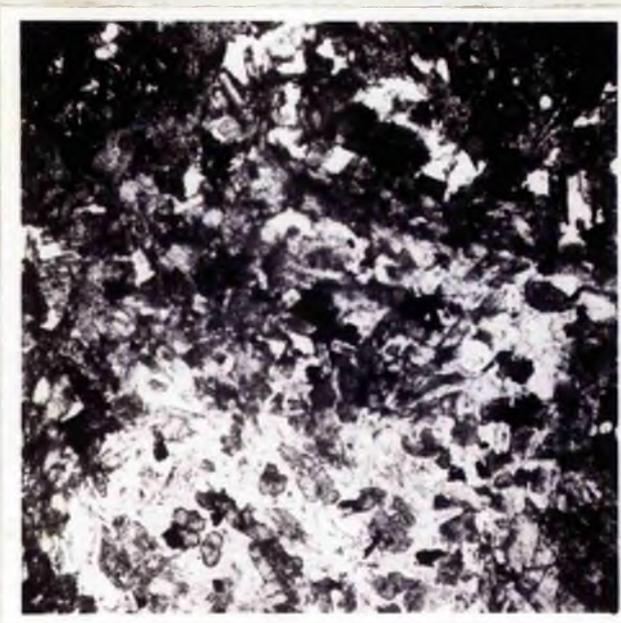


PLATE 22. Hypersthene-
micropegmatite patches in the
Takane quartz-dolerite.

X 20



PLATE 23. Bronzite-phyric
dolerite of the Shoshong sill.

X 20



PLATE 24. Downes Mountain-type
dolerite of the Shoshong sill.

X 20



PLATE 25. Dolerite-pegmatite
of the Shoshong sill.

X 20

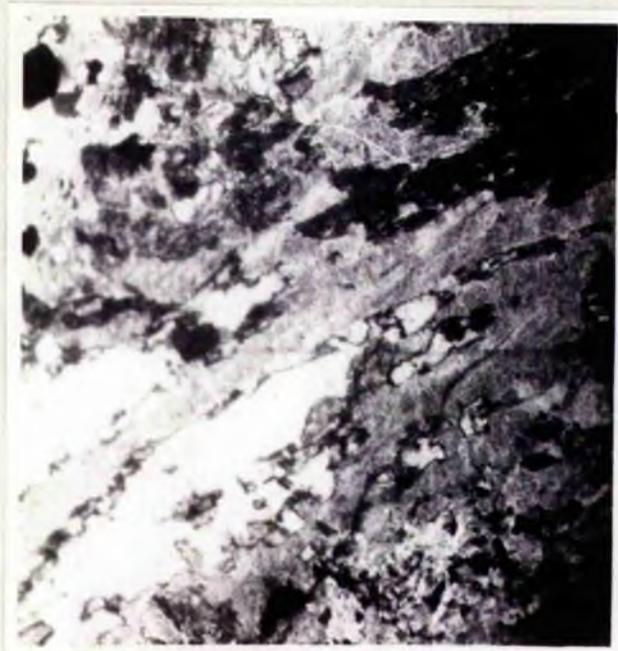


PLATE 26. Albite-aplite vein
from Marutwe. Ordinary light.
X 20.



PLATE 27. "Herringbone"
exsolution in inverted pigeonite
from the Shoshong sill.
Crossed nicols. X 40.

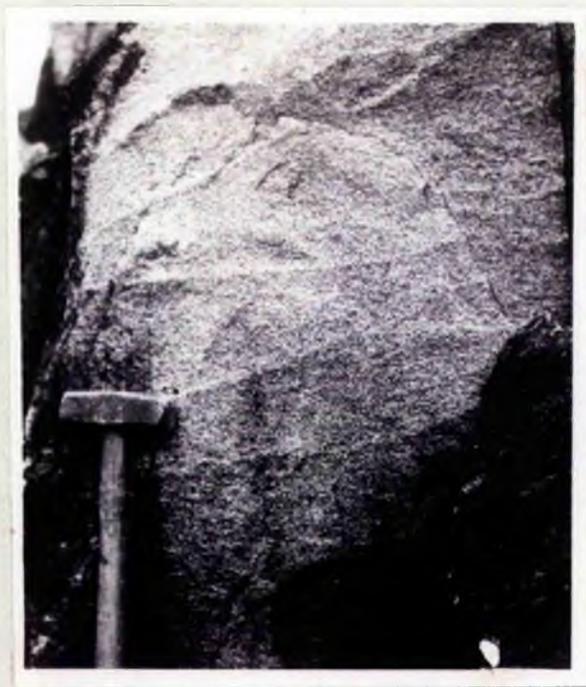


PLATE 28. Anorthositic bands in the
Shoshong sill at Manakalowe.



PLATE 29. Microphotograph of
the Manakalowe anorthositic
bands. Crossed nicols. X 20.



PLATE 30. Part of the Hybrid xenolith-rich rim to the large Dekokong-Bobelane 'basin', or depression, in the Shoshong sill.

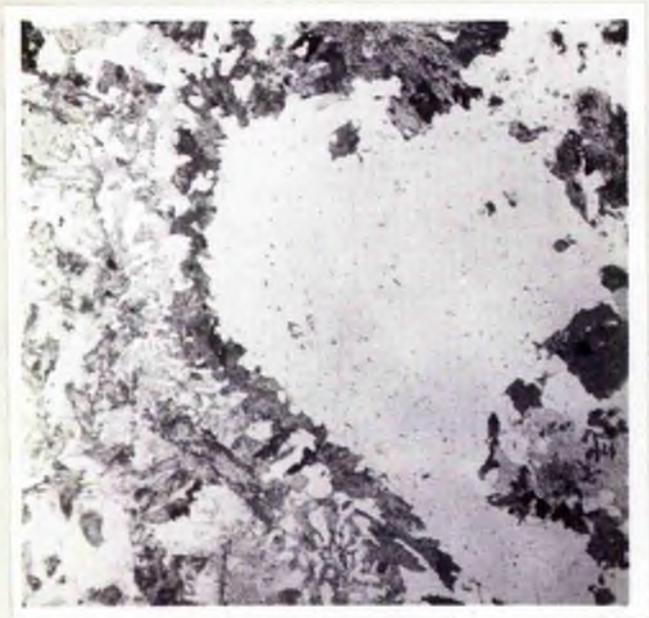


PLATE 31. Quartz xenocryst in the Mosulutsane xenolith surrounded by a rim of reaction hornblende. Ordinary light.

X 15.



PLATE 32. Coarse red floor granite of the Shoshong sill. Ordinary light. X 10.

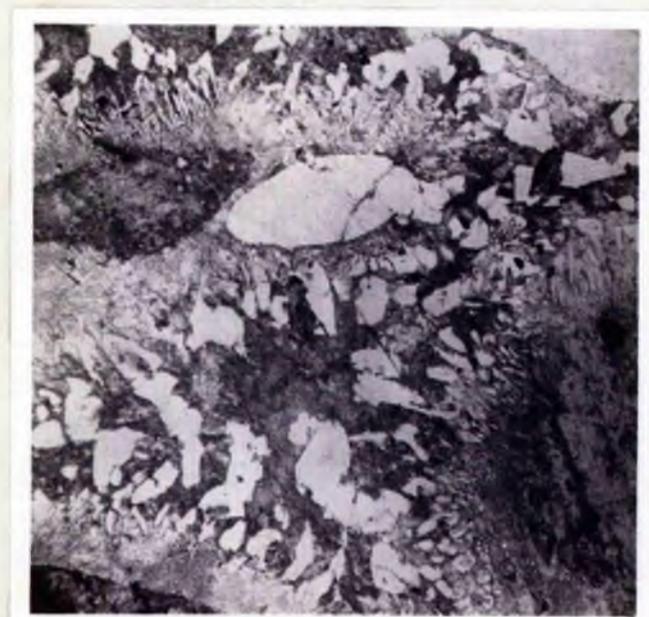


PLATE 33. Granophyric roof granite of the Shoshong sill. Ordinary light. X 15.

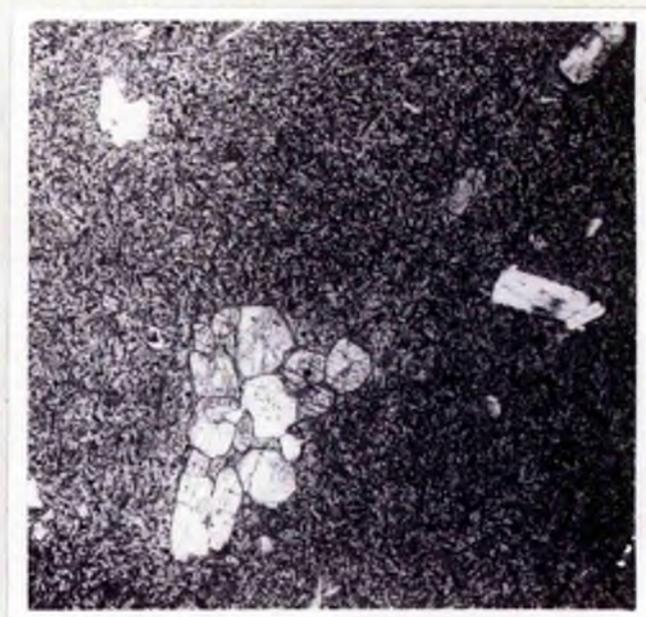


PLATE 34. Chilled basal phase of the Makhware sill. Ordinary light. X 15.

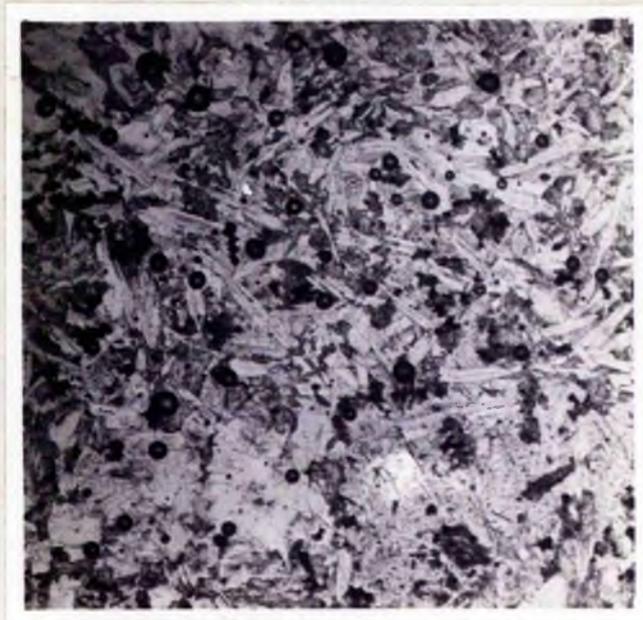


PLATE 35. Makhware Basal
Diorite. Crossed nicols.
X 15.



PLATE 36. Makhware Red Rock.
Ordinary light. X 15.

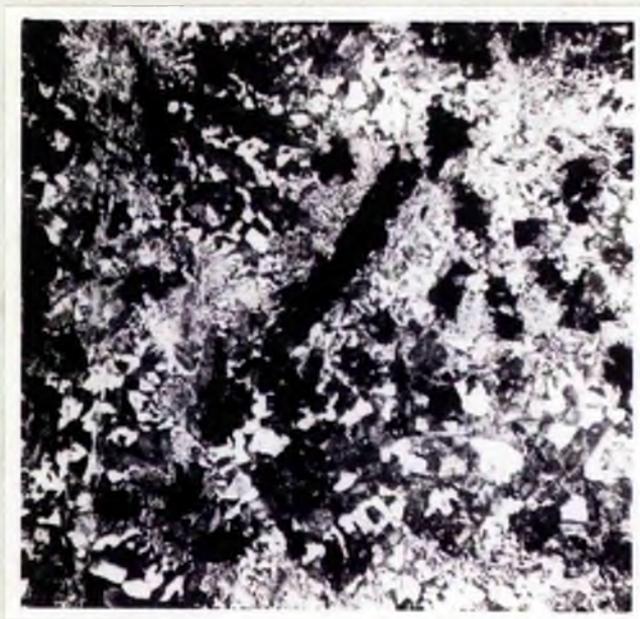


PLATE 37. Makhware Hornblende-
granophyre from Tshuhung.
Ordinary light. X 15.



PLATE 38. Uniform red
Makhware granophyre.
Ordinary light. X 15.

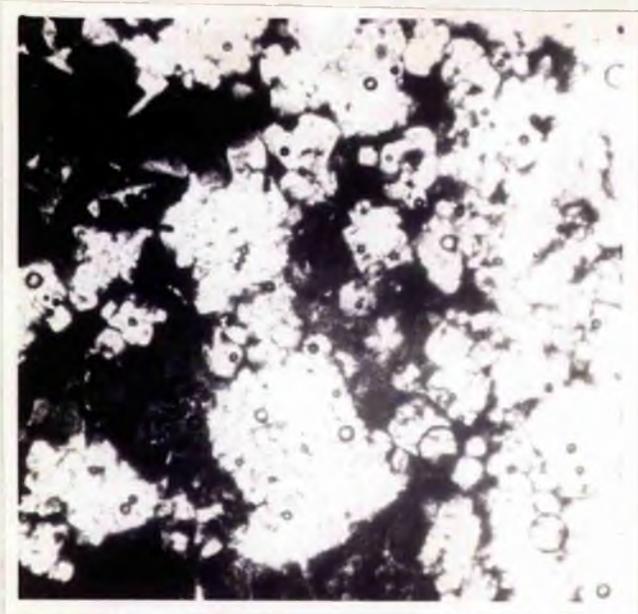


PLATE 39. Feldspathised Shoshong quartzite from Tshuhung. Ordinary light. X 20.

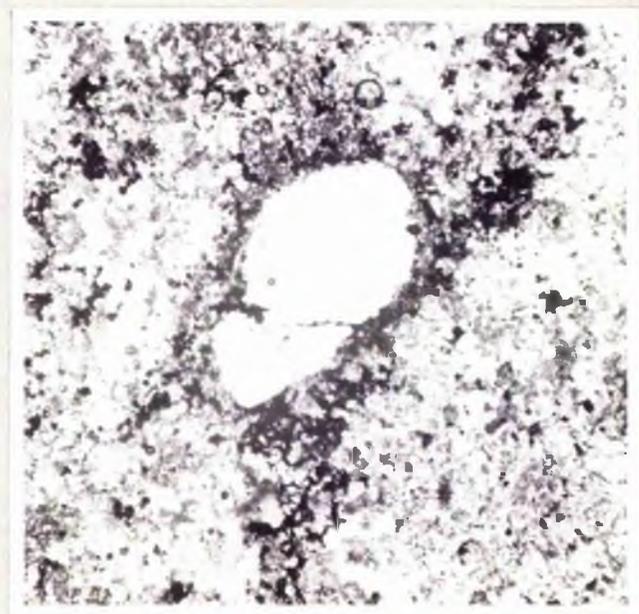


PLATE 40. Syntectonic vein in The Makhware Red Rock showing quartz xenocryst. Ordinary light. X 20.

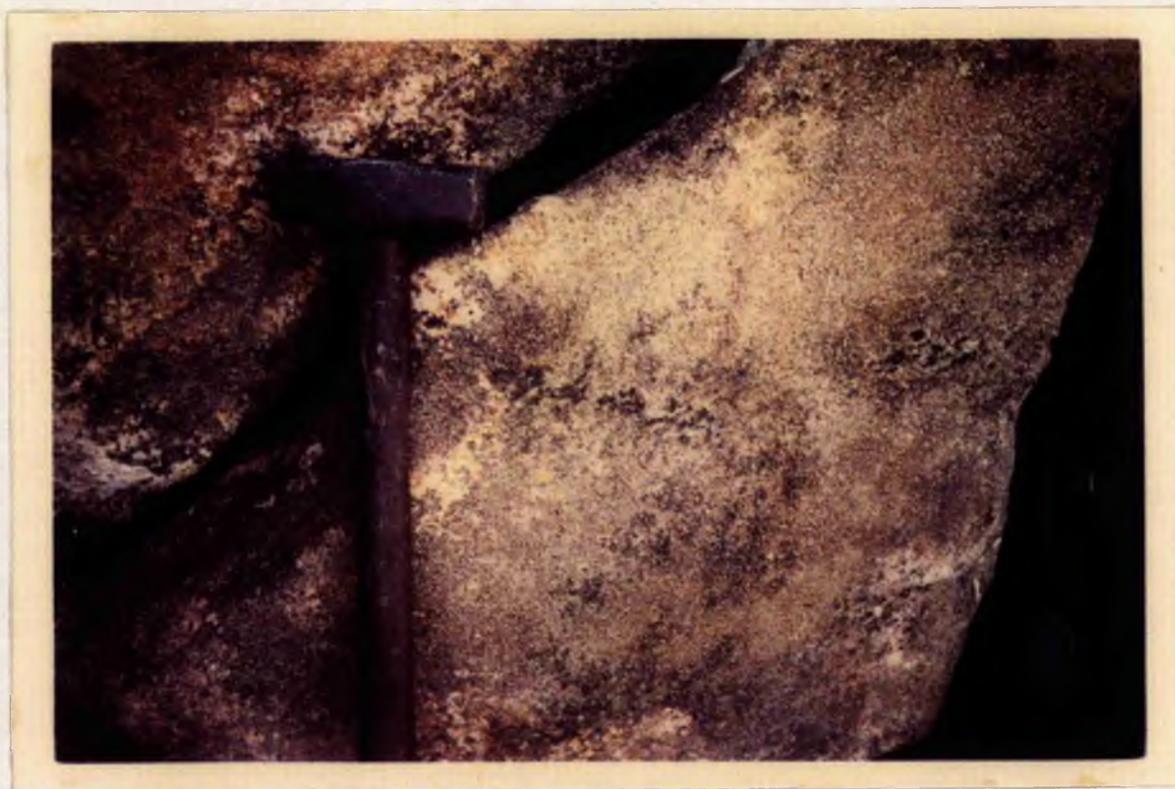


PLATE 41. Hornblende xenolith clots with pink micropegmatite rims in the Makhware Red Rock horizon.

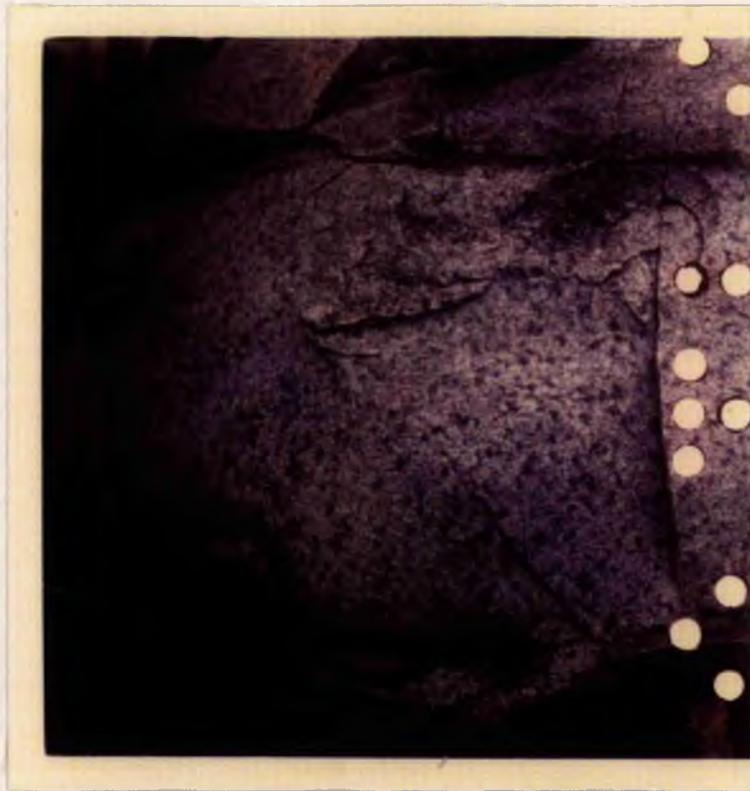


PLATE 42. Fragments of the earlier quartz-hornblende-diorites included in the 'granite' syctetic rocks of the Takane sill at Site 'A'.



PLATE 43. Normal quartz-hornblende-diorites. Ordinary light. X 30.

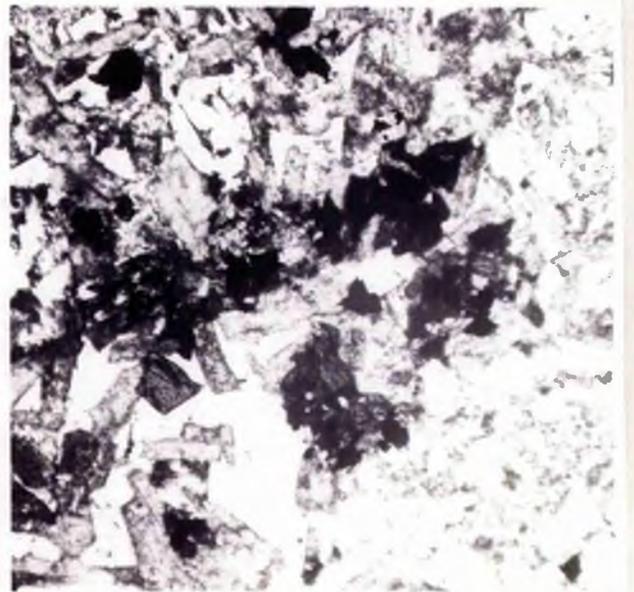


PLATE 44. Granitic quartz-hornblende-diorites of syctetic origin. Ordinary light. X 20.

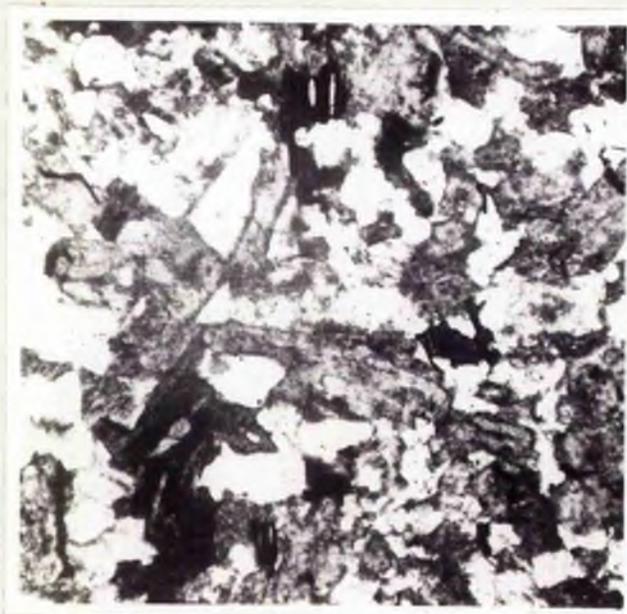


PLATE 45. Syntectonic acid vein in the Takane sill. Ordinary light. X 20.

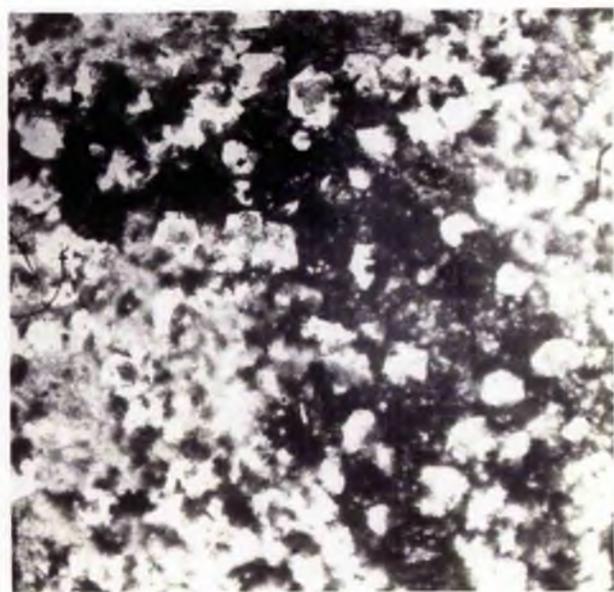


PLATE 46. Metasomatised siltstone at Takane. Stage I. Ordinary light. X 20.

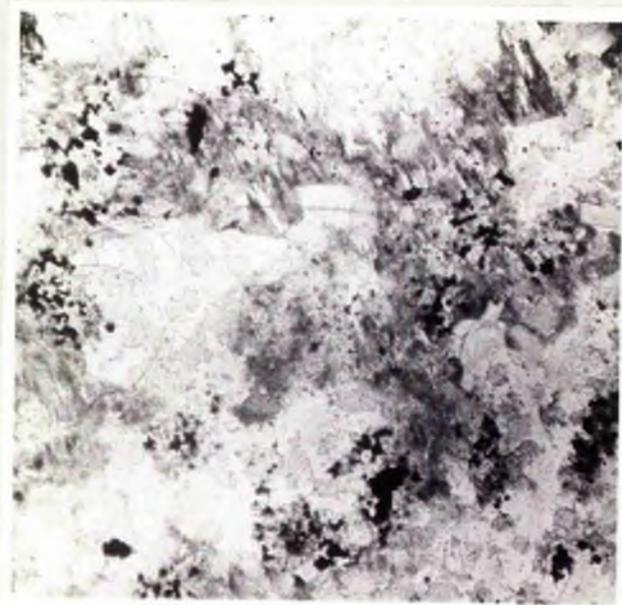


PLATE 47. Metasomatised siltstone at Takane. Stage 3. Ordinary light. X 20.



PLATE 48. Kalamare gabbro. Ordinary light. X 20.



PLATE 49. "Intrusion breccia" of siltstone fragments enclosed within a recrystallised quartz-felspar matrix at Takane.

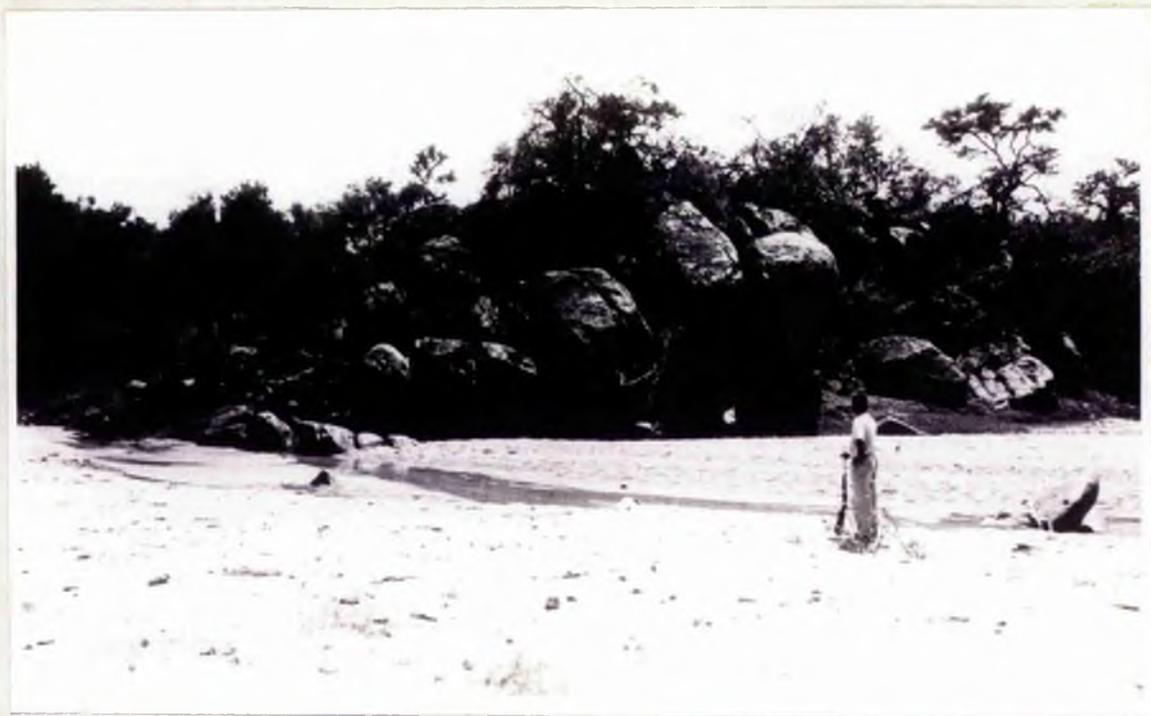


PLATE 50. River cutting of the Mahalapshwe quartz-diorite dyke 8 miles north of Mahalapye.



PLATE 51. Pink quartz-diorite from Phate hill showing hypersthene prism (dark). Ordinary light. X 20.



PLATE 52. Hybrid quartz-diorite from Phate hill showing small white quartz xenocrysts. Approximately natural size.



PLATE 53. Phate hill quartz-diorite showing large hornblende and magnetite prisms. Ordinary light. X 20.

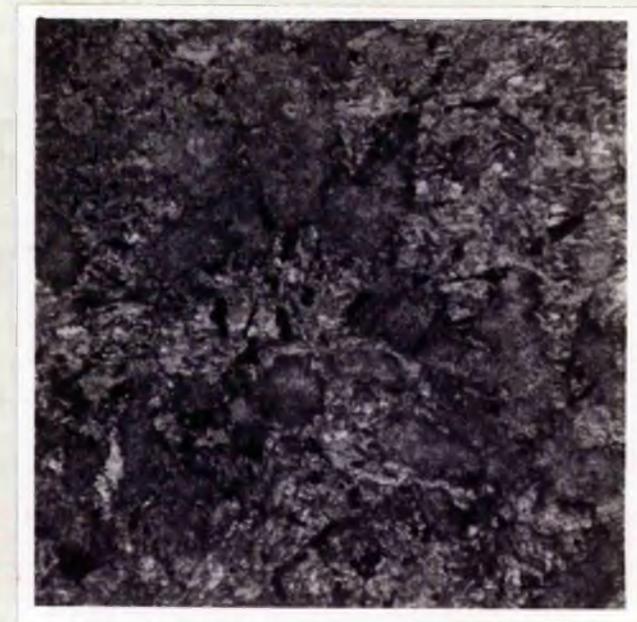


PLATE 54. Chilled quartz-diorite from Phate hill, showing uralitised pyroxene phenocrysts. Ordinary light. X 20.

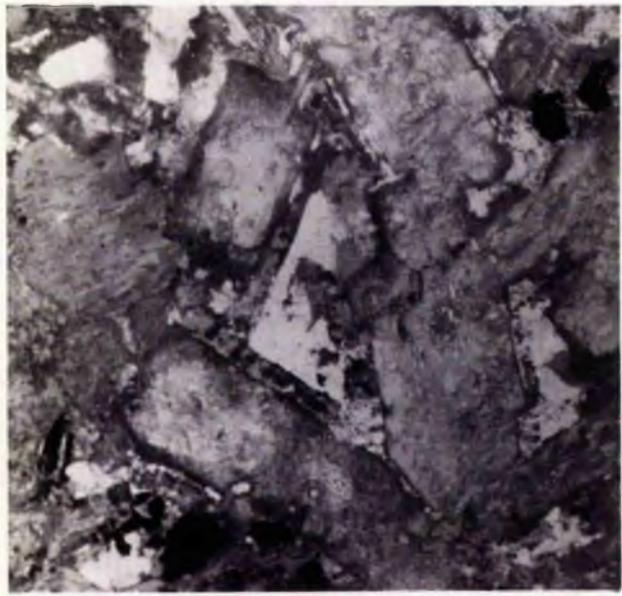


PLATE 55. Quartz-diorite from the Mahalapshwe dyke. Ordinary light. X 7.

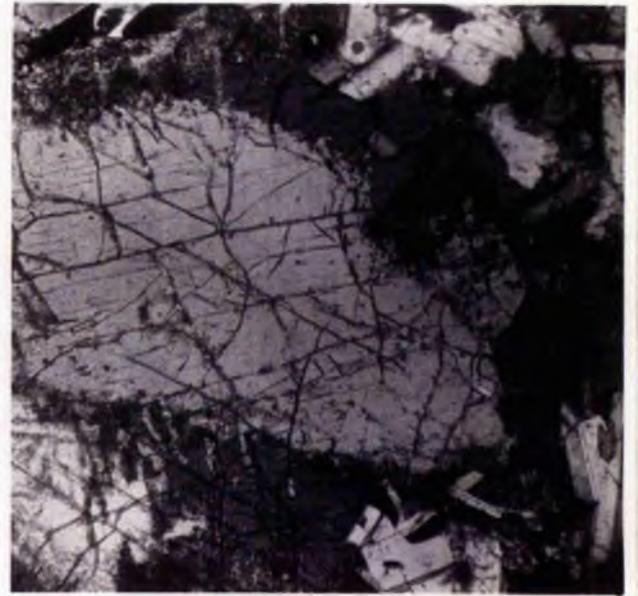


PLATE 56. Uninverted pigeonite rimming orthopyroxene phenocryst in the Shoshong sill. Crossed nicols. X 40.



PLATE 57. Pigeonite rim now inverted and showing (001) exsolution lamellae. Crossed nicols. X 40.

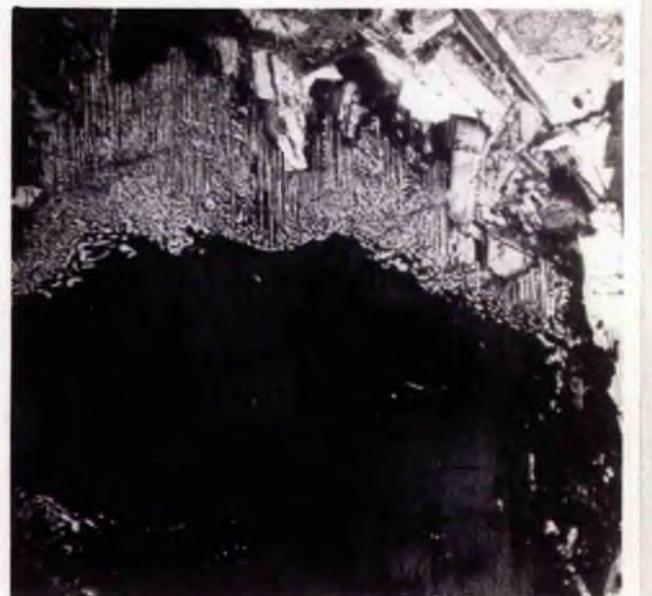


PLATE 58. Normal marginally exsolved orthopyroxene phenocryst with both (001) and (100) exsolution lamellae. Crossed nicols. X 40.



PLATE 59. Orthopyroxene phenocryst now almost completely exsolved. Crossed nicols. X 40.



PLATE 60. Prominent (110) cleavage of orthopyroxene induced in inverted pigeonite rim. Crossed nicols. X 40.

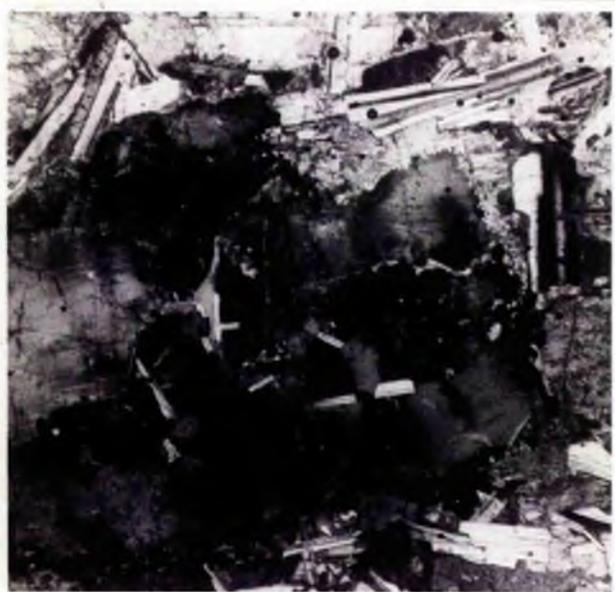


PLATE 61. "Mottled" extinction in orthopyroxene. Crossed nicols. X40.



PLATE 62. "Cross-fracture" exsolution in orthopyroxene. Crossed nicols. X40.

LEGEND.

THE GEOLOGY OF THE SHOSHONG—MAKHWARE AREA.

- FELSITIC DYKE SUITS
- LOOSE-PACKED SEDIMENTS
- SHOSHONG SHALES & SILTSTONES
- SHOSHONG QUARTZITES
- SHOSHONG ARKOSES.
- BASEMENT GRANITE & ALLUVIUM

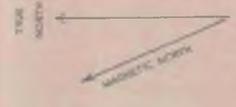
- INTRUSIVE IGNEOUS ROCKS
- MICROGRANITE DYKE SUITE
- BASIC DYKE SUITE
- MAFIC DIORITE
- TAKANE, MAPALA, & MAITSEANE DOLERITES
- SHOSHONG DOLERITE
- DOLERITE FEEDER DYKES

STRUCTURES.

- FLOW-BANDING OF GRANITE
- DIP & STRIKE OF SEDIMENTS
- FAULTS
- SHEAR ZONES
- FOLD AXES

TOPOGRAPHY.

- VILLAGES
- ROADS
- TRACKS



MAITSEANE

PHATE

MAITSEANE SHEET

TAKANE

YOMANI

MAPALA

MOGOLUTSANE

KALAMISE

SHOSHONG

MAKHWARE



THE GEOLOGY OF THE SHOSHONG—MAKHWARE AREA.

LEGEND.

-  FELSPATHIC ECCA GRITS
-  LOSKOP—WATERBERG SEDIMENTS
-  SHOSHONG SHALES & SILTSTONES
-  SHOSHONG QUARTZITES
-  SHOSHONG ARKOSES.
-  BASEMENT GRANITE & ALLUVIUM

- INTRUSIVE IGNEOUS ROCKS
-  MICROGRANITE DYKE SUITE
 -  BASIC DYKE SUITE
 -  MAKHWARE DIORITE
 -  TAKANE, MAPALJA, & MAIYEBANE DOLERITES
 -  SHOSHONG DOLERITE
 -  DOLERITE FEEDER DYKES

STRUCTURAL

-  FLOW-BANDING OF GRANITE
-  DIP & STRIKE OF SEDIMENTS
-  FAULTS
-  SHEAR ZONES
-  FOLD AXES

TOPOGRAPHY

-  VILLAGES
-  ROADS
-  TRACKS

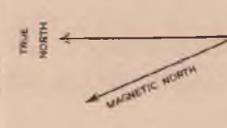


PLATE 2.

LEGEND

- ECCA FELSPATHIC GRITS
 - SHOSHONG SILTSTONES
 - SHOSHONG SHALES
 - SHOSHONG QUARTZITES
 - SHOSHONG ARKOSID GROUP
 - MAMALAPYE GRANITE & ALLUVIUM
- INTRUSIVE IGNEOUS ROCKS.
- MICROGRANITE & PORPHYRITE DYKES
 - KALAMARE GABBRO DYKE
 - DOLERITE-PEGMATITE ZONE
 - DOWNES MOUNTAIN-TYPE DOLERITE
 - RHONZITE-PHYRIC DOLERITE
 - (INTRUSION-BRECCIAS)
 - DOLERITE DYKES
 - TAKANE & MAPAIJA DOLERITES

STRUCTURAL.

- DIP & STRIKE OF JOINTS & BEDDING PLANES
- APPROXIMATE DIP & STRIKE OF SILL FLOOR
- DIP & STRIKE OF PRIMARY FLOW BANDING
- SHEAR ZONES
- FAULTS

TOPOGRAPHY.

- VILLAGES
- WELLS

TRUE NORTH

SCALE 1:30,000



PLATE 3.

THE GEOLOGY OF THE EASTERN SHOSHONG AREA.

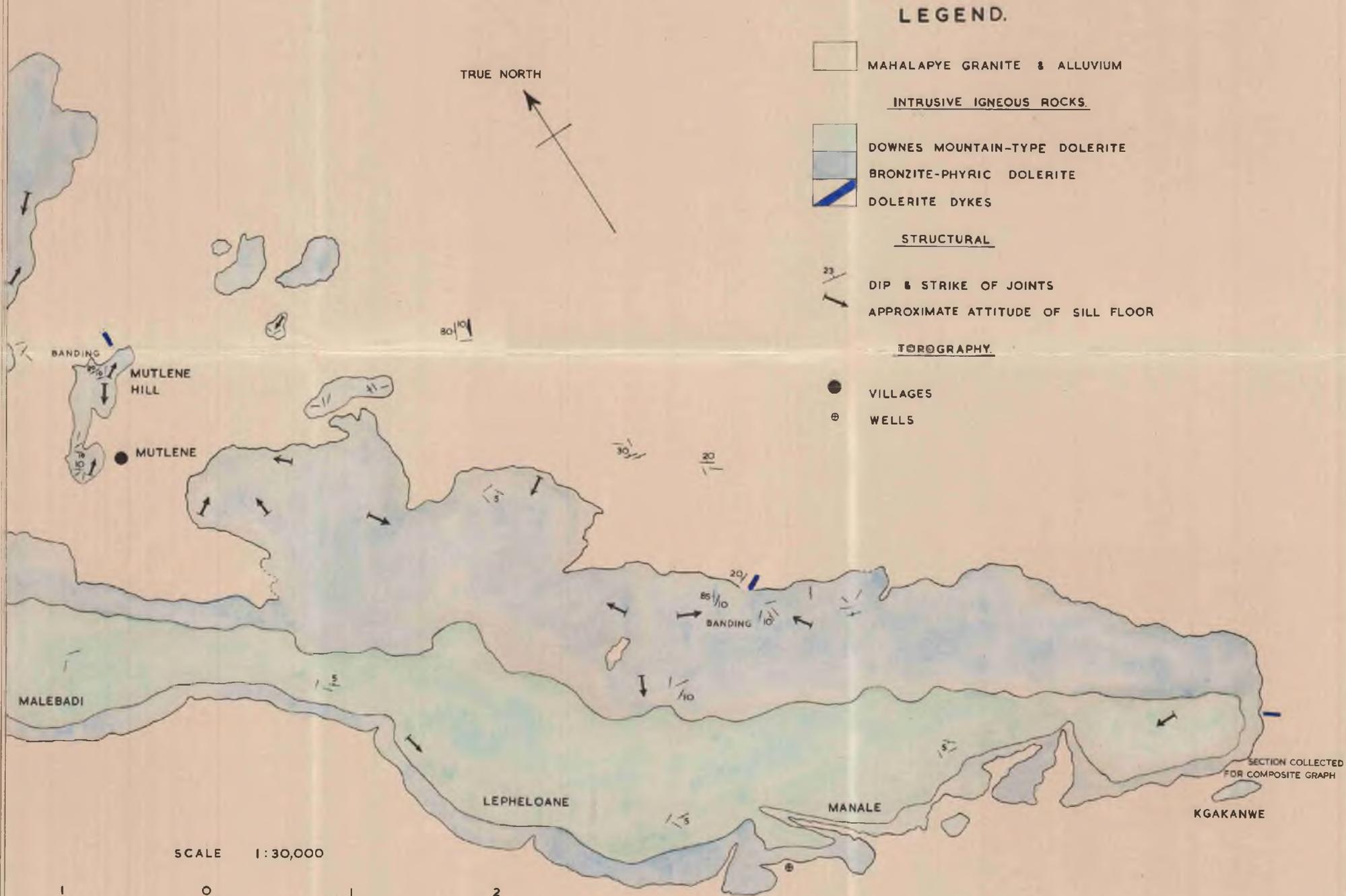


PLATE 4.

THE GEOLOGY OF

LEGEND.

-  SHOSHONG SHALES
-  SHOSHONG QUARTZITES
-  SHOSHONG ARKOSE GROUP
-  MAHALAPYE GRANITE & ALLUVIUM

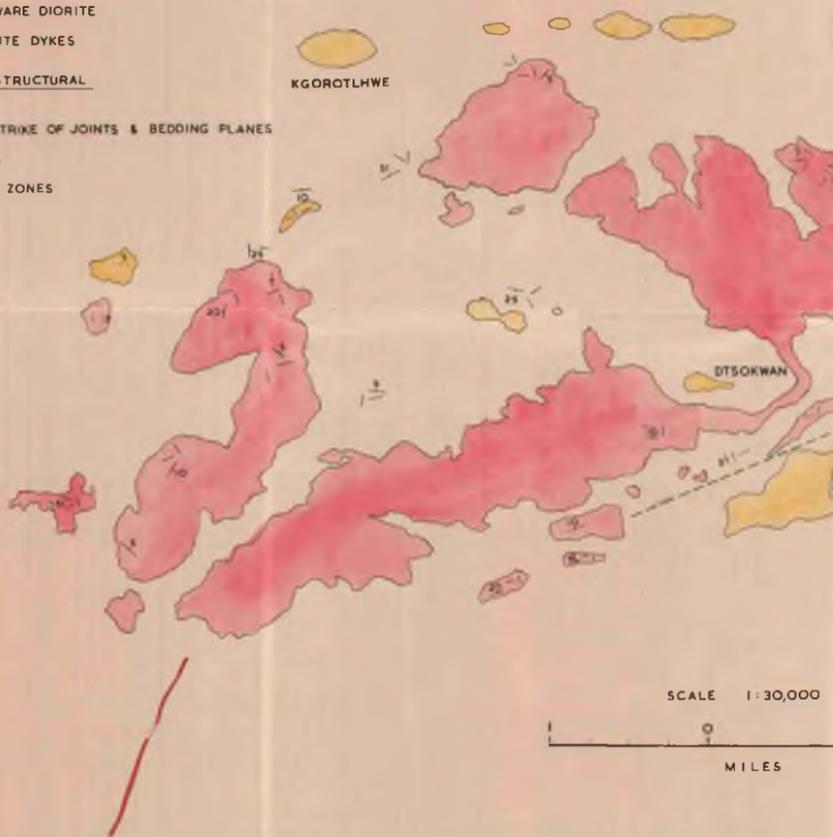
INTRUSIVE IGNEOUS ROCKS

-  MICROGRANITE DYKES
-  MAKHWARE DIORITE
-  DOLERITE DYKES

STRUCTURAL

-  DIP & STRIKE OF JOINTS & BEDDING PLANES
-  FAULTS
-  SHEAR ZONES

TRUE NORTH



SCALE 1:30,000

MILES

THE WESTERN MAKHWARE HILLS.

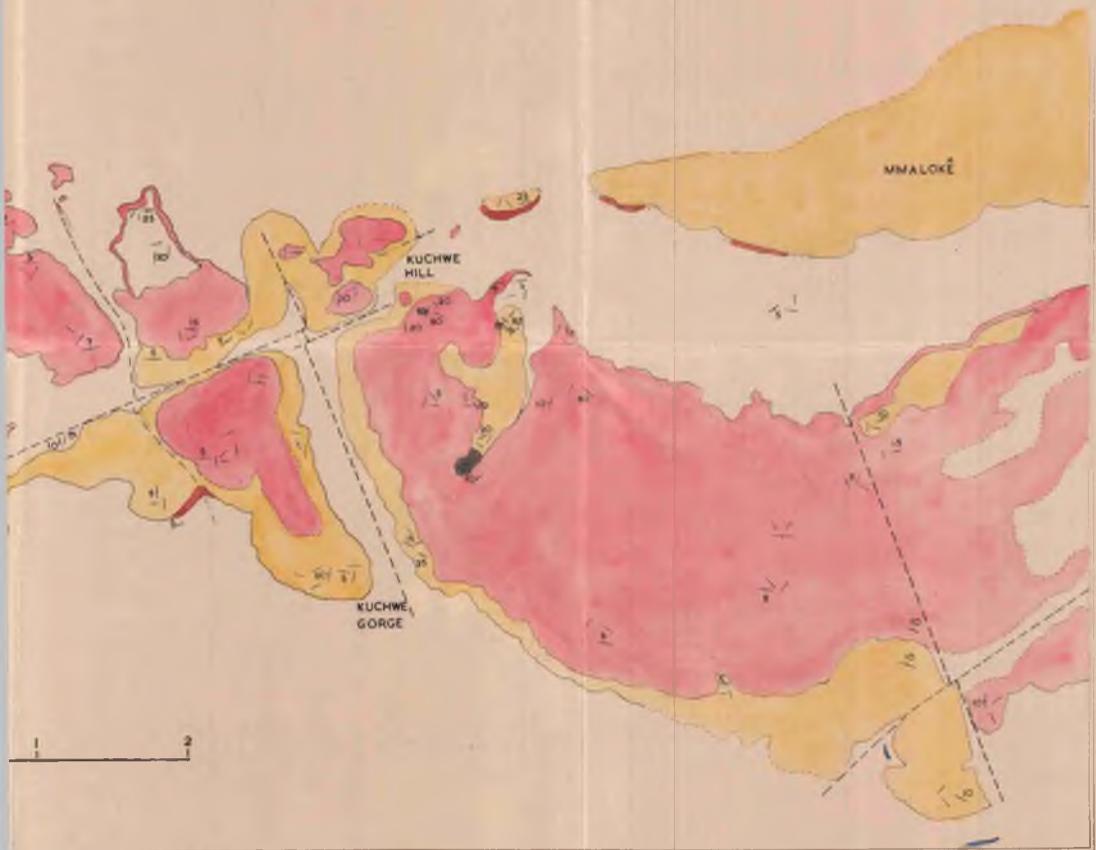


PLATE 5.

THE GEOLOGY OF THE EASTERN MAKHWARE HILLS.

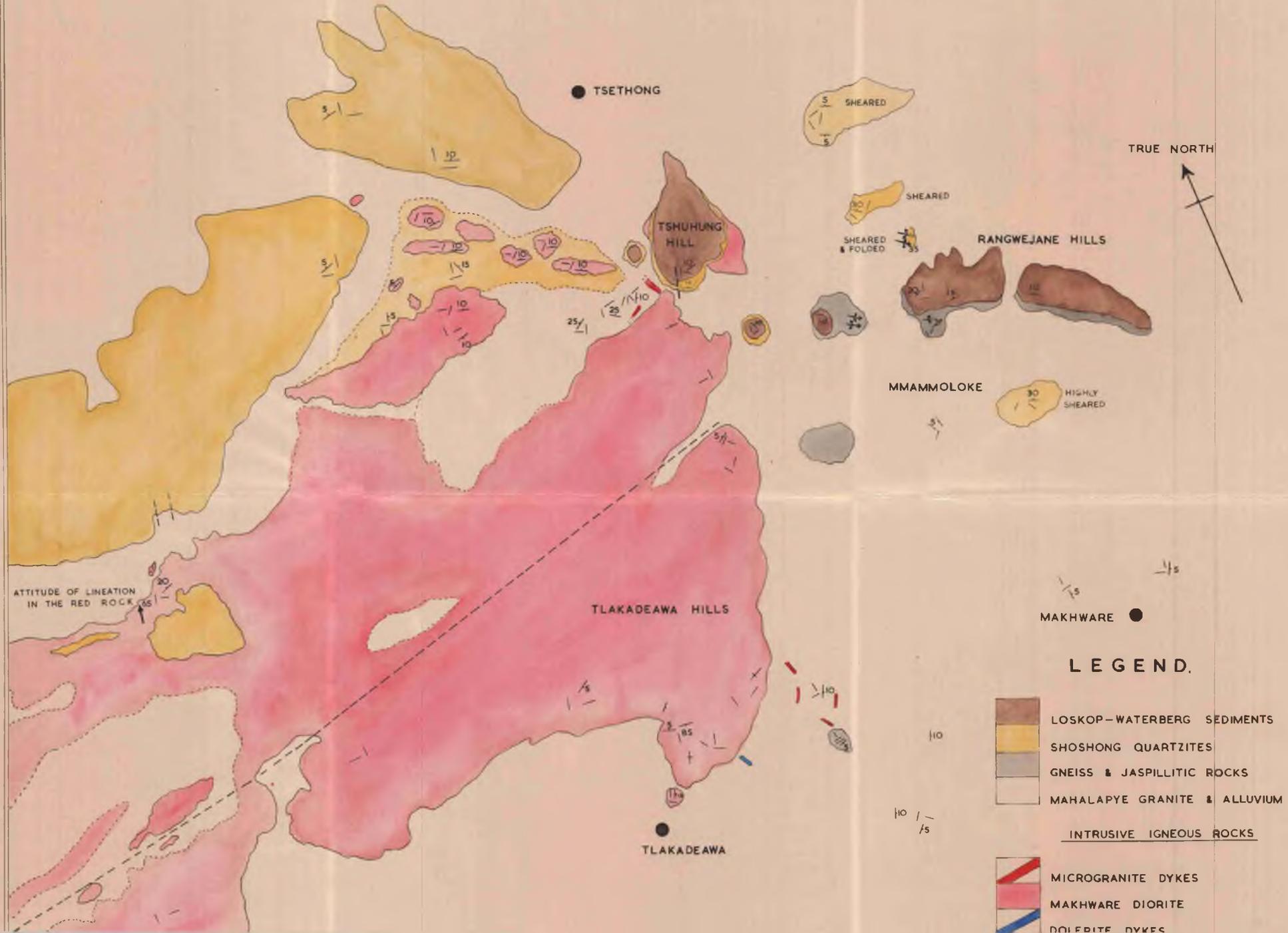


PLATE 6.

THE GENERAL GEOLOGY OF THE EASTERN PROTECTORATE.

