

THE PETROLOGY OF THE MESSUM IGNEOUS COMPLEX, SOUTH-WEST AFRICA

By Morna Mathias

[PLATES VI—IX]

ABSTRACT

The Messum Ring-Complex of South-West Africa, 105 miles N.N.W. of Walvis Bay, measures 14 miles by 12 miles. It shows a wide variety of rock types. This paper provides a petrological supplement to Martin's¹⁰ previous work on the structure and general geology. Thirty-three new rock analyses are included together with spectrographic data for the trace elements of twenty-eight of these analysed rocks. The sequence of events can be divided into three main phases (*a*) volcanic (*b*) intrusive (*c*) alkaline. In the volcanic and intrusive phases which are characterized by a repetition of the basic-acid rock association this Complex shows affinity with some of the British Tertiary ring-complexes. Limestone syntaxis is thought to be the cause of the change in chemistry from calc-alkaline to alkaline. Virtually no carbonatite occurs associated with the felspathoidal rocks of the alkaline phase. The extensive metasomatism accompanying the intrusion of a foyaitic magma was facilitated by the permeable nature of the acid tuffs and agglomerates, while the latter are admirably suited to show relict structure. Basalts and dolerites here acted as 'resisters' and their continuity of outcrop within the area of fenitization proves that the surrounding rocks were the products of metasomatism and not of igneous intrusion.

CONTENTS

I.	INTRODUCTION	24
II.	SEDIMENTS	25
III.	VOLCANIC PHASE	25
	A. BASIC LAVAS AND ASSOCIATED DYKES	25
	(i) Peripheral	25
	(ii) Middle	26
	(iii) Core	26
	B. ACID LAVAS AND PYROCLASTS	27
	C. COMPARATIVE CHEMISTRY	28
IV.	INTRUSIVE PHASE	30
	A. EUCRITES, ASSOCIATED ANORTHOSITES, GABBROS AND PYROXENE GRANULITES	30
	(i) General characters and relationships	30
	(ii) Petrography	31
	B. MICROGRANITES AND GRANOPHYRES	33
	C. GRANITES AND HYBRIDS	34
	D. RADIAL DOLERITE DYKES	37
	E. PETROGENESIS	37
	(i) Gabbroic rocks	37
	(ii) Granitic rocks	39
V.	ALKALINE PHASE	40
	A. TINGUAITES AND SYENITE-PORPHYRIES	40
	B. FOYAITE	43
	C. MELANOCRATIC FENITES	43
	D. LEUCOCRATIC FENITES	46
	E. RHEOMORPHIC FENITES	47
	F. NEPHELINITES AND OLIVINE TEPHRITES	48
	G. PETROGENESIS	50
	(i) Tinguaites and syenite-porphyrines	50
	(ii) Foyaitic	50
	(iii) Melanocratic fenites	52
	(iv) Leucocratic fenites	53
	(v) Rheomorphic fenites	53
VI.	COMPARISONS	53
VII.	SUMMARY OF THE PETROLOGICAL SEQUENCE	55
VIII.	ACKNOWLEDGMENTS	56
IX.	REFERENCES	56

I.—INTRODUCTION

This work is complementary to the previously published paper 'The Messum Igneous Complex in South-West Africa' by Drs. H. Korn and H. Martin which described the field and structural relationships of the Complex, while this paper deals specifically with petrography and petrogenesis. The identification of rock types has been the responsibility of the present author.

The author visited Messum in April, 1955, in the company of Dr. and Mrs. Martin and was then able to make observations and sample crucial outcrops which greatly helped in elucidating some of the petrological problems.

As a consequence of the additional field and petrographic information gained, the geological map of Messum has been revised and is reproduced with alterations at the end of this paper by courtesy of Dr. Martin.

Every effort has been made to avoid undue repetition and consequently it will be assumed that the reader is already familiar with the geological setting which has been so ably depicted by Martin.¹⁰ However, for the benefit of those who have not Martin's paper freshly in mind, a very brief resumé of those of his conclusions most pertinent to this paper is given here.

The Messum Complex occupies approximately 144 square miles and lies between Cape Cross and the Brandberg in latitude 21° 25' S. and longitude 14° 15' E. It is probably of Late Karroo age. Subsequent to the outpouring of Stormberg plateau lavas in this region activity became centralised. One of the foci was situated at Messum. Here alternating acidic and basic lavas and pyroclasts built up a volcanic pile. This outward-dripping lava cone was intruded by gabbro in the form of thick sheets and lenses. Differentiation of the thicker lower gabbroic sheets produced anorthosites. No complementary mafic differentiates have been observed. Two ring-fracture systems developed—an inner, separating the core from the outer zone, and a peripheral set. Subsidence within these zones caused an inversion of dips and the development of radial fractures. This subsidence was accompanied by a quiet upwelling of granite magma which followed preferred paths along porous or fissured pyroclastic and volcanic beds between the gabbro layers. Recrystallization and granitization of the volcanic rocks followed giving rise to granite and intermediate calc-alkaline rocks. Only remnants of the original lavas are left. Faulting along a NNE—SSW axis has caused the preservation in the SE sector of rocks originally higher in the sequence and given a degree of asymmetry to the Complex as a whole. Intrusion of dolerites along radial fractures preceded further down-faulting of the core. At this stage there was a radical change in the chemistry of the complex. Subsequent activity was confined to the core and consisted of felspathoidal types. Due to the greater subsidence of the core the volcanic rocks preserved represent a higher original level than exposed elsewhere in the Complex. Into these dominantly acidic volcanics foyaitic magma was intruded and is preserved as an approximately central foyaitic pluton surrounded by a zone of fenitised lavas and tuffs and as a ring-dyke system of tinguaitic and microsyenite with radial offshoots. The fenitised products of acid lavas and pyroclasts form an outer zone of syenite and possibly rheomorphic nordmarkite while those of basic volcanics grade into theralites.

The final phase of activity consisted of the intrusion of radial dykes of olivine nephelinite and related types.

Mineral compositions were determined by normal optical methods. The refractive indices may therefore have an error of ± 0.002 unless otherwise stated. The graphs used for olivines and orthopyroxenes were those of Poldervaart.¹⁴ Modes are given as percentage composition by weight. The classification of rocks on the basis of grain-size follows the recommendation of the British Association committee on petrographic nomenclature.³

II.—SEDIMENTS

Subsequent to the initiation of central activity at Messum, sedimentation proceeded intermittently during intervals between the outbursts of volcanic activity. Only a few interbedded sediments or their metamorphic equivalents appear in the sequence. This is no doubt partly due to the fact that, excluding tuffs, there were originally few sediments and partly to the intense metamorphic and metasomatic activity which would destroy evidence of parentage among all but the most resistant rocks. The few arkoses, siltstones and quartz sericite schists which occur between the early porphyritic basalts and the tuffs were probably preserved by faulting sealing them from circulating solutions. Higher in the lava column rare cordierite metanorites are associated with the lowest eucrites of the north-west sector and indicate the former presence of argillaceous bands. Higher still in the sequence are quartzites, sericitic quartzites and andalusite hornfelses which form definite horizons in the down-faulted volcanic rocks of the core.

III.—VOLCANIC PHASE

A. Basic Lavas and Associated Dykes

The evidence for the sequence of central activity at Messum is ably set out by Martin¹⁰ (pp. 11–16) and need not be repeated here. Basic lavas and tuffs are now best preserved around the periphery of the Complex where they appear as concentric ridges and constitute the early phase of vulcanicity. The higher horizons exposed can be seen in the marginal hills surrounding the core, whereas in the intervening area only remnants have escaped alteration.

(i) *Peripheral*

Basaltic rocks occur near the periphery of the Complex as radial dykes intrusive into the Damara schists and as basaltic flows forming concentric ridges. Petrographically they can be sub-divided into four types the age relationships of which are not always clear but in general appear to be in the following sequence, starting with the oldest. There may however, be local repetitions and reversals.

(a) non-phyric or sparsely phyric basalts. These have plagioclase (An_{80}) as their main and usually their sole phyric constituent. Other rarer phyric minerals are olivine (Fa_{20}) and augite ($\beta=1.691$; $2V\gamma=48^\circ$). The groundmass varies from intergranular to intersertal. A typical example is the analysed rock L11

which is a member of the dyke swarm in the south-west. This group is the most widely represented.

(b) felspar-phyric basalt which, apart from the abundance of plagioclase (An_{80}), is similar to the first group. L 13 (analysed) is a representative sample of this type.

(c) fine-grained tholeiitic basalt W 3 (analysed) which occurs near the top of the lava flows in the bed of the Messum River is a good example of this rather rare type. It shows minor secondary silicification.

(d) bronzite basalts. These have orthopyroxene (Of_{21}) phenocrysts which tend to alter to a fibrous bastite and a plagioclase which generally shows marked zoning. The average composition of the plagioclase is approximately An_{60} . The associated clinopyroxene has $\beta = 1.699$ and $2V\gamma = 41^\circ$. The analysed rock L 14 is a representative bronzite basalt.

(ii) *Middle*

The younger basalts occurring inside the peripheral ring-dykes are, as is to be expected, highly altered. Notable amongst these are the coarsely phyric types (plate VIII, fig. 1) which comprise not only felspar phyric but also augite phyric basalts, both types occurring in close association. Weathering of the phyric basalts produces a surface on which the phenocrysts of felspar or augite stand out in sharp relief. In some cases the felspars show flow-layering; exceptionally they attain a length of 2.5 cms., while commonly they measure approximately 5 mm. Augite phenocrysts measure up to 1 cm. in length. Basalts having the big varieties of phenocrysts generally have only one phyric constituent while those containing smaller phenocrysts are commonly both plagioclase and augite phyric.

The non-phyric basalts and the groundmass of the phyric basalts are usually severely altered. Mostly they have been converted to fine-grained aggregates in which amphibole and biotite figure largely while there is frequently an introduction of quartz, alkali felspar and more sodic plagioclase causing a change in composition to intermediate calc-alkali types. This granitising process is dealt with more fully in the section devoted to the granite-basalt hybrids.

The phenocrysts of the basalts, while retaining their identity longer than the groundmass minerals, have also suffered metasomatic attack. Outlines have frequently been blurred and there is notable clouding of the felspars and darkening of the pyroxenes.

In composition the plagioclase phenocrysts are sodic bytownites or calcic labradorites; the measured range, taking into account zoning, extends from from An_{84} - An_{50} . Augite phenocrysts typically show a brown colouration and concentric zoning due to black, presumably magnetite, dust. The $2V$ varies from 52° to 56° and β from 1.688 to 1.692. The amphibole of the groundmass has $\beta = 1.661 - 1.663$.

(iii) *Core*

Basaltic rocks of the core comprise flows, boulders in agglomerate and a few altered dykes. The basalts are usually plagioclase phyric types with either

zoned phenocrysts measuring up to 4 mm. in length and ranging in composition from An_{60} (centre) to An_{45} (margin), or smaller lath-like individuals of calcic labradorite. More rarely augite and ore occur in two generations. The finer-grained basalts are frequently amygdaloidal. Most of the basalts and all the radial dykes are amphibolitised and dykes occurring within the area of foyaite have been fenitised.

B. Acid Lavas and Pyroclasts

Few of the original acid lavas and pyroclastic rocks of the Messum volcano have escaped intensive metasomatism and few, hence, have an unequivocal origin. This applies more particularly to those acid volcanic rocks lying outside the core which were more deeply buried than their counterparts occurring inside the inner ring-dyke system. Very fine-grained microgranophyres and microgranitic rocks occur with the basaltic lavas near the outer rim and also higher up in the sequence amongst the granites and basic intrusives. In some cases relict structural and textural features are strongly indicative of a volcanic origin while in others it is impossible to say for certain whether the rocks are metamorphosed fine-grained arenaceous sediments or acid lavas or tuffs. In hand specimen many of these rocks look like fine-grained quartzites, while in thin section they appear as very delicate graphic intergrowths of quartz and alkali feldspar.

Within the ring-dyke system which demarcates the core, acid as well as basic volcanic rocks from higher horizons have been preserved by downfaulting. These lavas, tuffs and agglomerates occur in the marginal hills and are best exposed in the NE and S. They, too, have suffered considerable alteration and they must have been buried under quite a cover of later extrusives which have since been denuded, to cause their exposure at the same general level as the coarse-grained foyaite in the central part of the core. The oversaturated volcanic rocks here predominate and consist of quartz-porphyrines, agglomerates, tuffs and rhyolites. Banding, perlitic cracks and vesicular structure can be seen in some of the less altered fine-grained rocks, but all trace of glass has vanished and the rocks now consist essentially of a fine aggregate of quartz, altered feldspar and disseminated ore with microcrystalline, microspherulitic or micropoikilitic textures. The recrystallized tuffs which are recognisable as such show the ghost outlines of assorted angular fragments now identifiable solely by slight colour and textural differences. Where all original features have been obliterated by recrystallization it is impossible to tell whether the rock was formerly a tuff, rhyolite or felsite. From the field evidence it appears that most of the quartz-porphyrines are recrystallized porphyritic rhyolites. They contain phenocrysts of quartz, altered potash feldspar or perthite and less frequently, oligoclase. The perthite is sometimes sufficiently coarse to show albite twinning in the sodic component. The groundmass may be microspherulitic, microgranitic or granophyric. Biotite and ore are the chief melanocratic minerals. Zircon occasionally builds crystals up to 0.4 mm. in length. Green and brown tourmalines occur sporadically. Augite, apatite and a reddish-brown orthite are variable accessories. The orthite in one quartz-porphyry has the following properties: $\alpha = 1.782$ (very pale yellow almost colourless); β (reddish brown); $\gamma = 1.803$ (deep brown). The presence of

perthite in the quartz-porphyrines may be due to exsolution taking place during the period of metamorphism due to the foyaite intrusion. The potash feldspar of the tuffs is too altered for determination of the optic axial angle and no fresh sanidine could be found.

C. Comparative Chemistry

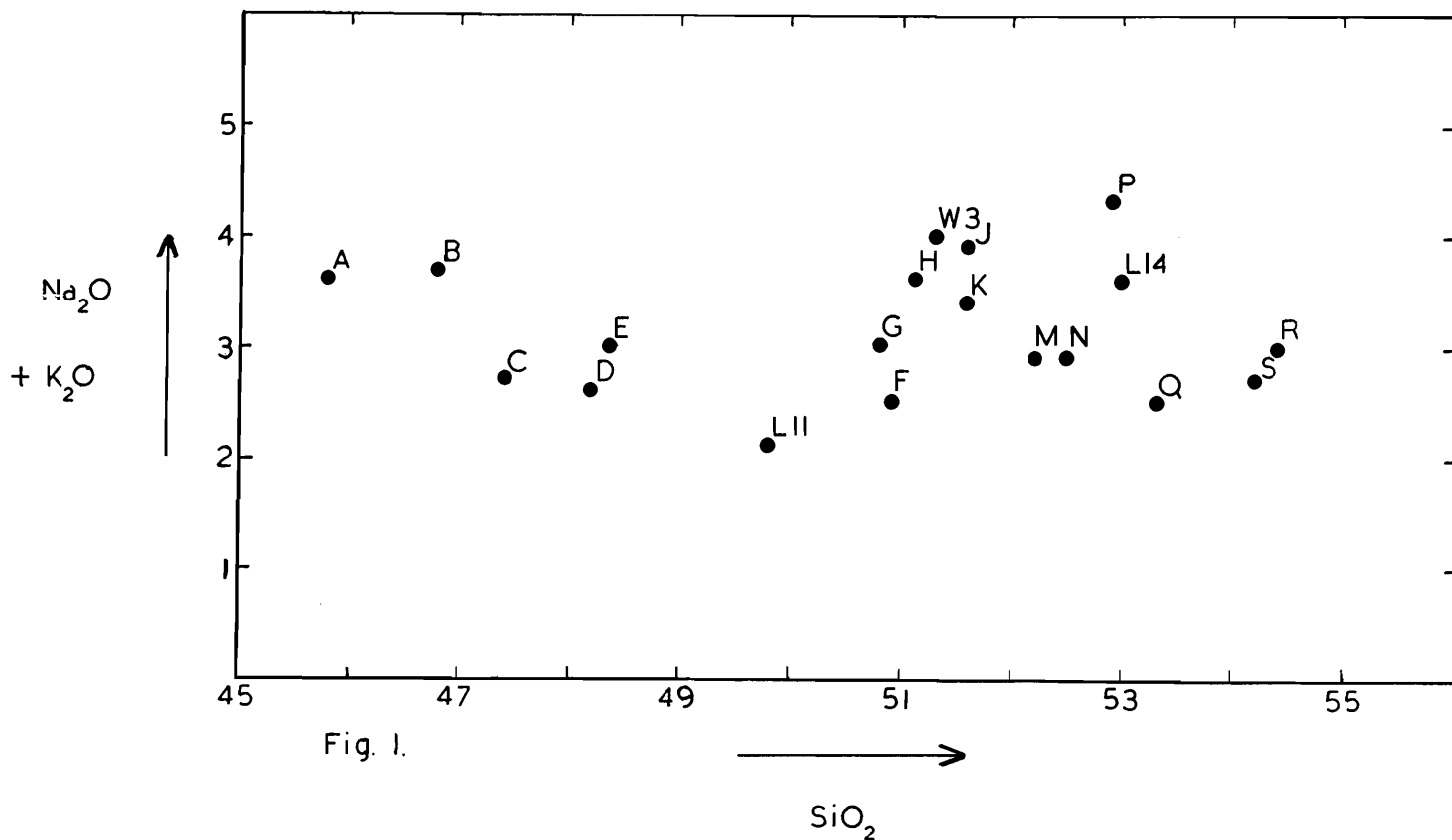
Only the basalts of the periphery are sufficiently fresh and unaltered to be considered in assessing possible magma types. Four of these basalts were analysed but one, L 13, is a strongly phyrlic type and therefore need not be considered further.

The basalt L 11 is representative of the most abundant variety. It is closest to the olivine basalt magma-type but differs from such well-known examples in this category as the Hebridean, the Skaergaard and the Hawaiian in being somewhat richer in silica and poorer in alkalis. These differences are shown graphically in fig. 1 in which the other Messum basalts and comparable types are also plotted, having been recalculated, where necessary, to 100 per cent. anhydrous.

The rock W 3 has suffered slight secondary silicification but even allowing for an extra 2 per cent. silica introduced it is still a typical central-type tholeiite.

L 14 is a bronzite basalt comparable to the Hangnest-type dolerite but lower in magnesia and higher in potash. Compared with the bronzite dolerites of the Falkland islands²⁵ it is lower in silica and lime and higher in magnesia and potash.

Here then again is the old problem of the association of olivine-basalt and tholeiitic types in a central complex. It is too wide a subject for proper consideration in this paper, but it might be remarked that of the two main theories one, the settling of early crystals advocated by Bowen,² admits of simple quantitative treatment. It has however, the disadvantage that when applied beyond the production of tholeiite to that of the more siliceous calc-alkaline rocks it fails to explain the preponderance of oversaturated rocks. The rival theory, i.e. the assimilation of sial by olivine basalt magma is unconvincing when treated quantitatively. Using Nockold's average analyses¹³ (table 7, columns VII and IX), calculation shows that assimilation of 10 per cent. by weight of pure quartzite would give a rock similar to tholeiite, except that magnesia would be approximately 2 per cent. too high and alumina and lime each 1 per cent. too low. As it is unlikely that a nearly pure quartzite would occur at the base of the sial it is necessary to invoke differential assimilation of material of the low-melting quartzo-feldspathic eutectic composition with subsequent loss of some alkaluminous material by outward transfusion. This is precisely the hypothesis advanced by Holgate⁶ and his theory, which involves limited miscibility of basaltic and silicic material, has the great advantage of accounting satisfactorily for the fact that so many rocks of intermediate composition appear to be hybrids. It is for this reason that Holgate's theory is preferred in this paper.



A. Average normal alkali basalt and dolerite (Nockolds 13); B. Average alkali basalt without olivine (Nockolds 13); C. Average Hebridean olivine basalt (Walker and Poldervaart 25); D. Average Skaergaard chilled phase (Walker and Poldervaart 25); E. Average olivine basalt, Hawaiian Archipelago (Macdonald 12); F. Average basalt (melaphyre) Cape Cross (Gevers 5); G. Average normal tholeiitic basalt and dolerite (Nockolds 13); H. Average central basalt (Nockolds 13); J. Average non-porphyrific central magma (Walker and Poldervaart 25); K. Average South American basalt (Walker and Poldervaart 25); L.11. Normal basalt (Messum); L.14. Bronzite basalt (Messum); M. Average Stormberg lava (Walker and Poldervaart 25); N. Average Karroo dolerite (Walker and Poldervaart 25); P. Average north-eastern Otago magma (Walker and Poldervaart 25); Q. Average Tasmanian chilled basalt (Walker and Poldervaart 25); R. Average Hangnest dolerite (Walker and Poldervaart 25); S. Bronzite dolerite, Falkland Islands (Walker and Poldervaart 25); W3. Tholeiitic basalt (Messum).

IV.—INTRUSIVE PHASE

A. Eucrites, Associated Anorthosites, Gabbros, and Pyroxene Granulites

(i) *General characters and relationships*

These rocks form a series of inward-dipping inclined sheets or sills ; massive and few in number in the N.W. sector, but numerous, thin and disconnected in the E. and S.E.

Petrographically the rocks consist of fine-grained olivine eucrites grading upward into anorthosites, and hypersthene microgabbros rich in biotite. Granulitic types are sparsely represented. They occur associated with the eucrites in the N.W. sector and also amongst the lavas in the S.S.E. near the outer ring-dyke. Fluxion structures occur in many marginal eucrites and occasionally also in anorthosite. Judged by grain-size all these rocks fall within the hypabyssal class. The typical texture is ophitic. However, for the sake of conformity with the two previous papers on the Messum Complex,^{9, 10} they will be referred to as microeucrites and microgabbros instead of the corresponding types of dolerite, which strictly speaking, they are.

Special care was taken in studying these basic rocks to determine whether there was any regular sequence of variation of mineral composition with height, i.e. cryptic layering. No sign of rhythmic layering has here been encountered. Samples were taken and studied from the base and top of the thick sheets in the N. and N.W. and from successively higher positions within the original volcanic cone proceeding inwards to the core. The result of this study showed that the two massive sheets which occupy the lowest horizons consist of olivine microeucrite which frequently shows an upward gradation into remarkably pure anorthosite. A higher horizon of microeucrites is also found among the thinner disconnected microgabbro sheets of the plain. It lies approximately halfway between the top of the massive microeucrites and the outer edge of the core. Apart from the variation in the proportion of plagioclase felspar present, the composition of the constituent minerals varies only within narrow limits. (Table 1).

The biotite hypersthene microgabbros occur at horizons above the massive sheets of the W. N.W. and N. and outcrop mainly in the S.E. sector, but they also form small disconnected bodies in the sand-covered plain in the W. and S.W. (see map). The relationship between the eucrites and microgabbros is uncertain. No field evidence indicating an intrusive relationship of one to the other was seen, but owing to the sand-cover and the block weathering both of which tend to obscure any contact zone, this by itself cannot be considered conclusive evidence of the absence of an age difference. The occurrence of anorthosite at the top of the massive microeucrites and the lack of cryptic layering within them favours the idea of a separate intrusion distinct from and in the main earlier than the microgabbros ; on the other hand the occurrence of a higher horizon of eucrites and the fact that the most basic representatives of the microgabbros are olivine-bearing and close in composition to the eucrites makes it quite reasonable to suppose that they formed from one parent magma. In all probability the eucrite represents this original magma enriched in early-crystallizing bytownite, whereas the microgabbro is a differentiated and

TABLE 1
MODAL AND OPTICAL DATA
'A' OLIVINE MICROEUCRITES

Reference No.	Position	Per cent Plagioclase	Per cent Olivine	Per cent Orthopyroxene	Per cent Clinopyroxene	Per cent Biotite	Per cent Hornblende	Per cent Ore
Me 4 ..	Base of lowest sheet in N-W	58 (An ₈₁)	17.9 (Fa ₂₅)	1.7 (Of ₂₂)	21.0 (β 1.695)	0.5	nil	1.0
Me 5 ..	Base of lowest sheet in N-W	45.5 (An ₈₁)	15.1 (Fa ₂₅)	1.1 (Of ₂₂)	35.0 (β 1.695)	0.8	0.4	2.1
Me B57 ..	Top of lowest sheet in N-W	48.7 (An ₇₇)	8.7 (Fa ₂₆)	4.1 (Of ₂₁)	35.8 (β 1.695 2V γ 46°)	nil	nil	2.7
Me 3 ..	Base of second sheet in N-W	45.9 (An ₈₀)	11.4 (Fa ₂₈)	<1 n.d.	40.5 (β 1.703 2V γ 47°)	nil	nil	2.2
Me B56b ..	Base of second sheet in N-W	46.8 (An ₈₀)	12.8 (Fa ₂₆)	2.7 (Of ₂₂)	36.1 (β 1.695 2V γ 47°)	nil	nil	1.6
Me B58 ..	Base of second sheet in N-W	31.6 (An ₈₂)	18.2 (Fa ₂₃)	<1 n.d.	50.0 (β 1.693 2V γ 48°)	nil	nil	0.2
Me T50 ..	Top of second sheet in S-W	46.8 (An ₈₂)	11.0 (Fa ₂₅)	<1 n.d.	42.2 (β 1.693 2V γ 50°)	nil	nil	nil
Me B56a ..	Top of second sheet in N-W	28.9 (An ₈₂)	11.0 (Fa ₂₃)	1.0 n.d.	58.8 (β 1.697 2V γ 47°)	nil	nil	0.3
Me T69 ..	Midway between inner and outer ring-dykes in E	61.0 (An ₈₂)	11.7 (Fa ₂₃)	<1 n.d.	27.3 (n.d. schillerized)	nil	nil	nil
Me 2 ..	Midway between inner and outer ring-dykes in N-E	60.7 (An ₈₀)	17.3 (Fa ₂₅)	2.5 (Of ₂₃)	18.3 (β 1.695 2V γ 46°)	nil	nil	1.7
Me Y30 ..	Midway between inner and outer ring-dykes in S	45.6 (An ₈₀)	11.0 (Fa ₂₈)	<1 n.d.	36.4 (n.d. 2V γ 51°)	nil	nil	7.0
B PYROXENE GRANULITES								
Me K58 ..	Among outer lavas in S-E	29.9 (An ₇₇)	11.9 (Fa ₂₆)	41.2 (Of ₂₇)	12.2 (β 1.697)	0.4	nil	4.4
Me 11 ..	At top of lower eucrite in N-W	30.2 (An ₈₀)	40.4 (Fa ₂₄)	0.6 n.d.	23.6 (β 1.698)	nil	nil	5.2
Me P16 ..	Near top of upper eucrite in N-W	44.0 (An ₈₅)	<1 n.d.	13.7 (Of ₁₁)	31.8 (β 1.697)	nil	nil	10.5
C HYPERSTHENE MICROGABBROS								
Me T10 ..	Just above eucrite in S-W	46.0 (zoned An ₆₀ average)	10.0 (Fa ₃₅)	12.0 (Of ₂₈)	19.7 (2V γ 46°)	9.9 (a 1.583)	nil	2.4
Me T58 ..	Slightly higher in S-W	49.7 (zoned An ₆₀ average)	11.6 (Fa ₃₆)	13.0 (Of ₂₆)	14.0 (β 1.693 2V γ 50°)	6.2 (a 1.583)	1.9	3.6
Me B38 ..	Midway between inner and outer ring-dykes in W	47.9 (zoned An ₅₀ average)	12.6 (Fa ₃₄)	12.1 (Of ₂₆)	15.7 (β 1.695)	8.0 (a 1.583)	1.0	2.7
Me Q23 ..	Lowest in S-E	48.8 (zoned An ₆₀ average)	10.1 (Fa ₃₄)	6.4 (Of ₃₁)	17.3 (β 1.693 2V γ 51°)	8.8 (a 1.583)	3.0	5.6
Me Y25 ..	Slightly higher in E	35.9 (zoned An ₆₀ average)	11.9 (Fa ₃₅)	19.2 (Of ₃₀)	15.7 (β 1.693 2V γ 47°)	14.9 (a 1.583)	0.7	1.7
Me Y5 ..	Same horizon as above in ESE	56.9 (zoned An ₅₅ average)	6.9 (Fa ₃₇)	17.4 (Of ₃₀)	6.9 (β 1.696)	8.1 (a 1.583)	nil	3.8

contaminated product. Further discussion of the petrogenesis of these rocks follows a brief account of their petrography.

(ii) *Petrography*

Olivine microeucrites.

The average length of the plagioclase of these rocks ranges from .5 mm. to 1.5 mm. Ophitic texture predominates though granitic texture is also fairly common. Fluxion structure, more or less perfectly developed characterizes most of the marginal rocks, and some show the development of imperfect microbanding. The bands consist of alternating layers of aligned plagioclase laths and clinopyroxene ophitically enclosing plagioclase. Olivine tends to be segregated between the clinopyroxene layers thus forming olivine-rich streaks within the plagioclase bands. The width of the bands is of the order 5 – 10 mm. and the banding is not sufficiently well developed to be seen in hand specimen.

A typical olivine microeucrite contains approximately 12 per cent. olivine ; 37 per cent. clinopyroxene ; 50 per cent. plagioclase and 1 per cent. ore. Olivine is fresh, anhedral and varies in composition from Fa_{23} – Fa_{28} . Clinopyroxene has $2V\gamma = 47^\circ - 50^\circ$ and $\beta = 1.693 - 1.703$ which, using Hess's curves, corresponds to an augite of composition approximately $\text{Wo}_{40}\text{En}_{40}\text{Fs}_{20}$. The clinopyroxene is frequently much schillerized, in extreme cases being rendered quite opaque. This schillerization may be marginal or patchy and there is usually a clear zone around inclusions of iron ore pointing to the crystal having cleared the vicinity of available iron.

The plagioclase feldspar is a bytownite having an anorthite content of 80 – 82 per cent. It is usually fresh, well-twinned and shows little zoning. Clouding occurs but is not as frequent or conspicuous as the schillerization of the augites. As noted by Poldervaart and Gilkey¹⁵ iron ore is not necessarily the cause of clouding and in the Messum eucrites the particles responsible, whenever they are large enough to be distinguished, appear very like minute pyroxene crystals. No regular orientation occurs within the host. In a few instances clouding occurs which is inverse to the normal i.e. a relatively clear core and more intense peripheral clouding. Clouded feldspars with clear rims are here the exception and the clouding is generally even throughout the crystal.

Accessory constituents include orthopyroxene, ore, biotite and hornblende. Orthopyroxene is a bronzite ($\text{Of}_{22} - 23$) occurring as a reaction product around olivine. It frequently forms the same type of graphic outgrowth with ore as described by Simpson²⁴ for the Ridge gabbros of Okonjeje.

With increase in the proportion of bytownite feldspar there is a gradual passage through anorthositic gabbros and gabbroic anorthosites to true anorthosites. The intervening types are not marked by any special features except that olivine and augite become more noticeably interstitial to the plagioclase.

Anorthosites

Anorthosites occur at or very near the top of the two thick sheets of olivine microeucrite and, as Martin¹⁰ points out, their occurrence between the outer margin and the porphyritic lavas in the S.E. is additional evidence of the greater

subsidence in this sector. Many of the anorthosites are extraordinarily pure having over 95 per cent. and occasionally over 97 per cent. of bytownite. Flow structure may sometimes be seen while a rude banding, due to certain layers containing more interstitial clinopyroxene or olivine is a feature of those anorthosites which have a sufficient ferromagnesian content. The grain-size averages 1 mm. which is similar to that of the microeucrites. Granulation is quite frequent. The olivine and clinopyroxene present are similar in properties and composition to the same minerals in the eucrites. Augite is a little oftener schillerized, otherwise the only difference apart from the proportion of minerals is that the plagioclase is slightly more calcic containing 82–86 per cent. anorthite and there is a tendency for the iron ore, when present, to assume euhedral form.

Altered anorthosites occur in the S.S.E. amongst altered lavas and near the marginal ring fissures. Where alteration has not proceeded too far it can be seen that originally these had the same composition as the unaltered anorthosites—the cores of plagioclase crystals having the same composition in both varieties. Alteration was evidently brought about by hydrous alkaline emanations as the feldspar has been saussauritised, the olivine serpentinised and the augite first schillerized and then replaced by either chlorite and clinzoisite or by epidote. In some cases both ferromagnesian and plagioclase have evidently contributed to the formation of secondary zoisite, clinzoisite, epidote, chlorite, sillimanite and calcite.

Hypersthene microgabbros.

In hand specimen these rocks generally require examination with the aid of a hand-lens to distinguish them from the olivine microeucrites, the presence of flakes of biotite then serves for their identification. In grain-size they are strictly comparable to the microeucrites; in texture they are ophitic.

Samples of these rocks were examined from all parts of the Complex and modal and optical data of a few representative examples are listed in Table 1. They show remarkable uniformity in the composition of the individual minerals. The plagioclase is typically zoned. In extreme cases the outermost zones have a composition of sodic oligoclase, while the cores have the same composition as the bytownite of the olivine microeucrites. The calcic cores are frequently clouded while the sodic margins are unaltered. The average composition corresponds approximately to sodic labradorite. Olivine is present and is a more iron-rich variety than that found in the eucrites. It has a composition of $Fa_{35} \pm 2$. Orthopyroxene occurs both as rims to crystals of olivine and as discrete individuals. It is slightly less ferriferous than the associated olivine due, no doubt, to the inversion olivine/orthopyroxene being accompanied by exsolution of iron. Clinopyroxene is frequently schillerized. β varies from 1.693 to 1.696 and $2V\gamma$ from 46° to 51° . Iron ore is nearly always surrounded by biotite. Small amounts of serpentine, hornblende and a pale fibrous amphibole may occur and are secondary after olivine, clinopyroxene and orthopyroxene respectively.

Pyroxene granulites.

Under this heading is included a rather mixed assemblage of fine-grained granular basic rocks occurring amongst basalts in the S.S.E. and microeucrites in the W., N.W. and N.

(a) In the southern group the average grain-size is 0.1 mm. Some of these granulites are very similar in appearance to the granulitic gabbros of Okonjeje and they include types with felspar-rich lenticles and patches and also relict amygdules now filled with calcite, amphibole and mica. A rough foliation due to orientation of the felspar is sometimes shown, as is ophitic and poikilitic enclosure of plagioclase by augite and olivine respectively. There is considerable variation in the proportion of minerals present and in their optical properties. Plagioclase ranges in composition from approximately $An_{65} - An_{80}$. Olivine has a fayalite content of from 25 to 30 per cent. Orthopyroxene is generally a major constituent and may exceed clinopyroxene in amount. It occurs as pleochroic granules showing the characteristic alteration to fibrous amphibole and has an Of. content of from 27 to 35 per cent. Clinopyroxene is unshillerized and has $\beta = 1.695 - 1.698$. Iron ore is fairly plentiful. Biotite is an accessory constituent.

(b) The north-western pyroxene granulites occur amongst the eucrites either interbedded or in dyke-like form. The average grain-size varies from 0.1 mm. to 0.25 mm. With one exception they are fine-grained equivalents of the eucrites having similar foliation, occasional banding of alternating troctolitic and olivine-poor layers and mineral composition. The one exception is a well-foliated orthopyroxene-rich rock with no olivine or biotite. It is peculiar in having exceptionally magnesia-rich orthopyroxene (Of_{11}) associated with a labradoritic plagioclase. In composition it thus corresponds to neither the microeucrites nor to the microgabbros. Notable features of many of these granulites are the clouding of the felspars and the intense schillerization of the clinopyroxene. A pale greenish-brown amphibole sometimes rims the schillerized clinopyroxene.

B. Microgranites and Granophyres

Aplitic granophyres and microgranites occur cutting the basic lavas of the outer rim and also the gabbroic and eucritic sheets. The predominant vein direction is outward and intersects the dip of the basic sheets at approximately right angles. Subsidiary connecting veins are parallel to the dip. Other microgranites and granophyres have a non-transgressive relationship and occur in the ring valleys with a conformable attitude to the lava sheets or gabbroic rocks.

The average grain-size of these rocks is approximately 0.25 mm. but every gradation is shown to very fine recrystallized tuffs or sediments on the one hand and to granophyric granites on the other. Distinction between transgressive and non-transgressive types is essentially a matter of good exposures for neither texture nor mineralogy is by itself of diagnostic value. Granophyric texture is developed in rocks interbedded with basic sheets and with a grain-size so fine (± 0.01 mm.) that a volcanic origin seems well nigh certain, while other rocks with a typical sedimentary seriate texture which would almost certainly be classified as fine-grained sandstones or siltstones from their appearance in thin section, have intrusive relationships in the field.

Mineralogically the microgranites and granophyres are similar to the granites and consist essentially of an aggregate of quartz and alkali felspar, the latter

usually being more or less perthitic, with subordinate oligoclase, ore, zircon and orthite. Variable amounts of biotite, hornblende, aegirine-augite and augite may be present and, as in the granites, are probably indicative of contamination by basaltic material. The intrusive types are not dealt with further here as the optical properties of their minerals are similar to those of the granites. Two series gradational from volcanic material will now be described as furnishing evidence of an origin by recrystallization for some of the microgranites and granophyres.

The first series occurs in the outermost ring valley lying between hills of basaltic lava. The specimens are all from this same horizon but occur in different parts of the Complex. In this case there can be no doubt about the volcanic origin of the least altered sample. In it phenocrysts of sodic labradorite occur in a partly devitrified glassy base showing prominent perlitic cracks. The refractive index of the glass is 1.53 and the rock is therefore of intermediate type. (Plate VI, fig. 1). Next in sequence is a closely comparable rock with phenocrysts of the same composition and size set in a very fine microcrystalline base. (Plate VI, fig. 2). In the third rock type the plagioclase phenocrysts show well-marked clouding and the groundmass minerals are clearly defined having an average size of approximately 0.03 mm. Quartz is abundant and is almost certainly due to secondary silicification. (Plate VI, fig. 3). In the fourth and subsequent types the identity of the original rock is gradually effaced; the phenocrysts are in process of replacement by potash feldspar and the grain-size shows a further increase so that these rocks grade imperceptibly into microgranites. (Plate VI, fig. 4).

The second series of rocks is characterized by the presence of aegirine-augite and fluorite and they occur in the south-west above the outermost eucrites. The finest of these is comparable in grain-size to the second of the previous series; no glassy types having been collected. Metasomatism of these rocks leads to the production of granophyric textures, at first very fine and delicate but gradually coarsening. The finest-grained types are as rich in quartz as the coarsest and metamorphism has apparently been simply a process of recrystallization. (Plate VII, figs. 1-4).

C. Granites and Hybrids

Aplogranite forms the floor of the ring valleys between the outer lava sheets and between the eucritic and gabbroic hills as far as the inner ring-faulting. Exposures are usually poor owing to sand-cover. Martin has remarked on the striking difference between the amount of assimilation of basaltic material in the two halves of the Complex. In the less down-faulted north-western sector practically no assimilation has taken place and the granite is typically aplitic. In the south-eastern sector there is an astonishingly fine display of assimilation of basaltic material in every stage of digestion and a direct variation between the degree of contamination of the granite and the diffuseness of the basic xenoliths. The resulting hybrid rocks vary in composition according to the amount of assimilation and range from dioritic and monzonitic to granodioritic.

In various parts of the Complex granite can be seen intruding gabbros and eucrites, while the apparently anomalous observation that the gabbro contact is sometimes chilled against the granite is ably explained by Martin¹⁰ who assumed that the gabbro originally chilled against tuffs and lavas and that these tuffs formed privileged paths for granitising fluids which transformed them. The granitising fluids accompanied the upwellings of granite magma and the resulting granitic rocks are believed to be partly magmatic, partly metasomatic in origin.

As in the case with the microgranites and granophyres, microscopic study reveals no certain criteria for distinguishing between these two types. Many of the granites have a peculiar seriate texture which might easily be an inheritance from a porphyritic tuff or lava but, on the other hand, might also be produced by partial granulation. (Plate VIII, fig. 2).

A short description of the granites and hybrids is given before proceeding further with a consideration of their origin.

The texture is either granitic, granitic with granophyric patches, or seriate. The mineral components are quartz and alkali feldspar ('orthoclase' or perthite) with minor variable quantities of oligoclase, ore, biotite, zircon and orthite. Aegirine-augite and fluorite are present in some specimens. Samples contaminated by the incorporation of basic material have, in addition, hornblende \pm augite, sphene and a more basic plagioclase. A typical seriate-textured granite has a grain-size ranging from 5 mm. to 0.05 mm. and is composed of large irregular fretted crystals of perthite and quartz in a medium to fine-grained mosaic of alkali feldspar, oligoclase and quartz together with sparse ore, pale green clinopyroxene, rather large zircons, shreds of biotite or chlorite and occasional fluorite and orthite grains.

In the least contaminated granites the plagioclase varies in composition from An₁₅ - An₂₅. Biotite occurs in very minor quantity. Aegirine-augite is the only pyroxene which appears to be primary. It occurs as pleochroic green crystals with $\beta = 1.703 - 1.711$. Orthite is a constant accessory mineral. It builds irregular masses up to 0.63 mm. \times 0.34 mm. or smaller crystals and is fairly often zoned and occasionally surrounded by either epidote or clinozoisite. The refractive indices are variable; α ranges in value from 1.782 to 1.820, the lower figure being commoner. The colour change is typically from almost colourless, or pale yellow through reddish-brown to very deep brown or black, with absorption $\gamma > \beta > \alpha$. The refractive indices although much higher than those usually recorded for orthite are close to the values given for orthite from Yosemite National Park by C. O. Hutton⁷ and orthite from Ben Loyal, Sutherland, determined by G. R. McLachlan (private communication). Zircons are typically angular and stumpy and have a maximum frequency for the elongation ratio of 1 : 2. The basal plane is quite often developed and zircon occasionally forms crystals up to 1.275 \times 0.9 mm. in size.

Only a very brief description of the granite-basic rock hybrids will be given here as the sequence of this type of contamination is already so familiar to students of petrography and these hybrids conform to the normal pattern. They are evidently formed through the incorporation by granite of basaltic

lavas which formed part of the original volcanic cone. It will suffice to say that hybridization is exceptionally well displayed at Messum and that the following stages can be recognised :—

- (1) Clouding of the plagioclase and intense schillerization of the augite.
- (2) Invasion of granitic material — (principally quartz) — into the mechanically disintegrated basic rocks with strewing of basic fragments. This is accompanied by replacement of the outer zones of the plagioclase by more sodic plagioclase ; by alteration of hypersthene to a very pale brown fibrous amphibole and by incipient amphibolitization of the clinopyroxene. Some recrystallization of augite and plagioclase may occur at this stage. (Plate VIII, fig. 3).
- (3) Further zonal alteration of the plagioclase feldspar ; increase in quartz content ; complete disappearance of hypersthene ; replacement of augite by greenish-brown amphibole and formation of sphene at the partial expense of biotite and plagioclase.
- (4) Continuation of the above processes and replacement of sodic plagioclase by potash feldspar.

In the early stages the basic fragments can be recognised in hand specimen and thin section ; later, the hybrid character may be apparent only in the presence of abundant hornblende, ($\beta = 1.665 - 1.696$) occasional relics of augite and a higher proportion of plagioclase feldspar, while sphene is a typical accessory.

Modes of some granites and hybrids are given below :—

MODES OF GRANITES AND HYBRIDS

<i>Intrusive Microgranite Q 6b</i>				<i>Intrusive aplogranite K 47</i>					
Quartz	..	..	..	29.0	Quartz	..	..	..	27.0
Alkali feldspar	..	..	..	47.4	Perthite	..	..	..	68.1
Plagioclase feldspar (An_{16})	..	..	..	14.6	Biotite	..	..	..	1.6
Biotite and chlorite	..	..	..	7.0	Fluorite	..	..	..	.3
Ore	..	..	..	2.0	Ore	..	..	..	3.1
				<hr/>					<hr/>
				100.0					100.1
<i>Amphibole granite P 17</i>				<i>Pyroxene granite Y 15a</i>					
Quartz	..	..	..	15.5	Quartz	..	..	..	20.7
Alkali feldspar	..	..	..	63.6	Alkali feldspar	..	..	..	50.2
Plagioclase feldspar (An_{25})	..	..	..	13.7	Plagioclase feldspar (An_{26})	..	..	..	19.1
Augite	..	..	..	.3	Augite	..	..	..	2.6
Amphibole	..	..	..	4.2	Amphibole + little chlorite	..	..	..	1.2
Ore	..	..	..	2.6	Ore	..	..	..	6.2
Chlorite	..	..	..	.1					<hr/>
				<hr/>					<hr/>
				100.0					100.0
<i>Grandiorite Hybrid Y 20</i>				<i>Monzonite hybrid P 10</i>					
Quartz	..	..	..	16.9	Quartz	..	..	..	9.1
Alkali feldspar	..	..	..	13.6	Alkali feldspar	..	..	..	19.7
Plagioclase feldspar (An_{30})	..	..	..	35.1	Plagioclase feldspar (An_{35})	..	..	..	35.2
Augite	..	..	..	2.2	Augite	..	..	..	3.5
Amphibole	..	..	..	22.6	Amphibole	..	..	..	25.5
Biotite	..	..	..	6.6	Biotite	..	..	..	2.6
Ore	..	..	..	3.0	Ore	..	..	..	4.4
				<hr/>					<hr/>
				100.0					100.0

<i>Diorite hybrid Y 9</i>				<i>Diorite hybrid Y 26</i>			
Quartz	..	..	6.1	Quartz	..	..	2.2
Alkali felspar	..	..	5.7	Alkali felspar	..	..	1.1
Plagioclase felspar (An ₄₀)	..	..	41.7	Plagioclase felspar (An ₄₀)	..	..	50.1
Augite	..	..	22.0	Augite	..	..	16.2
Orthopyroxene (Of ₅₀)	..	..	7.4	Orthopyroxene (Of ₅₃)	..	..	11.9
Amphibole	..	..	5.1	Amphibole	..	..	1.0
Biotite ($\alpha = 1.590$)	..	..	7.1	Biotite ($\alpha = 1.590$)	..	..	13.1
Ore	..	..	4.9	Ore	..	..	4.4
<hr/>				<hr/>			
100.0				100.0			
<hr/>				<hr/>			

D. Radial Dolerite Dykes

These dykes represent the final phase of activity outside the core being truncated by the inner ring-dyke system. They are composed mainly of lath-like or rectilinear plagioclase which ranges in composition from An₆₅ in the least altered specimens to An₂₀ in the highly altered, albitised and chloritised samples. Augite occurs in the fresher rocks and iron ore in all types. Alteration is very prevalent and secondary minerals such as calcite and chlorite are common, while biotite, apatite, epidote and amphibole occur sporadically. The grain size is generally rather fine, the average dimensions of the feldspars ranging from 0.24 mm. \times 0.7 mm. in the coarser types, to 0.1 mm. \times 0.34 mm.

E. Petrogenesis

(i) *Gabbroic rocks*

The genesis of the microeucrites presents no problem. They were doubtless injected in the sill or sheet-like form envisaged by Martin¹⁰. In connection with the origin of the anorthosites the following points are relevant. Firstly the gradational contact with the olivine microeucrites; secondly the conformable alignment of the flow structures and banding with those of the microeucrite sheets; thirdly the similar composition of the minerals in the anorthosites and eucrites; fourthly and this modifies the third point, the slightly more calcic composition of the bytownite; fifthly the occurrence of the anorthosites at the top of the eucrite sheets; sixthly the mineral composition of the anorthosites throughout the Complex except where altered by secondary processes and finally the extreme purity of the anorthosites. The first three points all lead one to conclude that there is a close genetic relationship between the anorthosites and the eucrites; the fourth point signifies a slightly earlier crystallization period for the plagioclase of the anorthosites as compared with the bulk of the eucrite; the fifth and sixth points lead to the assumption that the eucritic magma was injected into the lopolith essentially as one body and not as successive surges separated by appreciable time intervals; while the purity of the anorthosites argues strongly for an accumulative origin. Furthermore, the analyses agree well with other cumulative types and show the characteristic high alumina and lime and low silica and alkalis compared with the Alpine or 'massif' type (Nockolds).¹³ The mechanism of accumulation is uncertain but a likely cause is gas flotation, the vapour phase being able to escape through porous beds or fissures in some cases, whereas in others it may have been temporarily impounded thereby causing some autometamorphism.

This process is invoked because it is considered that simple upward flotation of plagioclase crystals would be ineffective owing to the probable density relationships. The analysed eucrite Me 3, has a density of 2.99 (measured) at 19°C. and 3.0 (calculated). It is thus comparable to a diabase with a density of 2.975 at 20°C. of which the melt at 1250°C. has a density of 2.59 (Daly).⁴ Plagioclase crystals with 70 per cent. anorthite have a density of 2.63 at a temperature of 1480°C. (Birch).¹ Now if the assumption that the anorthosites are of accumulative origin is correct the parent magma must have had a composition between that of the eucrites and the anorthosites and have been somewhat less dense than the pure eucrite melt. It therefore appears probable that the bytownite crystals were very slightly heavier than the magma and would tend to sink slowly if left undisturbed.

The absence of melanocratic counterparts of the leucocratic anorthosites may be due, as Martin suggests, to the non-exposure of the lower portions of the thicker eucrite sheets but it might also be due simply to the parent magma being enriched in argillaceous material owing to assimilation. This would cause early precipitation of plagioclase crystals. Upward accumulation of these by gas flotation would account for the anorthosites. By gas flotation is meant the separation of a gaseous phase probably due to decreased pressure on intrusion and the attachment of bubbles of gas to the early-formed crystals of plagioclase causing them to move upward to the top of the sheet. The theory has the additional advantage that a continuation of the assimilation process together with some differentiation would account for the overlying hypersthene microgabbros and for the occurrence of cordierite metanorites. Argillaceous material is readily at hand in the form of the mica-schists of the Damara system.

The Messum eucrites are notably low in iron and alkalis and high in lime and magnesia. They show this characteristic when compared with the early Messum basalts, the Okonjeje ridge and core gabbros,²⁴ the Ardnamurchan biotite eucrite, gabbroic eucrite and olivine hypersthene gabbro²⁰ and also the average gabbro and olivine gabbro listed by Nockolds.¹³ This peculiarity is thought to be due to the upward transfusion of alkalis and possibly also of iron from the magma chamber into the overlying sial. It is evidently not simply due to a relative settling of mafic minerals and corresponding upward migration of plagioclase, for the modal composition is quite normal for gabbros and the average analysed Messum eucrite even has approximately 8 per cent. more modal plagioclase than the analysed Okonjeje core gabbro 158²⁴ and yet has an alkali content of 1.17 compared with 3.89.

The hypersthene microgabbros lie partly intercalated with but in the main above the microeucrites. There is no observable chilling or veining between the two, nor is schillerization of augite or clouding of plagioclase felspar confined to or particularly intense in the marginal rocks. The microscopic evidence shows that the same minerals are present and strongly favours the conception of their origin from a common magma-source by a process of normal differentiation involving iron and alkali enrichment together with assimilation as envisaged above.

M. K. Wells²⁶ gives an excellent summary of the possible modes of origin of basic granulites and points out that the distinction between these is often

impossible in the absence of relict structures or unequivocal field evidence. The southern group of pyroxene granulites does, however, show just those relict amygdaloidal and porphyritic structures which Wells considers reliable criteria for an origin from basalts by thermal metamorphism. The variation in mineral composition and proportions is reasonably explained as a reflection of initial differences in the composition of the basalts. The north-western granulites, as pointed out previously, are fine-grained equivalents of the olivine microeucrites. They correspond closely to similar rocks described from the Tertiary Province of Britain and it is probable that they represent thermally metamorphosed marginal facies, the transgressive varieties being in all probability detached masses like those described by Richey & Thomas (p.220)²⁰ the transgressive nature of which is only apparent. The one orthopyroxene-rich granulite is probably a true beerbachite representing hypersthene dolerite magma intruded into the still-hot eucrites.

(ii) *Granitic rocks*

On the evidence, both field and microscopic, already cited, and considering also the more detailed account of field relationships given by Martin,¹⁰ it appears that there is very good reason to suppose that the gabbroic rocks were originally intrusive into acid and basic volcanics belonging to the Messum volcanic pile against which they chilled and that these volcanics have been granitized by an intrusive granite of deep-seated origin. Some of the granite is thus metasomatic and some magmatic.

The evidence of metasomatic origin is supplied by the occurrence of xenoliths of volcanics which show no sign of the settling which might be expected had there been a significant liquid phase present. Of these volcanic xenoliths those of basic composition have persisted longer and show more noticeable evidence of transformation. There is a strong initial contrast in colour, chemistry and mineralogy and the stages of alteration from angular basalt xenoliths occurring in a granitic matrix, to a final homogeneous rock of intermediate composition, can be traced with comparative ease. Where the volcanic layers were acid there are none of these advantages and evidence of transformation rests on tracing a sequence of microscopic changes.

Some granite was evidently mobile as is shown by its intrusive relationships with the peripheral basic lavas and the gabbroic rocks. This mobile portion was either truly magmatic or of rheomorphic origin. Now rheomorphism of the acid tuffs and lavas outside the core is only likely to have been accomplished at the time of the gabbroic intrusions and the evidence of the disposition of the granite veins approximately at right angles to the dip of the lavas and gabbros and its occurrence in steeply dipping breccia zones indicates that the granite was contemporaneous with subsidence and considerably later in age than the gabbros.

Two problems remain; that of deciding how much granite is magmatic and how much metasomatic and secondly the origin of the magmatic granite. Neither of these two problems can be really satisfactorily solved. One of the chief difficulties on the former score is that the metasomatic granite is from volcanic source-material so that criteria for sedimentary parentage are here

inapplicable. Thus, for example, the fact that the properties of the orthites occurring in the acid volcanic rocks of the outer rim and the core are essentially similar to those from the granites and granophyres, can be interpreted either as indicating that the granites are transformed volcanics or that both acid volcanics and granites originated from a common parent at depth. Quantitative estimates are really not justified on the evidence available and the only warrantable conclusion is that both types of granite occur in significant amounts and that one probably grades into the other.

The origin of the magmatic granite is part of a much wider question which can only be very briefly dealt with here. The association basic-acid, so well known elsewhere, is here repeated in extrusive and intrusive phases. This, taken together with the fact that rocks of intermediate calc-alkaline composition present in the Complex are hybrids, is a strong argument against the origin of the granites by simple crystallization differentiation of a basaltic magma. Martin¹⁰ has argued for a palingenic origin due to depression and melting of the base of the sial and this seems the most reasonable solution particularly if qualified according to the hypothesis proposed by Holgate,⁶ which admirably accounts for the hybrid nature of intermediate rocks as well as the basalt-rhyolite association.

The analyses in Table 3 show that chemically the intrusive aplogranite and microgranite of Messum are quite normal rocks. The amphibole granite P 17 and the pyroxene granite Y 15a are almost certainly slightly contaminated by the incorporation of basic lava and show correspondingly lower silica and alumina and higher lime and magnesia. The Okonjeje marginal acid rock shows similar lower silica and alumina and higher lime and magnesia compared with the intrusive granites of Messum.

V.—ALKALINE PHASE

A. Tinguaites and Syenite-Porphyrries

The rocks dealt with in this and subsequent sections all occur within the inner ring-fault system surrounding the core. With the possible exception of the porphyry they post-date all the rocks of the Complex outside the core, as is shown by the fact that the youngest outer rocks—the radial dolerite dykes—are truncated by this peripheral ring-dyke system and the inner rocks here described are younger than the ring-dyke faulting.

The most abundant rock type found filling the ring-fissures and the associated radial and concentric fissures is tinguaitite. In texture it varies from trachytic to stellate. It is also generally phyrlic with the chief constituent, micropertthite or sodic orthoclase, forming phenocrysts which measure up to 6 mm. in length. Micropertthite or a sodic orthoclase ($2V\alpha = 72^\circ$) also occurs as lath-like crystals averaging approximately 0.2 mm. \times 0.05 mm. Separate small crystals of oligoclase (An_{20-30}) are sometimes present. Nepheline builds rectangular or hypidiomorphic crystals with average dimensions of 0.16 mm. \times 0.12 mm. Allotriomorphic sodalite is invariably present and may be accompanied by variable amounts of analcite. The chief melanocratic constituents are ferro-

hastingsite, aegirine-augite and biotite. Accessory minerals are iron ore, sphene, clinzoisite, zoisite, apatite, fluorite, eudialite, calcite and cancrinite.

There are certain notable differences between the ring-dykes on the one hand and the radial and concentric dykes on the other. Intermediate types do occur but these are exceptional. The characteristic differences are tabulated below :—

<i>Ring-dykes</i>	<i>Radial and Concentric dykes</i>
Texture trachytic.	Texture stellate.
Melanocratic minerals show sieve texture.	Melanocratic minerals occur as scattered individuals.
Felspathoids < 10%.	Felspathoids > 10%.
Ferrohastingsite principal melane.	Ferrohastingsite absent.

In general ferrohastingsite occurs in inverse ratio to aegirine-augite. It has the following properties :— γ (very dark brownish-green) = 1.717, β (deep green) = 1.716, α (pale brownish-yellow) = 1.693. It appears to be unzoned but owing to the intense absorption 2 V could not be measured and the accuracy of the refractive index determinations was decreased. Slight zoning is therefore not excluded. The analysed radial dyke, G 4, is exceptional in containing ferrohastingsite (β = 1.718) as its principal dark constituent.

Aegirine-augite and biotite occur in variable minor amounts in the ring-dykes but as the principal melane of the radial and concentric dykes. In the ring-dykes they are frequently intergrown with each other or with ferrohastingsite and typically exhibit sieve-texture. Aegirine-augite is variable in its optical properties particularly in the radial and concentric dykes. The α index varies from 1.710 to 1.727 and 2 V γ varies correspondingly from 70° to 88°. Clinzoisite, sphene and magnetite occasionally show sieve-texture, the former being erratic in distribution. The order of crystallization in all the tinguaite appears to be apatite, then micropegmatite and nepheline with overlapping crystallization periods, next sodalite and finally late-stage, probably deuteric melanes. This is the reverse of what is considered the normal magmatic sequence. It is, however, not without precedent in literature.^{8, 11, 16, 21.}

Zircon appears to be absent in the heavy residues of both tinguaite and foyaites. The zirconium recorded as a trace element with a maximum value of 350 parts per million in the tinguaite ring-dyke, E 1 is either present in the mineral eudialite or as very minute zircon crystals too small for identification.

MODES OF TINGUAITES

G 23. <i>Ring-dyke tinguaite</i>	E 1. <i>Ring-dyke tinguaite</i>
Microperthite 66.8	Microperthite 75.4
Oligoclase 1.5	Nepheline & Sodalite 8.0
Nepheline 8.6	Biotite 1.2
Sodalite 4.9	Hastingsite 8.5
Biotite 2.5	Aegirine-augite 3.5
Hastingsite 10.1	Clinzoisite 1.0
Aegirine-augite 2.8	Sphene 0.2
Zoisite & Clinzoisite 0.7	Ore 2.3
Sphene 0.3	
Ore 1.8	
<hr/> 100.0 <hr/>	<hr/> 100.1 <hr/>

G 4. <i>Radial dyke sodalite tinguaites</i>				66a. <i>Radial dyke tinguaites</i>			
Potash feldspar	..	..	60.7	Perthite	..	..	53.3
Oligoclase	..	..	2.3	Nepheline	..	..	26.2
Nepheline	..	..	15.8	Sodalite & Analcite	..	..	13.2
Sodalite	..	..	12.8	Aegirine-augite	..	..	4.9
Hastingsite	..	..	7.8	Ore	..	..	2.4
Aegirine-augite	..	..	0.7				
			100.1				100.0

Where tinguaites dykes have caught up basic xenoliths the products of reaction are similar to those developed between foyaites and basic xenoliths and they will therefore be described in the section dealing with melanocratic fenites.

Syenite-porphyry, referred to by Martin¹⁰ as microsyenite, occurs as ring, radial and concentric dykes intrusive into the early volcanics and capping the ridges and peaks in the marginal hills of the core. It forms radial and concentric dykes more frequently than does the tinguaites while it is much less common in the ring-dykes. In hand specimen some of the radial and concentric dykes are indistinguishable from the metasomatised lavas and the finer-grained varieties very closely resemble some intermediate lavas. The relationship of the porphyry to the tinguaites is not known with certainty. Martin¹⁰ considers that it is pre-tinguaites on the evidence of a breccia occurring on the southern boundary of the core which is composed of porphyry, granite and gabbro in a matrix that 'appears to be phonolite.' No specimen of this breccia was collected and the outcrop could not be located on the last visit to Messum.

In texture the syenite-porphyrines are sparsely porphyritic (peripatic) with an aphanitic groundmass in which the average grain-size varies from approximately 0.05 mm. to 0.2 mm. There is no fluxion structure in these dykes and the fabric is generally microgranitic, occasionally stellate. The phenocrysts are predominately of plagioclase between 1 and 2 mms. in length with a maximum of approximately 5 mms. Zoning is common and the composition varies from An₃₈₋₂₀. Some plagioclase phenocrysts are mantled by potash feldspar. More rarely phenocrysts of quartz, perthite, augite, amphibole and iron ore occur. The groundmass consists of potash feldspar and oligoclase with variable minor amounts of augite ($\beta = 1.704$); green to brown amphibole ($\gamma = 1.703$, $\alpha = 1.672$); quartz, sphene, biotite, apatite, fluorite, calcite and epidote. Zircon and rutile are rare accessories found only in the heavy residues.

The very fine-grained syenite-porphyrines are slightly younger, according to Martin¹⁰ and are more leucocratic. Their average grain-size is approximately 0.08 mm. They have iron ore and augite ($\beta = 1.704$) as their typical dark minerals together with minor sphene. Green to brown amphibole is rare. The feldspars are usually very altered. This type of porphyry occurs as concentric or radial dykes.

The ring-dyke porphyry is a rather coarser grained darker variety which has poikiloblastic-looking amphibole and occasional clots of ferromagnesian minerals reminiscent of the texture of the ring-dyke tinguaites. The amphibole sometimes has cores of colourless or pale green non-pleochroic clinopyroxene which it is replacing. The grain-size averages 0.2 mm. The more melanocratic

varieties have evidently been contaminated with basic material and partly digested xenoliths may occur.

MODES OF SYENITE-PORPHYRIES

M 30. <i>Porphyry, finer-grained type</i>					H 11. <i>Porphyry, ring-dyke type</i>				
Quartz	..	..	..	5.7	Quartz	..	..	..	1.5
*Felspar	..	..	..	79.2	Potash felspar	..	..	..	62.5
Augite	..	..	..	3.6	†Plagioclase felspar	..	..	..	17.5
Sphene	..	..	..	1.8	Amphibole	..	..	..	13.2
Ore	..	..	..	9.7	Ore	..	..	..	5.3
<hr/>					<hr/>				
100.0					100.0				
<hr/>					<hr/>				

* Potash and plagioclase felspar indistinguishable owing to alteration.

† Phenocrysts are andesine. Groundmass felspar is oligoclase.

B. Foyaite

Foyaite occurs in the central part of the core where it outcrops as conspicuous hills and minor low-lying boulders separated by sand cover. In places it shows concentric almost vertical flow structure. It is a medium to light grey rock with an average grain-size of between 1 and 2 mms. The texture is typically trachtyoid. The alkali felspar which is probably a cryptoperthite is present in large excess over plagioclase which is sodic oligoclase. Ferrohastingsite is the chief melane present. It is slightly zoned; the maximum and minimum refractive indices being respectively 1.711 (greenish brown to black) and 1.683 (pale brownish yellow). A very pale green augite and biotite occur in variable but lesser amount. The optical properties of the augite are as follows $\gamma = 1.737$; $\beta = 1.715$; $\alpha = 1.710$, $2V\gamma = 58^\circ$. The biotite has $\gamma = \beta = 1.670 \pm$. Nepheline ($\gamma = 1.541$; $\alpha = 1.537$) constitutes between 20 and 30 per cent. of the rock and builds euhedral to subhedral crystals which are fresher than the orthoclase. Apatite, ore and sodalite are the most abundant accessories; sphene is rare. Secondary minerals are sericite; cancrinite; calcite; chlorite and kaolin.

The mode of a representative foyaite is given below:—

Mode of foyaite V 9a

Potash felspar	..	..	..	47.2
Oligoclase	..	..	..	5.2
Nepheline	..	..	..	28.6
Sodalite	..	..	..	1.5
Hastingsite plus a little clinopyroxene and biotite	..	..	..	14.4
Ore	..	..	..	3.1
<hr/>				
100.0				
<hr/>				

C. Melanocratic Fenites

Pre-foyaite basic rocks in the form of xenoliths, dykes or sheets occur both in the central foyaite and in the surrounding aureole. The degree of fenitisation varies directly with distances from the intrusive rock. For example, basic dykes occurring amongst the altered volcanics of the peripheral hills show the least alteration; no nepheline is found but the pyroxene has been replaced by amphibole and the plagioclase altered to a more sodic variety, while at the

margins of these dykes there is considerable introduction of perthitic alkali felspar. In contrast to this, basic dykes or sheets which lie within the central mass of foyaite show a minimum level of fenitisation represented by the introduction of nepheline and conversion of the rock to a theralite, while isolated xenoliths or marginal facies have usually suffered much more profound changes and are last recognisable merely as mafic streaks and segregations within the foyaite. Although almost all intermediate types between foyaite and theralite are represented, individual occurrences rarely show more than a few of the successive stages. The complete picture must therefore be pieced together by evidence from several sources.

These are all conspicuous rocks which clearly show their hybrid nature owing to colour contrasts resulting from incomplete or patchy transformation. The naming of these hybrid types presents a problem. I prefer to call them collectively 'melanocratic fenites' but where individual designations must be used for the sake of clarity I suggest the nomenclature adopted in the following table of modes which illustrate the quantitative mineralogical changes taking place. (See overleaf.)

Besides the quantitative aspect illustrated above, the sequence of changes can be traced by the mutual relationships of the minerals and compositional variations within the mineral groups themselves. The more important of these will now be considered.

Olivine occurs in the theralite fenites and as an occasional accessory in the dolerite fenites. When present in the latter it forms cores to melanocratic clots. It is a normal magnesian type varying from Fa_{20} to Fa_{30} .

Augite is quantitatively important only in the theralite and dolerite fenites in which it occurs as a titaniferous variety which is often zoned, the zones showing a maximum increase in $2V$ of 8° from core to margin. The maximum and minimum measured values for $2V$ were 56° and 42° respectively and for β 1.705 and 1.713. The augite of the basaltic and other augite-bearing fenites shows clear evidence of replacement, the sequence of changes being as follows:—augite \rightarrow (pale green slightly sodic augite) \rightarrow magnesiohastingsite \rightarrow femaghastingsite \rightarrow ferrohastingsite. Mostly the augite alters directly to hastingsite but occasionally an intervening stage with a pale slightly sodic augite occurs ($\alpha = 1.698$). Augite cores to hastingsite crystals are a common feature of the melanocratic fenites.

Aegirine-augite is uncommon in these rocks and where it occurs it is probably attributable to crystallization from the foyaite magma. It is variable in composition $2V$ varying from 62° to 90° and β from 1.718 to 1.755.

Hastingsite is the chief melanocratic mineral in all but the theralites. It occurs in characteristically zoned crystals with cores of reddish-brown magnesiohastingsite surrounded by successively more iron-rich zones. The proportion of hastingsite and pyroxene together varies with the degree of contamination of the rock. The optical properties show the usual increase in refractive indices and decrease in optic angle with increasing iron content. The hastingsite of the basalt fenite G 28 has $\alpha = 1.677$; $\beta = 1.694$ and $2V\alpha = 66^\circ$. The properties of the ferrohastingsite are difficult to obtain accurately because of the high colour absorption, and the α index was considered the only reliable value. This increases up to a maximum of 1.690.

TABLE 2
MODES OF MELANOCRATIC FENITES

Minerals	Basalt fenite V 20	Basalt fenite G 11	Basalt fenite (Andesine essexite) G 28	Gabbro fenite (Theralite) G 9e	Gabbro fenite (Theralite) V 10	Foyaite fenite G 9c	Tinguaite fenite (Oligoclase essexite) E 17
Orthoclase	—	0·5	20·3	1·5	1·0	28·2	25·8
Labradorite	26·7	49·2	—	23·7	15·0	—	—
Andesine	—	—	30·3	—	—	—	—
Oligoclase	—	—	—	—	—	11·5	28·6
Nepheline plus minor analcite and/or sodalite	4·8	4·9	20·9	16·7	20·1	21·7	15·4
Olivine	—	—	—	11·2	12·6	—	—
Augite	18·9	9·0	—	31·6	35·2	4·2	—
Aegirine-augite	—	—	2·4	—	—	—	—
Hastingsite	47·0	21·9	23·6	—	—	28·4	24·8
Biotite	0·9	12·2	—	11·2	11·0	4·4	2·5
Ore	1·1	0·7	1·3	3·1	2·9	1·3	0·3
Apatite	—	0·5	1·2	1·0	2·2	0·4	1·1
Sphene	—	—	—	—	—	—	1·5
Calcite	0·6	—	—	—	—	—	—
Colour index	68	44	27	57	62	38	29

Potash felspar occurs in inverse ratio to the anorthite content of the plagioclase felspar due to soda preceding potash in the replacement sequence. It can be seen replacing sodic plagioclase in many slides.

Nepheline is always the predominant feldspathoid. Sodalite and analcite occur in variable but always accessory quantity. Nepheline clearly replaces plagioclase felspar. This is well illustrated in the case of the relatively coarse-grained theralites where nepheline forms poikiloblastic plates containing remnants of plagioclase in all stages of dissolution. In one instance a plagioclase crystal has had its central portion replaced by nepheline leaving the two ends separated but in optical continuity. The refractive indices of the nepheline vary, $\gamma = 1.537 - 1.541$ and $\alpha = 1.532 - 1.537$. No regular variation was found within the series but as nepheline has different properties in a single rock type, this is not surprising.

D. Leucocratic Fenites

These rocks fall into two groups :— (1) the foyaite fenites and (2) the syenite fenites.

(1) The foyaite fenites are not well exposed, the outcrops being small and scattered. They occur between the central foyaite and the syenite and in composition are gradational between these two types. The optical properties of the constituent minerals do not differ much from those recorded for the central foyaites and little need be said further beyond noting that orthoclase has a $2V$ of from 60° to 66° and is evidently a fairly soda-rich type; perthite has a correspondingly high proportion of albite; sodalite and analcite are generally more abundant in these rocks than in the melanocratic fenites; the amphibole present is a zoned ferrohastingsite and aegirine-augite has the following properties in the analysed rock G 27 :— $2V\gamma = 75^\circ$; $\alpha = 1.712$, $\beta = 1.731$. Modes of two typical leucocratic (foyaite) fenites are given below.

MODES OF LEUCOCRATIC (FOYAITE) FENITES

G 27.				G 13.			
Orthoclase	..	..	..	61.8	Perthite (Or. = 42% Ab. = 32.8%)	74.8	
Oligoclase	..	..	..	4.4	Nepheline + sodalite	..	4.1
Nepheline	..	..	..	16.9	Ferrohastingsite + little aegirine-		
Sodalite	..	..	..	5.7	augite and biotite	..	17.2
Ferrohastingsite	..	..	..	5.7	Sphene + apatite	..	1.7
Aegirine-augite	..	..	..	1.8	Ore	..	2.2
Sericite	..	..	..	0.8			
Ore	..	..	..	2.9			
				100.0			100.0

(2) The syenite fenites intervene everywhere between the foyaite fenites and the volcanic rocks of the core rim.

In many exposures they can clearly be seen replacing the agglomerates and tuffs. 'Ghost' agglomerate structure is well displayed in some of the northern syenites and these can be traced into agglomerates in which only the tuffaceous matrix has been converted into syenite fenite and thence into agglomerates which are unaltered except for recrystallization of the matrix.

Older dolerite dykes occurring in the syenite have been attacked, embayed and metasomatized but still retain their positions. One such is described and figured by Martin¹⁰ (p. 107 and Fig. 9) and another excellent example was found in 1955 on the eastern side of the 'Big Cave hill.' Here the dolerite shows its original fine-grained chilled border whereas the syenite, which intrudes and embays the dolerite, has a leucocratic rim but no chilling at the contact.

The grain-size of the syenite fenite is variable and gradational and ranges from 0.2 mm. for the microsyenite of the agglomerate matrix to a maximum of 20 - 30 mm. The sole essential constituent is very coarse perthite which has approximately equal potassic and sodic components. Quartz is characteristically present to the extent of about 5 per cent. The dark minerals are sporadic in distribution and variable in properties. They include amphibole (α - greenish-brown 1.667 - 1.672; γ - pale yellow 1.690 - 1.703) which sometimes shows alteration to arfvedsonite; aegirine-augite (2 V γ 65° - 80°, α 1.708 - 1.717; ferrohortonolite (Fa₈₀ - ₈₅); biotite; sphene; zircon; orthite; apatite; fluorite and ore. The modes of three syenite fenites are given below:—

MODES OF SYENITE FENITES

E 16. <i>Syenite fenite</i>					H 15. <i>Syenite fenite</i>				
Quartz	..	..	..	5.2	Quartz	..	..	..	4.7
Perthite	..	..	..	79.3	Perthite	..	..	..	83.0
Amphibole + little aegirine-augite	..	..	..	12.0	Amphibole	..	..	..	5.2
Biotite	..	..	..	0.5	Aegirine-augite	..	..	..	3.1
Accessories	..	..	..	0.7	Biotite	..	..	..	0.1
Ore	..	..	..	2.3	Apatite	..	..	..	0.6
					Ore	..	..	..	3.3
				100.0					100.0

H 16. <i>Syenite fenite</i>				
Quartz	..	..	..	5.0
Perthite	..	..	..	82.2
Amphibole	..	..	..	3.2
Aegirine-augite	..	..	..	3.6
Ferrohastingsite + serpentine	..	..	..	3.7
Apatite	..	..	..	0.4
Fluorite	..	..	..	0.2
Ore	..	..	..	1.7
				100.0

E. Rheomorphic Fenites

Rocks having a composition varying from nordmarkite to granite can occasionally be seen intruding the altered volcanics of the core rim. More detailed field study and sampling carried out in 1955 have revealed that it is possible to trace many of these veins back to the matrix of the agglomerates from which they proceed. With outward passage from the agglomerate the composition of the vein changes from syenitic through nordmarkitic to granitic. The texture varies from trachytoid to granitoid. The feldspars are coarsely perthitic in the syenitic and nordmarkitic varieties whereas in the granites the feldspar shows little perthitic exsolution and is accompanied by separate crystals of sodic plagioclase. Quartz appears to replace perthite. Iron ore is the chief

accessory constituent. Minor amounts of biotite, green amphibole ($\alpha = 1.679$); arfvedsonite; sphene; zircon and fluorite also occur.

Modes of the rheomorphic fenites are given below. The specimens numbered B 43, were collected from a vein emanating from the matrix of the agglomerate in the hills at the southern periphery of the core.

MODES OF RHEOMORPHIC FENITES

M 13.				K 5a.				M 28.			
Quartz	..	..	19.2	Quartz	..	..	34.6	Quartz	..	..	27.6
Perthite	..	..	73.4	Perthite	..	..	60.7	Potash felspar	..	..	42.5
Biotite	..	..	1.9	Biotite	..	..	0.2	Albite	..	..	26.5
Amphibole	..	..	1.8	Zircon	..	..	0.2	Biotite	..	..	0.7
Fluorite	..	..	1.1	Ore	..	..	4.3	Ore	..	..	2.7
Ore	..	..	2.7								
100.0				100.0				100.0			
<i>B 43 (a) rheomorphic vein near agglomerate</i>				<i>B 43 (b) rheomorphic vein further from agglomerate</i>							
Quartz	..	..	..	13.8	Quartz	..	..	..	29.9		
Perthite	..	..	..	78.2	Perthite	..	..	..	50.8		
Plagioclase	..	..	..	4.6	Plagioclase	..	..	..	13.6		
Biotite	..	..	..	0.6	Biotite + chlorite	..	..	..	1.7		
Amphibole	..	..	..	1.5	Amphibole	..	..	..	0.1		
Ore	..	..	..	1.3	Clinozoisite	..	..	..	0.1		
					Calcite	..	..	..	0.1		
					Ore	..	..	..	3.7		
100.0				100.0				100.0			

F. Nephelinites and Olivine Tephrites

Radial dykes of olivine nephelinite, nephelinite and olivine tephrite cut the pyroclastic syenitic and foyaitic rocks of the core and are the last visible phase of activity filling contraction cracks. They have borders with amygdalae consisting chiefly of calcite, analcite and natrolite which frequently show elongation parallel to the length of the dyke.

Olivine nephelinite is the most abundant type. It is phyrlic with phenocrysts of augite, olivine, nepheline and ore. The augite phenocrysts attain a length of up to 20 mm. Pale green non-pleochroic augite with $2V\gamma = 55^\circ - 60^\circ$ and $\gamma = 1.732$ occurs together with titanaugite ($2V\gamma = 47^\circ - 52^\circ$ and $\beta = 1.717$) either as separate crystals or as zones within one crystal. The olivine is chrysolite $Fa_{12} - 16$. Nepheline builds perfectly idiomorphic crystals and glomerophyrlic aggregates having a value of γ varying from 1.539 to 1.541. It often shows zoning of minute inclusions and a narrow border of optically continuous fresher nepheline with slightly higher refractive index. Staining tests using the method recommended by Shand²² showed slightly deeper staining of the peripheral zone which developed the same colour absorption as the groundmass nephelines. Correlation between composition, refractive indices and staining intensity is not considered to be sufficiently well established to warrant deductions concerning the composition of the nephelines.

In addition to nepheline the groundmass minerals are pale green or colourless augite, ore, and variable amounts of biotite, apatite and analcite. The average grain-size of the groundmass nepheline is approximately 0.1 mm.

The chemical analysis shows that the olivine nephelinite is nearer in composition to the average bekinkinite than the average olivine nephelinite¹³ but shows decidedly higher alumina and alkalis: this is probably a reflection of its higher nepheline content.

In places the olivine nephelinite dykes have picked up xenoliths of porphyry and syenite. These xenoliths may show fairly sharp boundaries or gradational contacts. In the latter case first plagioclase then potash felspar develops accompanied by poikiloblastic hastingsite and biotite, while olivine, nepheline and augite disappear. In the neighbourhood of partially incorporated syenitic material the olivine nephelinite gives place to olivine tephrite, or more rarely, nephelinite. The field relationships of the nephelinite are not clear but it appears likely that it represents one type of contamination of the olivine nephelinite magma. It differs from the olivine nephelinites only in the higher proportion of biotite and the almost complete absence of olivine. A few residual cores of olivine do occur but for the most part its place has been taken by an aggregate of biotite, ore, augite ± calcite.

All gradations from olivine nephelinite to olivine tephrite occur. A zoned hastingsitic amphibole with α 1.678 – 1.683 invariably occurs in the groundmass of the olivine tephrites; biotite is present and potash fespars occasionally occurs in the groundmass poikilitically enclosing nepheline and a zoned plagioclase which has an approximate average composition of sodic labradorite. The assimilation of alkali feldspars and a little quartz from the syenitic inclusions evidently leads to the formation of hastingsite, plagioclase and biotite at the expense of augite (or olivine) and nepheline. The optical properties of the minerals of the olivine tephrites and nephelinite are sensibly the same as in the olivine nephelinites. The following table gives the modal composition of typical undersaturated basic radial dykes.

MODES OF UNDERSATURATED RADIAL DYKES

H 13. <i>Olivine nephelinite</i>					Px5. <i>Olivine tephrite</i>					
Nepheline	34.2	Nepheline (+ little analcite)	..	..	..	22.7
Analcite	8.8	Labradorite	..	..	..	18.6
Olivine	2.6	Olivine	..	..	..	4.9
Augite	32.6	Augite	..	..	..	22.4
Biotite	11.6	Biotite and hastingsite	..	..	..	22.4
Ore	10.2	Ore	..	..	..	9.0
					<hr/>					<hr/>
					100.0					100.0

No. 16. *Nephelinite*

Nepheline + analcite	..	..	..	..	32.5
Augite	..	..	..	..	44.3
Biotite	..	..	..	..	13.1
Apatite	..	..	..	..	2.1
Ore	..	..	..	..	8.0
					<hr/>
					100.0

G. Petrogenesis

(i) *Tinguaites and syenite-porphyrries*

The tinguaites with their strongly developed trachytic texture can unhesitatingly be classed as magmatic. The difference in texture and mineralogy shown by the ring-dykes as distinct from the radial and concentric dykes present a minor problem. The chemical analyses are not helpful in this respect as the only analysed radial dyke is not typical. The approximate chemical composition of a representative radial dyke was calculated from the mode and showed lower silica and ferrous oxide and higher lime and alkalis. The greater abundance of feldspathoids accounts for the lower silica and higher alkalis and the presence of aegirine-augite rather than ferrohastingsite accounts for the higher lime and lower ferrous oxide. The higher alkali content of the radial and concentric dykes may possibly be due to their being somewhat further from source and therefore richer in the early crystallizing components. Rather similar textural and mineralogical differences occur between the trachytic and stellate tinguaites of Okonjeje²⁴. Both Okonjeje varieties are lower in feldspathoids and richer in melanes as compared with the Messum tinguaites. They are also similar chemically whereas the Messum tinguaites show distinct chemical differences. Simpson²⁴ considers that the two Okonjeje types are heteromorphic. This may also be the explanation in the case of the two varieties of tinguaites at Messum as differences in chemistry can be overemphasized and may be due merely to very local variations.

The genesis of the syenite-porphyry poses a more important question. The porphyry is certainly intrusive and according to Martin's interpretation probably represents the first phase of renewed activity after the downfaulting of the core and closely precedes the intrusion of the tinguaites. If this is so a reasonable explanation must be given for the change from oversaturated porphyry to strongly undersaturated tinguaites and for the fact that the porphyry is the only oversaturated magmatic rock to be intruded after the ring subsidence of the core. In order to avoid this difficulty and on grounds of petrological affinity the suggestion is here advanced that the syenite-porphyry, which strongly resembles the intermediate volcanics of the original core and the matrix of some of the agglomerates, represents older feeder dykes and uptilted lava sheets intruded prior to the subsidence. The fault-fissuring only parallels the porphyry for a comparatively short distance in the east and this may be due to subsidence following an old line of weakness and not to the porphyry filling the fault zone.

(ii) *Foyaite*

The foyaite was considered by Martin¹⁰ to be in the form of a stock with a diameter of approximately a mile. Evidence found on revisiting Messum in 1955 shows that either this is an overestimate and that the stock is considerably smaller and more in the form of a central plug, or that the foyaite was actually intruded as ring-dykes separated by screens of basic material which probably represent remnants of down-faulted gabbroic sheets. This new discovery was of a number of outcrops of basic material having a concentric dyke or sheet-like

form within the central foyaité. (See map). These basic rocks show strong fenitisation and attack by the surrounding foyaité which they obviously pre-date. At least three concentric sheets (or dykes) are present and their relatively undisturbed attitude is the strongest possible argument against the surrounding foyaité having been forcibly intruded as a stock. The map of the core shows these outcrops—which now have the composition of theralite—and shows, too, that if the foyaité surrounding them is metasomatic, very little, if any, magmatic foyaité is left. On the other hand the concentric flow structure of this foyaité is good evidence for emplacement while semi-liquid. These apparent anomalies can be resolved by postulating that the foyaité was intruded as a series of ring-dykes leaving between them narrow screens of gabbroic material which they have metasomatised to theralite. The only apparent alternatives to this solution are either that the foyaité is a metasomatic rock in which case older dykes etc. could be expected to retain their position more or less undisturbed, or that the concentricity of the outcrops is purely fortuitous and that they represent narrow elongated xenoliths brought up by a foyaité magma. The appearance in the field of those well-exposed outcrops renders this latter hypothesis very improbable.

In addition to the concentric basic dykes, radial basic dykes also occur within the central foyaité mass and have generally suffered more intense fenitisation. They probably represent radial dolerite dykes which on account of their finer grain-size and fracturing would be more prone to alteration.

As no chemical analysis had been made of the central uncontaminated foyaité the chemical composition was calculated from the mode of the foyaité V 9a and this is compared below with the calculated composition of a typical radial tinguaité.

CALCULATED ANALYSES OF A FOYAITÉ AND TINGUAITÉ

<i>Foyaité V 9a</i>				<i>Tinguaité 66a</i>			
SiO ₂	..	..	51.0	SiO ₂	..	..	52.3
TiO ₂	..	..	.5	TiO ₂	..	..	.1
Al ₂ O ₃	..	..	22.5	Al ₂ O ₃	..	..	24.3
Fe ₂ O ₃	..	..	3.2	Fe ₂ O ₃	..	..	2.3
FeO	..	..	3.1	FeO	..	..	1.1
MnO	..	..	.0	MnO	..	..	.1
MgO	..	..	1.2	MgO	..	..	.5
CaO	..	..	2.2	CaO	..	..	2.4
Na ₂ O	..	..	8.2	Na ₂ O	..	..	9.3
K ₂ O	..	..	7.0	K ₂ O	..	..	6.8
H ₂ O+	..	..	.3	H ₂ O+	..	..	.2
Cl	..	..	.1	Cl	..	..	.9
			99.3				100.3

There is a close similarity between the calculated compositions of the central foyaité and the radial tinguaité although they differ somewhat modally. The foyaité has a lower modal value for total felspathoid (approximately 30 per cent. as compared with 40 per cent. for the tinguaité) and contains 14 per cent. hastingsite in place of 5 per cent. aegirine-augite. Compared with the ring-dyke tinguaites the foyaité has somewhat less silica and higher alkalis,

this being a reflection of its higher modal nepheline. These compositional differences between foyaite and tinguaites are slight and no greater than between different specimens of tinguaites and may, almost certainly, be ascribed to slight contamination or local variation. It appears likely that they had a common magmatic source.

The genesis of the foyaite magma is a matter for speculation. The two major theories for the origin of felspathoidal rocks are here considered to be limestone syntaxis and fractional crystallization from a basaltic magma which is slightly more alkaline than usual. Origin by fractionation from an ultra-mafic magma appears just to put the problem one stage further back.

Now the evidence at Messum does not support simple basaltic fractionation. The theralite is clearly a product of fenitisation and there is no alkaline series. The basalts are not alkali-rich types and the gabbroic rocks are distinctly poor in alkalis having an average content of soda plus potash = 1.17 per cent compared with 2.01 per cent. for the biotite eucrite of centre 3, Ardnamurchan¹⁹ and 2.43 per cent. for the average olivine gabbro listed by Nockolds¹³. Fractional crystallization is therefore unlikely to give highly alkaline differentiates. On the other hand there is an abundant source of limestone in the underlying Damara System and with the very considerable downfaulting that has occurred in this ring-complex and notably in the core segment, it appears very likely that limestone syntaxis was the operative process. In this connection it should be borne in mind that the neighbouring complexes of Okorusu and Kalkfield are carbonatite-bearing and that a vein of carbonatite five feet wide occurs in the core at Messum and could be traced for a distance of 140 feet.

The solution to the enigma of related igneous complexes of such different chemistry as Erongo, Brandberg, Cape Cross, Messum, Okonjeje, Eisenberg-Kalkfield, Paresis and Okorusu is surely to be found in a combination of the two following conceptions (a) Shand's²³ idea of different erosion levels and (b) differential ring-subsidence causing syntaxis and palingenesis at different levels of the sial.

(iii) *Melanocratic fenites*

The process of fenitisation of the basic rocks follows the same general pattern with local variations due to difference in initial rock type and distance from the central foyaite. The normal sequence is briefly as follows. Alkali solutions, or emanations, from the foyaite have caused replacement of the calcic plagioclase which has given place to more sodic varieties of plagioclase and to nepheline. Olivine has been resorbed and together with iron ore has probably been used in the formation of biotite with which it is frequently associated. The biotite in turn has become unstable and has contributed to the formation of potash feldspar and hastingsite. Augite is usually converted first into magnesiohastingsite and thence into successively more iron-rich types of hastingsite. The pattern of these changes is very similar to that described by Simpson²⁴ for the alkali series at Okonjeje where they are attributed to magmatic differentiation. At Messum, however, there is good evidence to show that a similar sequence has developed as a result of fenitisation of basic rocks by foyaite. Rocks occurring within the central area of foyaite intrusion or caught up by the tinguaites dykes have been severely altered whereas those

which are progressively more remote also show diminishing metasomatic effects. Nepheline, too, is clearly of replacement origin in the melanocratic fenites.

(iv) *Leucocratic fenites*

The field and microscopic evidence for the transformation of agglomerate and tuff into syenite has been described. Dolerite dykes and basaltic inclusions in the agglomerates have remained 'in situ.' They are excellent examples of H. H. Read's¹⁷ 'basic resisters' and if Messum were more readily accessible would, almost certainly, become classic.

Rocks nearer the centre of fenitisation have lost their relict structures and textures, but they also contain a few radial 'resister' dolerite dykes and moreover are intermediate in position and composition between the metasomatic syenites and the intrusive foyaites. They must therefore represent a further degree of fenitisation of acid tuffs, lavas and agglomerates of the volcanic cone and can properly be termed 'leucocratic fenites.'

The fenitising process was essentially one of feldspathisation and recrystallization with expulsion of the excess silica to form a mobile fraction represented by the leucocratic rims and the rheomorphic nordmarkites and granites of the core.

(v) *Rheomorphic fenites*

The field evidence here points unmistakably to these rocks being of rheomorphic origin. During the fenitisation of the volcanics silica must have been leached out and a mobile silica-enriched fraction separated. This fraction was evidently responsible for the leucocratic rims around basic inclusions and for the mobility of the nordmarkite-granite veins. The trachytoid texture of some of the nordmarkites indicates that at that stage the intrusive material was partly solid and a gradual process is envisaged whereby with increasing amounts of the liquid phase the metasomatised tuff slowly became mobile. Some flow orientation would be shown near the parent body while further away the vein material was supplied almost entirely by the migrating pegmatitic liquid and crystallization was non-directional.

VI.—COMPARISONS

A few comparisons with other ring-complexes are instructive as differences in nomenclature and theories of origin are often apt to obscure the similarities.

The first and most obvious comparison is with the neighbouring complex of Okonjeje so well described by Simpson²⁴. Lavas are absent at Okonjeje so that a difference in erosion level must be taken into account. The earliest comparable rocks are therefore the eucrites and gabbros. Simpson distinguishes two series viz. the Tholeiitic and the Alkali, the basic end-members of which are respectively the ridge gabbros and the core gabbros. Field evidence indicates that the core gabbros are later than the ridge gabbros, otherwise the differences between the two are slight and the Messum eucrites show approximately the same similarities to, and differences from, either. The nomenclature employed in each case is partly a reflection of personal preference and is of

quite secondary importance. The Messum olivine eucrites are a variety of gabbro and their mineralogy corresponds closely to that of the Okonjeje inner ridge gabbros, while the ferrogabbros of Okonjeje are more ferrous but otherwise very similar to the hypersthene microgabbros of Messum.

Other similarities include banding, foliation, inward dip and the presence of anorthosite facies. Differences in erosion level and in the chemical composition of the earliest gabbroic representatives i.e. lower magnesia and lime and higher iron and alkalis at Okonjeje, may account for the greater degree of differentiation shown there. This differentiation is upward and inward at Messum, whereas at Okonjeje the late iron-rich types lie below and further from the centre of the complex.

An important difference in interpretation concerns the course of differentiation and thereby the origin of the syenitic, foyaitic and granitic rocks of the two complexes. Simpson considers that the normal end-product is represented by the ridge syenite and that the marginal acid rocks are the result of assimilation of acid sedimentary material by syenite. At Messum the origin of the syenite by metasomatic replacement of the former volcanic rocks is clear and unequivocal. An acid magma formed at depth, probably by the transfusion of alkalis and alumina into the depressed base of the sial, is considered to have been responsible for the intrusive granites and to have metamorphosed much of the older rhyolitic lava and tuff thereby converting them into coarser-grained equivalents and swelling the total volume of granite.

A magmatic origin for the foyaite is postulated for both complexes. Derivation from an alkaline basaltic magma by fractionation is favoured by Simpson while in the case of Messum limestone syntaxis is thought to be more probable.

Another interesting comparison can be drawn between the Slieve Gullion and Messum Ring-complexes which have certain features in common not shared with Okonjeje. On the other hand the felspathoidal rock types of Okonjeje and Messum are not represented at Slieve Gullion. Messum therefore, stands somewhere between the two, possessing characters in common with both. The essential similarity between Slieve Gullion and Messum lies in the recognition that both once represented volcanic cones intruded by basic sheets, the intervening acid tuff layers of which have been transformed into micro- and aplogranites. D. L. Reynolds¹⁸, who has made a detailed study of Slieve Gullion gives a convincing account of this transformation, while the evidence at Messum is also very strong. Leucocratic gabbros occur at both Messum and Slieve Gullion but here there is a difference in field relations and interpretation. The white gabbro of Slieve Gullion grades downward into a felspar phyric dolerite and both are thought to have been originally basaltic flows. Metamorphism converted the zeolite-filled amygdules into felspar porphyroblasts and it is concluded that the white gabbro represents the upper richly-amygdaloidal flows. At Messum the picture is different. The anorthosites are too leucocratic for them ever to have been amygdaloidal lavas and a cumulative origin seems to be the only tenable explanation. The transgressive granophyres of Messum are of a different type to the finely net-veined intrusion breccias of Slieve Gullion and other British Tertiary volcanic centres. At Messum these

granophyres typically form a widely-spaced rectilinear vein system in the outer basic lavas well illustrated and described by Martin¹⁰ (pp. 101 and 102) and although the possibility of an origin by fluidization was carefully considered, it was rejected on the ground that gas-fluxed material could be expected in a more or less vertical fault zone but not in the broad area or with the regularity of inclination of the transgressive granophyres of Messum. Even the brecciated zones are localised and conform in pattern to the general outward dip.

VII.—SUMMARY OF THE PETROLOGICAL SEQUENCE

1. Formation of a central volcano with alternating basic and acid extrusions, the former occurring mainly as flows and the latter as pyroclasts. A few intercalated sedimentary layers mark periods of quiescence.

2. Intrusion of eucritic dolerite sheets with upward accumulation by gas flotation of plagioclase to form anorthositic bands.

3. Assimilation of argillaceous rock at depth together with limited differentiation and intrusion of the resultant magma forming sheets of biotite-hypersthene dolerite.

4. Transfusion of alkalis, alumina and other volatiles from the basaltic layer into the overlying depressed sial giving rise to a palingenic granite magma which rose up ring-fractures.

5. Soaking of the volcanic rocks between the dolerite sheets by this granite magma and its accompanying metasomatising fluids—with the production of granite rocks from oversaturated volcanics and of intermediate calc-alkaline rocks from basic volcanics.

6. Fresh intrusion of basaltic magma to fill radial fissures.

7. Renewed subsidence of the core causing upwelling of a foyaitic magma which had been forming at depth due to limestone syntaxis. This magma cooled as tinguaites in narrow ring, radial and concentric fissures and as coarser-grained foyaite in wider ring-fissures near the centre of the core.

8. Fenitisation of the lavas and pyroclastic rocks of the core producing syenites and nepheline-poor foyaites from original oversaturated volcanics and theralites and nepheline-bearing intermediate rocks from basic material.

9. Accumulation and rheomorphic intrusion of a silica and volatile-rich fraction expelled from the oversaturated volcanics forming intrusive nordmarkites and granites.

10. Intrusion of olivine nephelinite magma to fill radial fissures in the core. This magma probably formed as a result of the contamination of basaltic magma by limestone syntaxis at depth.

The sequence of magma types is thus alternating basic and acid first in an extrusive and then an intrusive phase. This is followed by foyaite and finally olivine nephelinite in the core segment only.

The governing mechanism in the production of these diverse magmas is believed to be downward movements of the crust, while limited miscibility between basaltic and rhyolitic melts, as proposed by Holgate,⁶ is considered

to account for the chemistry. The first depression of the crust under the weight of Karroo sediments may have initiated the Stormberg vulcanism. Centralization of activity along a zone of weakness parallel to the north-east trend of the basement rocks followed. Throughout this time the top of the depressed sima probably contained pockets of magma or else required very little relief of pressure to liquefy it. Transfusion of volatiles including alkalis and alumina would take place into the already heated overlying sial and as soon as a composition is reached which will melt at the prevailing temperatures, a rhyolitic liquid is formed. This mechanism satisfactorily accounts for the alternating acid and basic extrusive and intrusive members of the Complex.

The occurrence of felspathoidal rocks exclusively in the most deeply down-faulted core segment is thought to be significant. Deep subsidence of the Damara marbles could be expected to bring them into contact with first the rhyolitic melt and later the basaltic melt thereby giving rise by syntexis to foyaitic and then olivine nephelinitic magmas.

VIII.—ACKNOWLEDGEMENTS

It is with great pleasure that I acknowledge a debt of gratitude to Dr. H. Martin for his unfailing courtesy in answering my many queries by post, for stimulating discussions and, here I must include Mrs. Martin, for exceptional kindness on a most enjoyable field trip to Messum in April, 1955.

To Professor F. Walker I extend my most sincere thanks for reading the draft script and for his kindness and many helpful suggestions. I should also like to thank Mr. H. C. G. Vincent and Dr. E. S. W. Simpson for reading the draft script and for their ready co-operation at all times.

I am indebted to the C.S.I.R. for making 32 chemical analyses of rocks and to the Staff Research Fund of the University of Cape Town for grants for five further rock analyses and for travelling expenses; also to Dr. S. R. Nockolds and Mr. R. S. Allen of the Department of Mineralogy and Petrology, Cambridge, for kindly carrying out the spectrographic determination of the minor elements.

IX.—REFERENCES

- (1) BIRCH, F., SCHAIRER, J. F., and SPICER, H. C. (1942). Handbook of physical constants. *Geol. Soc. Amer.*, Special Paper No. 36.
- (2) BOWEN, N. L. (1928). The evolution of the igneous rocks. Princeton University Press.
- (3) BRITISH ASSOCIATION COMMITTEE. (1936). Petrographic Nomenclature. *Geol. Mag.*, 73, 319-325.
- (4) DALY, R. A. (1944). Volcanism and petrogenesis as illustrated in the Hawaiian islands. *Bull. Geol. Soc. Amer.*, 55, 1363-1400.
- (5) GEYERS, T. W. (1932). Kaoko-eruptives and alkali rocks at Cape Cross. *Trans. Geol. Soc. S. Afr.*, 35, 85-96.
- (6) HOLGATE, N. (1954). The role of liquid immiscibility in igneous petrogenesis. *J. Geol.*, 62, 439-480.
- (7) HUTTON, C. O. (1951). Allanite from Yosemite National Park, Tuolumne Co., California. *Amer. Min.*, 36, 233-248.
- (8) KING, B. C. (1948). The Napak area of southern Karamoja, Uganda. *Geol. Surv., Uganda*, Mem. 5.
- (9) KORN, H. and MARTIN, H. (1953). Der intrusionsmechanismus der grossen Karroo-plutone in Sudwestafrika. *Geol. Rdsch.*, 41, 41-58.

- (10) KORN, H. and MARTIN, H. (1954). The Messum igneous complex in South-West Africa. *Trans. Geol. Soc. S. Afr.*, 57, 83-124.
- (11) LARSEN, E. S. (1941). Alkalic rocks of Iron Hill Gunnison County, Colorado. *U.S. Geol. Surv.*, Prof. Paper 197A.
- (12) MACDONALD, G. A. (1949). Hawaiian petrographic province. *Bull. Geol. Soc. Amer.*, 60, 1541-1596.
- (13) NOCKOLDS, S. R. (1954). Average chemical compositions of some igneous rocks. *Bull. Geol. Soc. Amer.*, 65, 1007-1032.
- (14) POLDERVAART, A. (1950). Correlation of physical properties and chemical composition in the plagioclase, olivine and orthopyroxene series. *Amer. Min.*, 35, 1067-1079.
- (15) POLDERVAART, A. and GILKEY, A. K. (1954). On clouded plagioclase. *Amer. Min.*, 39, 75-91.
- (16) PULFREY, W. (1949). Ijolitic rocks near Homa Bay, Western Kenya. *Quart. J. Geol. Soc. Lond.*, 105, 425-459.
- (17) READ, H. H. (1951). Metamorphism and granitisation. Alex. L. du Toit Memorial Lectures, No. 2. *Geol. Soc. S. Afr.*, Annexure to Vol. 54.
- (18) REYNOLDS, D. L. (1951). The geology of Slieve Gullion, Foughill and Carrickcarnan: an actualistic interpretation of a Tertiary gabbro-granophyre complex. *Trans. Roy. Soc. Edin.*, 62, 85-144.
- (19) REYNOLDS, D. L. (1954). Fluidization as a geological process and its bearing on the problem of intrusive granites. *Amer. J. Sci.*, 252, 577-614.
- (20) RICHEY, J. E., THOMAS, H. H. et al. (1930). The geology of Ardnamurchan, north-west Mull and Coll. *Mem. Geol. Surv. Scotland*.
- (21) SHAND, S. J. (1928). The geology of Pilansberg (Pilaan's Berg) in the western Transvaal: a study of the alkaline rocks and ring intrusions. *Trans. Geol. Soc. S. Afr.*, 31, 97-156.
- (22) SHAND, S. J. (1939). On the staining of feldspaths and on zonal structure in nepheline. *Amer. Min.*, 24, 508-513.
- (23) SHAND, S. J. (1947). Eruptive rocks. 3rd edition. Wiley, New York.
- (24) SIMPSON, E. S. W. (1954). The Okonjeje Igneous Complex, South-West Africa. *Trans. Geol. Soc. S. Afr.*, 57, 125-172.
- (25) WALKER, F. and POLDERVAART, A. (1949). Karroo dolerites of the Union of South Africa. *Bull. Geol. Soc. Amer.*, 60, 591-706.
- (26) WELLS, M. K. (1953). The structure and petrology of the hypersthene-gabbro intrusion, Ardnamurchan, Argyllshire. *Quart. J. Geol. Soc.*, 109, 367-397.

DEPARTMENT OF GEOLOGY,
UNIVERSITY OF CAPE TOWN,
CAPE TOWN, C.P.

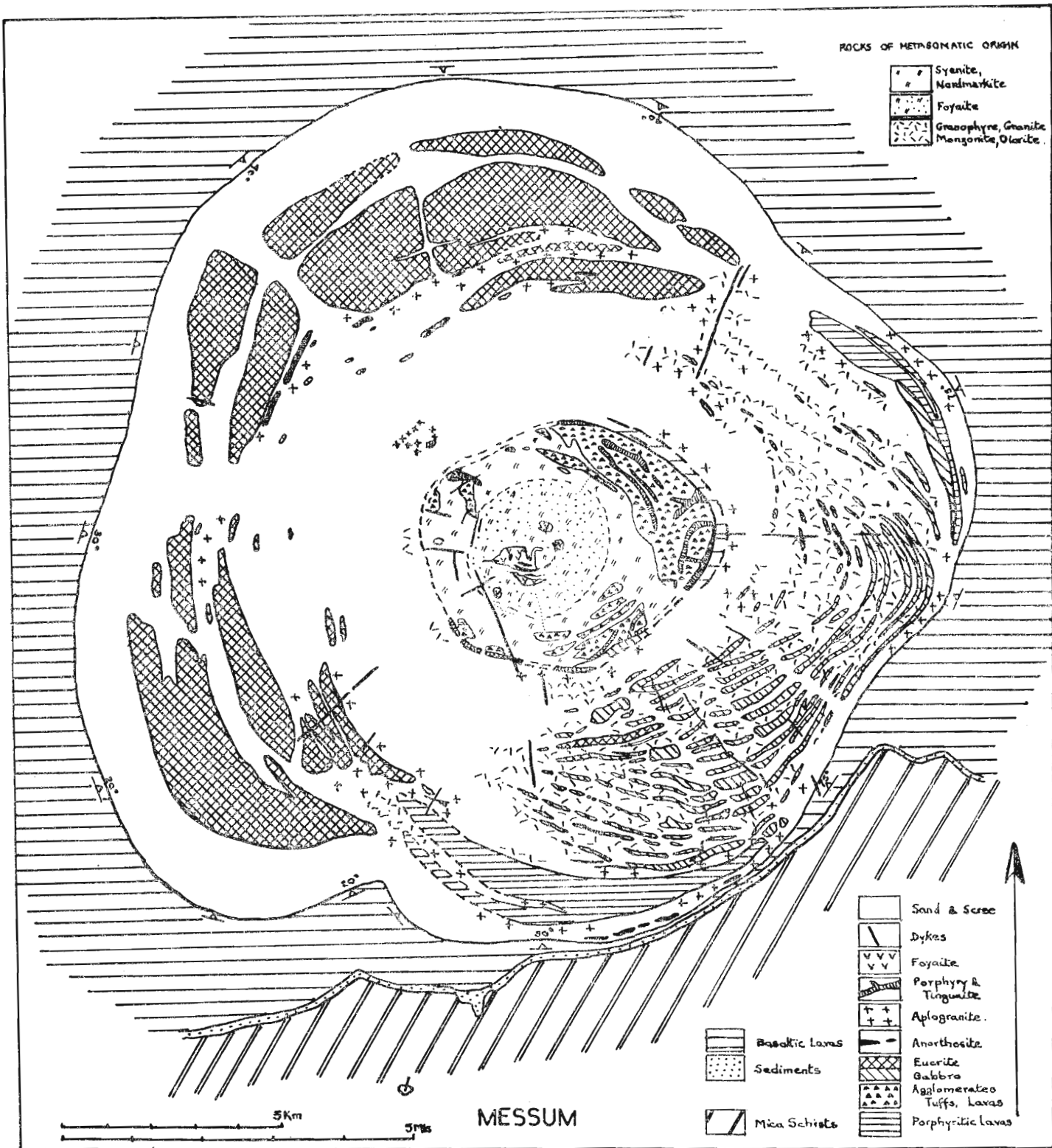
Accepted for publication by the Society
on 7th April, 1956.

TABLE 3.
CHEMICAL, SPECTROGRAPHIC AND NORMATIVE DATA.

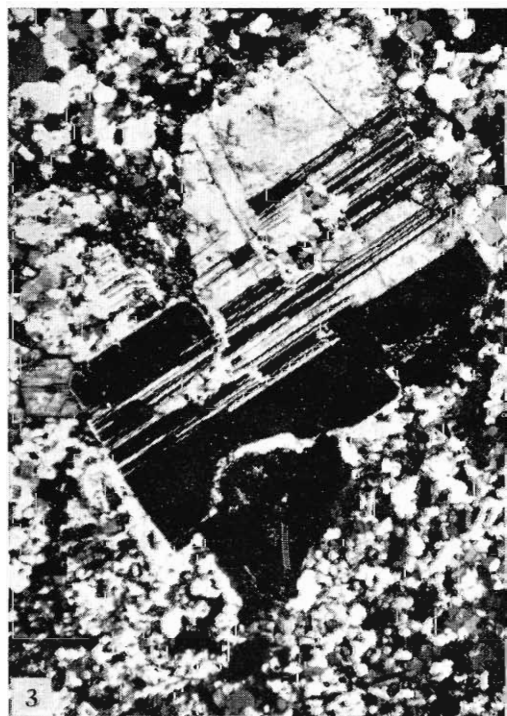
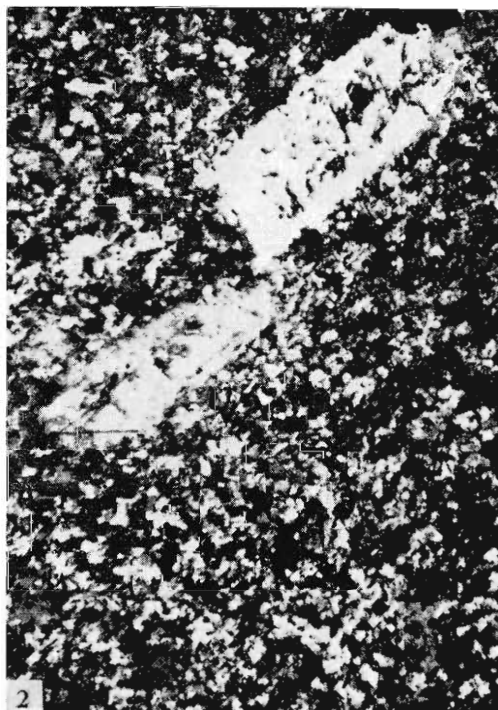
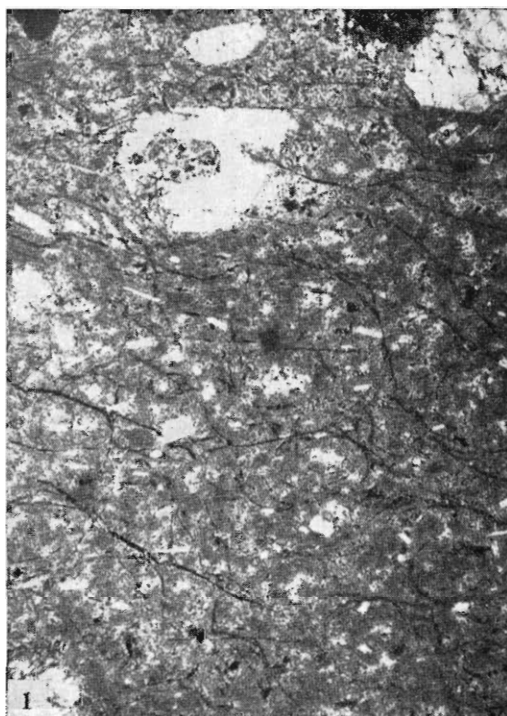
	VOLCANIC PHASE.					INTRUSIVE PHASE.												
	Basalt	Tholeiitic Basalt	Phyric Basalt	Bronzite Basalt	Quartz Porphyry	Eucrite	Eucrite	Hypers-thene Gabbro	Anor-thosite	Anor-thosite	Grano-phyre	Micro-granite	Aplo-granite	Amphibole Granite	Pyroxene Granite	Grano-diorite Hybrid	Monzonite Hybrid	Diorite Hybrid
	L 11	W 3	L 13	L 14	M 52	3	T 50	T 58	14	K 43	O 12	Q 6	K 47	P 17	Y 15	Y 20	P 10	Y 9
SiO ₂	48.48	50.29	49.15	52.26	75.21	47.02	47.40	47.15	45.98	45.77	74.97	74.18	73.05	67.66	69.04	62.86	58.44	52.79
TiO ₂	0.60	1.35	1.30	1.03	0.28	0.20	0.25	0.83	0.08	0.42	0.08	0.38	0.22	0.37	0.63	0.52	0.90	1.26
Al ₂ O ₃	16.52	16.35	19.71	15.03	12.10	19.86	17.20	18.51	32.97	28.38	12.57	13.39	13.47	15.61	14.28	14.49	15.44	15.98
Fe ₂ O ₃	4.38	5.57	2.94	2.22	2.24	1.20	1.68	2.73	1.04	1.67	0.64	0.36	1.13	2.03	3.23	2.79	2.70	3.40
FeO	5.12	5.19	5.63	7.29	0.14	4.10	3.59	6.75	0.22	2.08	0.32	2.19	1.64	1.20	1.35	4.25	5.63	7.01
MnO	0.12	0.18	0.15	0.18	0.02	0.09	0.09	0.15	0.02	0.06	0.02	0.05	0.04	0.06	0.07	0.14	0.15	0.18
MgO	9.55	6.32	4.37	6.23	0.36	9.76	11.51	9.80	0.74	2.23	0.28	0.14	0.13	0.96	0.51	3.31	3.73	5.70
CaO	9.80	8.78	10.59	9.26	0.36	15.84	16.44	9.70	16.72	14.26	1.08	1.13	0.48	1.52	1.72	5.00	5.98	7.70
Na ₂ O	1.84	2.33	2.46	2.04	2.83	1.22	0.98	2.46	1.62	2.13	3.38	2.94	5.13	4.50	3.80	4.16	3.52	3.27
K ₂ O	0.14	1.47	1.13	1.44	5.44	0.06	0.08	0.52	0.07	0.41	5.78	5.09	4.42	5.23	5.27	1.43	2.16	1.59
H ₂ O+	2.27	1.90	1.16	1.29	0.45	0.37	0.35	0.85	0.18	1.87	0.24	0.38	0.32	0.36	0.43	0.67	0.78	0.65
H ₂ O-	0.19	0.13	0.12	0.12	0.07	0.10	0.11	0.16	0.13	0.17	0.06	—	0.08	0.05	0.07	0.07	0.16	0.18
CO ₂	0.58	0.13	1.11	1.42	—	—	—	0.13	—	0.49	—	—	—	—	—	—	—	—
P ₂ O ₅	0.11	0.20	0.20	0.15	0.02	0.05	0.04	0.15	0.05	0.07	—	—	—	—	—	—	—	0.17
TOTAL	99.70	100.19	100.02	99.96	99.52	99.87	99.72	99.89	99.82	100.01	99.42	100.23	100.11	99.55	100.40	99.69	99.59	99.88
Be ⁺²	—	—	5 [?]	—	5	—	—	—	—	—	5	n.d.	n.d.	—	—	—	—	5
Ga ⁺³	25	30	30	30	20	40	35	25	35	35	20	n.d.	n.d.	20	20	35	30	30
Cr ⁺³	450	40	100	200	20	575	1,500	40	20	25	2	n.d.	n.d.	—	—	15	5	40
V ⁺³	250	275	200	200	—	125	125	200	50	100	—	n.d.	n.d.	55	20	100	100	200
Mo ⁺⁴	—	—	—	—	—	—	—	—	—	—	—	n.d.	n.d.	—	—	—	—	—
Sn ⁺⁴	100	35	25	—	—	—	—	—	100	—	—	n.d.	n.d.	—	—	—	—	30
Li ⁺¹	15	20	25	15	7	30	15	20	3	15	10	n.d.	n.d.	20	5	35	40	40
Ni ⁺²	125	50	40	50	10	150	275	275	—	10	—	n.d.	n.d.	5	15	25	10	50
Co ⁺²	40	20	25	30	—	40	45	55	—	10	—	n.d.	n.d.	5	—	15	10	25
Sc ⁺³	30	—	15	40	—	60	60	15	—	—	—	n.d.	n.d.	—	—	—	—	15
Zr ⁺⁴	70	150	125	100	400	—	—	70	—	10	125	n.d.	n.d.	200	1,250	300	125	150
Yt ⁺³	25	25	30	20	50	—	—	20	—	—	70	n.d.	n.d.	50	60	50	20	30
La ⁺³	—	—	—	—	—	—	—	—	—	—	—	n.d.	n.d.	50	150	—	—	—
Sr ⁺²	100	250	200	125	15	125	125	300	250	250	25	n.d.	n.d.	400	100	200	200	70
Pb ⁺²	—	—	—	—	—	—	—	—	—	—	—	n.d.	n.d.	10	—	10	—	—
Ba ⁺²	80	450	300	250	600	10	10	200	25	40	150	n.d.	n.d.	2,250	1,000	450	600	200
Rb ⁺¹	—	80	50	100	300	—	—	15	—	10	500	n.d.	n.d.	350	200	125	125	100
Cs ⁺¹	—	—	—	—	—	—	—	—	—	—	10 ?	n.d.	n.d.	10 ?	—	—	—	—
Qz	3.42	4.98	3.00	7.14	37.26	—	—	—	—	—	30.78	33.78	24.93	17.04	22.92	17.22	10.56	2.16
Or	0.56	8.90	6.67	8.34	32.25	0.56	0.56	2.78	0.56	2.22	34.47	30.02	26.13	30.58	31.14	8.34	12.79	9.45
Ab	15.72	19.39	20.96	17.29	23.58	9.96	8.38	20.96	13.62	17.82	28.82	24.63	42.97	38.25	31.96	35.11	29.34	27.77
Ne	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
An	36.42	29.75	39.20	27.52	0.56	48.65	42.26	37.81	82.01	66.72	1.95	5.56	0.83	6.95	6.39	16.68	20.02	24.19
C	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Wo	—	—	—	—	—	1.43	—	—	0.10	—	—	1.02	—	—	—	—	—	—
Di	3.25	4.99	2.32	3.60	—	12.18	16.12	3.60	—	—	0.70	0.81	—	0.58	0.23	0.81	3.36	4.06
En	2.40	3.80	1.40	2.10	0.90	8.80	12.40	2.40	1.00	—	0.70	—	—	0.10	0.20	0.70	2.00	2.20
Fs	0.53	0.66	0.79	1.32	—	2.24	1.98	0.92	—	—	—	—	—	0.53	—	1.19	1.72	1.98
Hy	21.50	12.00	9.50	13.70	—	1.80	2.40	6.30	—	3.20	—	0.30	—	2.20	0.60	6.30	7.10	11.00
Fs	4.22	2.24	5.28	8.84	—	0.53	0.40	2.38	—	1.06	—	3.17	—	—	—	3.70	5.15	6.34
Oi	—	—	—	—	—	9.66	9.80	11.06	0.28	1.68	—	—	—	—	—	—	—	—
Fa	—	—	—	—	—	2.65	1.84	4.49	—	0.61	—	—	—	—	—	—	—	—
Mt	6.50	8.12	4.18	3.25	—	1.86	2.55	3.94	0.70	2.55	0.93	0.70	1.62	3.02	2.55	4.18	3.94	4.87
Haem	—	—	—	—	2.24	—	—	—	0.48	—	—	—	—	—	1.44	—	—	—
Il	1.22	2.58	2.43	1.98	0.46	0.46	0.61	1.52	0.15	0.76	0.15	0.76	0.46	0.76	1.22	0.91	1.67	2.43
Ap	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	—	—	—	—	—	—	—	0.34
Cal	1.30	0.30	2.50	3.20	—	—	—	0.30	—	1.10	—	—	—	—	—	—	—	—
Sph	—	—	—	—	0.20	—	—	—	—	—	—	—	—	—	—	—	—	—
H ₂ O	2.46	2.03	1.28	1.41	0.52	0.47	0.46	1.01	0.31	2.04	0.30	0.38	0.40	0.41	0.50	0.74	0.94	0.83
TOTAL	99.84	100.08	99.85	100.03	99.74	100.16	100.10	99.81	99.55	100.10	99.61	100.32	100.07	99.64	100.23	99.73	99.49	100.23

TABLE 4
CHEMICAL, SPECTROGRAPHIC AND NORMATIVE DATA
ALKALINE PHASE

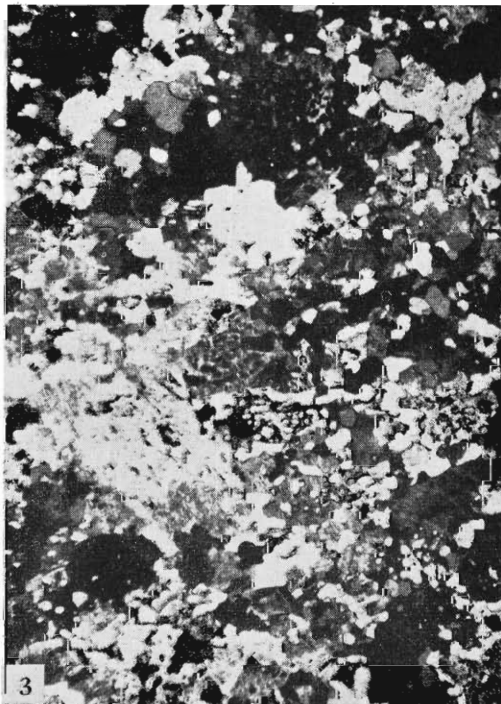
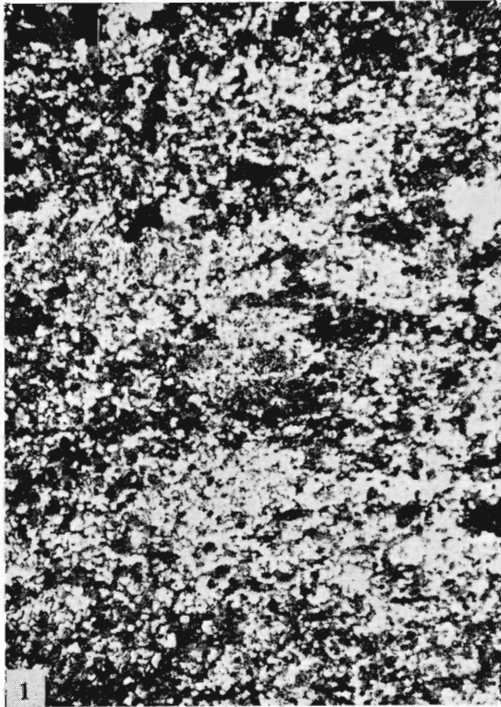
	Ring-dyke Tinguaité	Ring-dyke Tinguaité	Radial Tinguaité	Porphyry	Melano- cratic Fenite	Gabbro Fenite	Basalt Fenite	Basalt Fenite	Foyaite Fenite	Syenite Fenite	Nord- markite Fenite	Granite Fenite	Granite Fenite	Olivine Nephelinite	Olivine Tephrite
	G 23	E 1	G 4	M 30	E 17	G 9e.	V 20	G 11	G 27	H 15	M 13	K 5	M 28	H 13	P 5
SiO ₂ ..	57.93	57.58	55.00	61.92	50.96	46.26	45.72	46.86	57.03	64.84	70.24	74.82	73.84	43.65	44.22
TiO ₂ ..	0.48	0.45	0.38	0.56	1.03	1.20	1.57	1.22	0.43	0.48	0.30	0.18	0.25	1.25	1.25
Al ₂ O ₃ ..	19.97	20.02	21.95	16.03	21.33	16.38	17.25	18.29	21.17	15.98	14.43	12.29	13.30	18.73	17.90
Fe ₂ O ₃ ..	2.40	2.17	1.77	5.35	2.56	2.30	2.22	1.58	1.46	2.17	2.27	2.95	1.94	4.03	3.59
FeO ..	2.44	2.30	1.80	1.64	4.02	6.84	7.21	7.19	1.77	2.76	0.49	0.14	0.13	4.71	5.40
MnO ..	0.26	0.21	0.13	0.24	0.23	0.18	0.19	0.23	0.14	0.26	0.03	0.03	0.03	0.20	0.21
MgO ..	0.84	0.81	1.05	0.70	2.28	9.84	7.05	6.13	0.71	0.47	0.37	0.22	0.30	6.21	7.76
CaO ..	1.16	1.84	2.40	2.62	4.90	10.52	8.95	8.74	2.54	1.22	1.14	0.14	0.32	9.04	8.92
Na ₂ O ..	7.66	7.74	7.90	5.48	6.67	3.61	4.61	4.28	7.63	5.68	5.44	3.83	3.74	6.78	4.97
K ₂ O ..	5.64	5.51	5.76	4.29	3.98	1.60	2.46	2.33	5.44	5.38	4.78	4.50	4.98	2.55	2.11
H ₂ O ⁺ ..	0.67	1.11	1.38	0.59	1.12	0.68	1.39	1.64	1.30	0.32	0.36	0.37	0.66	1.32	2.28
H ₂ O ⁻ ..	0.08	0.08	0.09	0.20	0.07	0.07	0.09	0.25	0.09	0.08	0.14	0.10	0.20	0.09	0.13
CO ₂ ..	—	—	—	—	—	—	—	0.44	—	—	—	—	—	0.75	0.57
P ₂ O ₅ ..	0.12	—	—	0.10	0.55	0.10	0.47	0.43	—	0.11	—	0.02	0.05	0.20	0.25
Total ..	99.65	99.82	99.61	99.72	99.70	99.58	99.62	99.83	99.71	99.75	99.99	99.59	99.74	99.51	99.56
Re ⁺² ..	—	5	—	n.d.	—	—	—	n.d.	—	n.d.	5	5	5	—	—
Ga ⁺³ ..	20	25	20	n.d.	20	15	20	n.d.	20	n.d.	10	25	20	10	15
Cr ⁺³ ..	7	—	15	n.d.	10	650	275	n.d.	—	n.d.	—	—	—	300	500
V ⁺³ ..	—	5 ?	15	n.d.	50	225	150	n.d.	5	n.d.	—	5	5	150	100
Mo ⁺⁴ ..	3	10	10	n.d.	—	—	3	n.d.	5	n.d.	—	—	—	—	3
Sn ⁺⁴ ..	—	80	—	n.d.	—	40	—	n.d.	—	n.d.	30	75	—	—	—
Li ⁺¹ ..	50	45	40	n.d.	80	15	30	n.d.	25	n.d.	45	50	15	25	30
Ni ⁺² ..	—	3	5	n.d.	—	200	100	n.d.	—	n.d.	5	5	—	100	150
Co ⁺² ..	—	—	—	n.d.	10	40	25	n.d.	—	n.d.	—	—	—	30	30
Sc ⁺³ ..	—	—	—	n.d.	—	20	—	n.d.	—	n.d.	—	—	—	—	—
Zr ⁺⁴ ..	200	350	175	n.d.	150	125	150	n.d.	150	n.d.	500	650	150	100	70
Yt ⁺³ ..	35	60	20	n.d.	30	25	20	n.d.	30	n.d.	60	35	30	25	20
La ⁺³ ..	60	100	50 ?	n.d.	50 ?	—	—	n.d.	60	n.d.	150	—	100	—	—
Sr ⁺² ..	—	30	350	n.d.	700	500	500	n.d.	350	n.d.	5	5	30	1,500	1,500
Pb ⁺² ..	—	—	20	n.d.	—	—	—	n.d.	—	n.d.	—	—	—	—	—
Ba ⁺² ..	—	200	400	n.d.	1,000	800	650	n.d.	1,200	n.d.	100	20	400	1,000	800
Rb ⁺¹ ..	300	500	350	n.d.	250	50	150	n.d.	300	n.d.	450	600	300	100	100
Cs ⁺¹ ..	—	—	10 ?	n.d.	—	—	—	n.d.	—	n.d.	—	—	—	—	—
Qz ..	—	—	—	8.16	—	—	—	—	—	7.56	18.36	35.22	32.40	—	—
Or ..	33.36	32.80	34.47	25.58	23.35	9.45	15.01	13.90	32.25	31.69	28.36	26.69	29.47	15.01	12.23
Ab ..	40.08	35.63	25.68	46.63	25.68	9.96	11.53	18.08	34.06	48.21	46.11	31.96	31.44	2.49	10.74
Ne ..	13.49	16.19	22.15	—	16.47	11.08	14.77	9.66	16.47	—	—	—	—	29.89	16.90
An ..	3.34	3.34	7.23	6.12	16.68	23.91	19.18	23.63	7.23	2.22	0.56	—	0.56	12.79	20.29
C ..	—	—	—	—	—	—	—	—	—	—	—	1.22	1.53	—	—
Wo ..	—	—	—	0.35	—	—	—	—	—	—	1.04	—	—	—	—
Di. { Wo ..	0.70	2.44	1.97	2.09	1.86	11.48	8.00	5.45	2.20	1.28	1.04	—	—	11.14	7.77
Di. { En ..	0.30	1.50	1.20	1.80	1.00	7.70	4.90	3.10	1.10	0.40	0.90	0.60	0.80	8.10	5.60
Di. { Fs ..	0.40	0.79	0.66	—	0.79	2.90	2.64	2.11	1.06	0.92	—	—	—	1.98	1.45
Hy. { En ..	—	—	—	—	—	—	—	—	—	0.80	—	—	—	—	—
Hy. { Fs ..	—	—	—	—	—	—	—	—	—	1.98	—	—	—	—	—
Ol. { Fo ..	1.26	1.75	0.98	—	3.29	11.83	8.89	8.54	0.49	—	—	—	—	5.18	9.66
Ol. { Fa ..	1.43	1.02	0.61	—	2.45	4.79	5.00	6.32	0.51	—	—	—	—	1.32	2.86
Ol. { Mt ..	3.48	3.25	2.55	4.41	3.71	3.25	3.25	2.32	2.09	3.25	0.93	—	—	5.80	5.34
Haem. ..	—	—	—	2.40	—	—	—	—	—	—	1.60	2.88	1.92	—	—
Il. ..	0.91	0.76	0.76	1.06	1.98	2.28	3.04	2.28	0.76	0.91	0.61	0.46	0.30	2.28	2.43
Ap. ..	0.34	—	—	0.34	1.34	0.34	1.34	—	—	0.34	—	0.34	0.34	0.34	0.67
Cal ..	—	—	—	—	—	—	1.00	1.50	—	—	—	—	—	1.70	1.30
Sph. ..	—	—	—	—	—	—	—	—	—	—	—	—	0.20	—	—
H ₂ O ..	0.75	1.19	1.47	0.79	1.19	0.75	1.48	1.89	1.39	0.40	0.50	0.47	0.86	1.41	2.41
Total ..	99.84	100.66	99.73	99.73	99.79	99.72	100.03	98.78	99.61	99.96	100.01	99.84	99.82	99.43	99.65



[Reproduced by courtesy of Dr. H. Martin and amended.]



Figs. 1-4. Phyrlic lava (Me 12) showing perlitic cracks in fig. 1 and subsequent stages of recrystallization marked by increasing grain-size in figs. 2-4. (R 11; Me 9; Me 73. Crossed nicols. Magnification $\times 32$).



Figs. 1-4. Stages in the recrystallization of an acid tuff or lava characterized by the presence of aegirine-augite and by granophyric intergrowths of quartz and felspar. (T 67; T 12; T 13; T 8. Crossed nicols. Magnification $\times 32$).

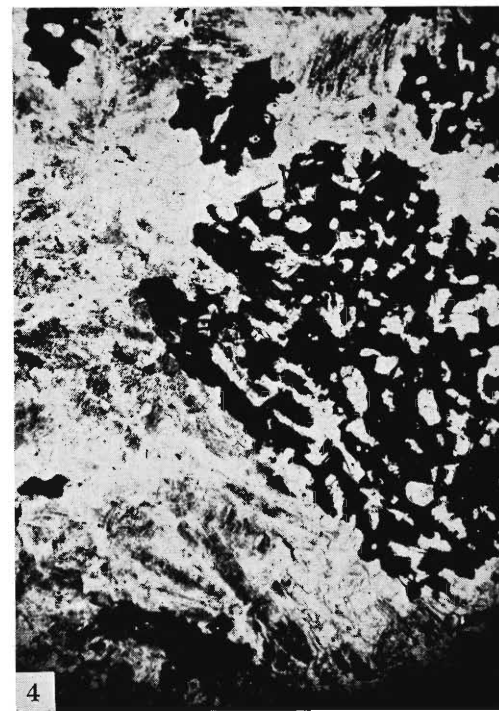
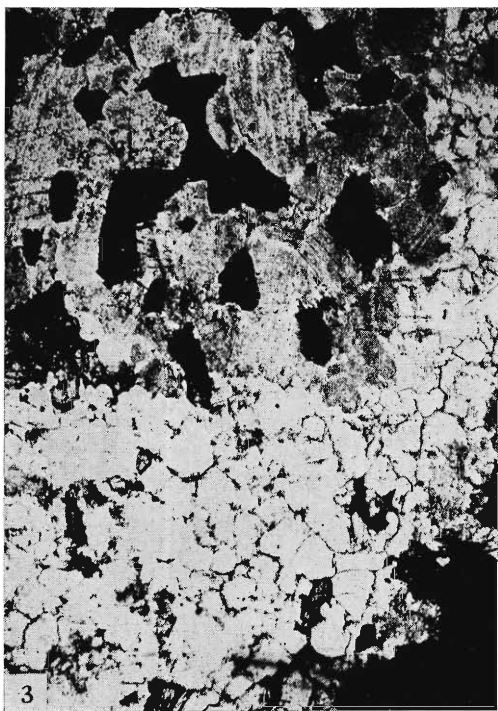
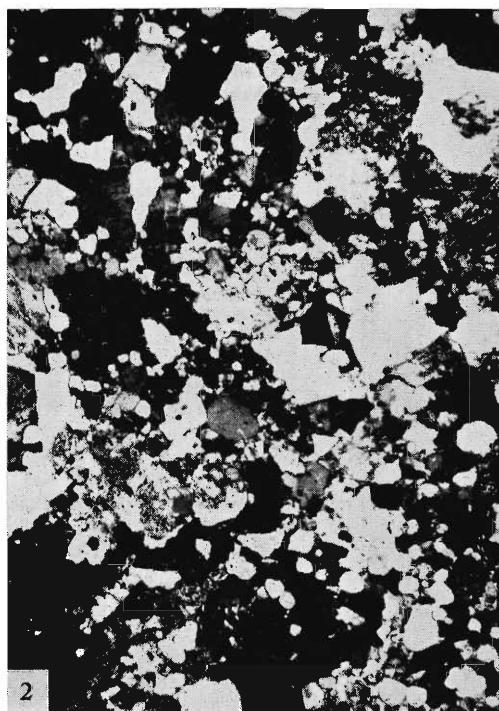


Fig. 1. Felspar-phyric basalt. (T 34. Magnification $\times 4$).
 Fig. 2. Seriate texture in granite. (Me 1. Crossed nicols. Magnification $\times 32$).
 Fig. 3. Basic hybrid showing fragments of basalt consisting of clouded plagioclase (grey) and heavily schillerized clinopyroxene (black) separated by a quartz-feldspar aggregate (light). (P 16. Crossed nicols. Magnification $\times 32$).
 Fig. 4. Tinguaitite ring-dyke showing sieve texture in ferrohastingsite. Crossed nicols. Magnification $\times 24$).