11. *The TERTIARY VOLCANIC ROCKS of the DISTRICT of MOZAMBIQUE.* By ARTHUR HOLMES, D.Sc.(Lond.), D.I.C., A.R.C.S., F.G.S. (Read June 28th, 1916.)

[PLATES XX & XXI.]

CONTENTS.

	Page
Introduction.	
I. History of Exploration	222
II. General Features	223
III. The Coastal Belt	224
IV. Bibliography	225
The Volcanic Area.	
V. The Distribution and Former Extent of the Lavas ...	228
VI. Period of Eruption	229
VII. Order of Eruption, and Classification	231
Petrographic Descriptions and Analyses.	
Rocks of Group A.	
VIII. Sölvbergite	233
IX. Ægirine-Trachyte	235
X. Trachytoid-Phonolite	236
XI. Tephritic Pumice	239
XII. Basalt	241
XIII. Pierite-Basalt	244
Rocks of Group B.	
XIV. Basalts: Sills and Dykes	246
XV. Basalts: Lava-Flows	250
XVI. Hornblende-Andesite	256
XVII. Pyroxene-Andesite	259
Relationships and Origin of the Volcanic Rocks.	
XVIII. Distribution of Similar Lavas in Eastern Africa	260
XIX. Variation-Diagrams	264
XX. Origin of the Lavas	271
XXI. The Radioactivity of the Lavas, and its Bearing on their Origin	275

Introduction.

I. HISTORY OF EXPLORATION.

THE Portuguese East-African District of Mozambique was, until recently, one of the least known of the East-African coastlands. Livingstone explored the regions on the south-west (1865) and north (1874), but Mozambique itself he did not touch. Sadebeck (1879) was the first to give a geological description of the sedimentary rocks that fringe the coastal plain of the mainland north and south of Mozambique¹ Island. This work was followed up by Choffat (1903) in an important palæontological memoir on the Cretaceous formations of Conducia Bay. Exploration beyond the coastal zone was initiated by Lieut. H. E. O'Neill, who made a number of successful journeys westwards across the mainland during the years 1881-1884. In his papers (1882, 1884, 1885) he

¹ The name Mozambique has been used indiscriminately for (a) Portuguese East Africa, (b) the district lying between the Luli and Ligonia Rivers, (c) the Island of Mozambique, and (d) the city of Mozambique.

gives a very complete and faithful account of the natives and their customs; but, beyond the suggestion that the prevailing rocks are gneisses and granites, he makes no reference to the geology of the territory. In 1887, Mr. J. T. Last made a journey from Blantyre to the Namuli Peaks, which had for long been considered to be of volcanic origin. This view he disproved (Last, 1887), describing the summit as 'an almost perpendicular mass of white stone.' I have since learned from Mr. Last that he referred in this expression to the grey granite and gneiss which builds up the Namuli Peaks, as it does the other mountainous masses of the country.

Thus, until a few years ago, Mozambique, with the exception of part of the Cretaceous coastal fringe, was practically a *terra incognita* to geologists. In 1910, a prospecting and surveying expedition was organized by the Memba Minerals Ltd., under the leadership of Mr. E. W. E. Barton. The coastal belt was investigated during the first season with Memba as the base of operations; but, owing to the hostility of the natives, little progress was made inland. Early in 1911, a fresh party was formed with headquarters at Mosuril, and Mr. E. J. Wayland, Mr. D. A. Wray, and myself, were appointed as geologists to the expedition. A short account of the geographical work accomplished, together with the map made during the two seasons' work, has already been published (Reid, 1913), and in two papers introductory to the present more detailed treatment Mr. Wray and myself have described the geography of the country and the outstanding features of the geology (Holmes & Wray, 1912 & 1913; see also Wray, 1915).

The present paper deals with the Tertiary volcanic rocks of Mozambique, and will be followed by one describing the Pre-Cambrian rocks.

II. GENERAL FEATURES.

With the exception of a coastal zone of variable width, formed by a narrow belt of Cretaceous and Tertiary sediments and flanked on the west by later Tertiary volcanic rocks, the whole territory consists of a complex of gneisses and other foliated rocks with granitic and other intrusions belonging to at least two different periods. Although we proceeded inland for 250 miles, as far west as longitude 37° E., we met with no signs of unmetamorphosed sedimentary rocks, once the coastal zone had been left behind. The oldest rocks lying on the basal complex are of Lower Cretaceous age, and consequently there is no close stratigraphical evidence for the age of the complex.

The petrological details and architecture of the complex suggest for the greater part of it a Pre-Cambrian age, and in a subsequent paper an attempt will be made to show that this view is justified: for a direct measurement of the age of the gneisses, and that of one of the later granites, by the radioactive method, proves that an approximate correlation can be made between the older rocks of Mozambique and those of other countries far removed from the tropics.¹

¹ A. Holmes, Proc. Geol. Assoc. vol. xxvi (1915) p. 305.

The geological sequence in Mozambique may be summarized as follows:—

Recent Deposits. Overlying drifts, lateritic deposits, coral reefs, and raised beaches.		
Tertiary.	2. Volcanic rocks.	Post-Oligocene.
	1. Mozambique Limestone and Mochelia Conglomerate. }	Oligocene.
Cretaceous.	3. Conducia and Monapo Beds.	Upper Cretaceous.
	2. Mount Meza Beds.	Middle Cretaceous.
	1. Fernão Velloso Beds.	Lower Cretaceous.
Pre-Cambrian Complex.	4. Pyroxenites.	
	3. Granites and pegmatites.	
	2. Gneisses, amphibolites, and eclogites.	
	1. Schists and crystalline limestones.	

III. THE COASTAL BELT.

The narrow Coastal Belt is formed essentially of Mesozoic deposits, and extends intermittently along the whole East African coast, broken only where the sea has eaten away the sedimentary formations and reached the more resistant rocks beyond. Throughout the length of Mozambique, no sediments older than Cretaceous are known along this zone, but on the north, in Portuguese Nyasaland and in the German (1914) and British areas, Upper Karoo and Jurassic formations are also found.

In Mozambique the coastal zone varies in width up to 10 miles. The shore itself is fringed with loosely-cemented coral-rocks and raised beaches. The underlying sedimentary rocks extend almost continuously from the Lurio in the north to Moginquale in the south, and are nearly all of Cretaceous age. Mozambique Island and the outlying parts of the adjoining mainland are unconformably capped with Tertiary sediments, which were referred by Sadebeck (1879) to the Upper Eocene or Oligocene.

Mr. Wray has divided the Cretaceous formations into three main groups, the succession of which, with their lithological characters and distribution, is expressed in the following table:—

Name.	Age.	Lithological Character.	Distribution.
3. Conducia and Monapo Beds.	Senonian.	Limestones, calcareous shales and sandstones, with a calcareous conglomerate at the base.	Mokambo Bay to the Mikati River.
2. Mount Meza Beds.	Albian to Aptian.	Sandstones, often felspathic, with calcareous bands.	Mount Meza and the adjoining district.
1. Fernão Velloso Beds.	Neocomian.	Alternating limestones and shales.	South of Fernão Velloso Harbour to Memba.

The prevailing dip is southward or south-eastward, except north of Mokambo Bay, where the Conducia Beds appear to be brought up by a syncline. Folding, however, wherever seen, is very gentle. Evidences of movements of a vertical type are more common, and small north-and-south faults have broken up the Monapo Beds along the northern shores of Mokambo Bay. Mr. Wayland determined their junction with the gneissose rocks on the west to be a faulted one. The Conducia Beds south of Sokoto Hill are faulted against the gneissose rocks, for the conglomerate basement-beds are not seen, and marine limestones are brought to a level with the older rocks. Mr. Wray considers that Fernão Velloso Harbour, with its rugged gneissose cliffs on the west and low-lying limestones and shales on the east, represents a line of fault picked out by marine erosion between the Cretaceous sediments and the Pre-Cambrian complex. On linking up all our observations, it seems clear that a series of nearly north-and-south faults has slowly displaced the Cretaceous beds, generally dropping them down on the eastern side, and locally cutting them off sharply from the ancient rocks beyond. It is a significant feature that the average direction of these faults is parallel to the general trend of the adjoining coast-line and to the basaltic dykes associated with the Tertiary volcanic rocks. The strike of the foliation and banding of the gneisses is truncated obliquely by the coastal belt, and the coast has therefore a typically Atlantic character.

IV. BIBLIOGRAPHY.

1879. A. SADEBECK.—'Geologie von Ost-Afrika' in Von der Decken's 'Reisen in Ost-Afrika,' Leipzig, vol. iii, pp. 35, 36.
1882. C. MAPLES.—'Makua Land, between the Rivers Rovuma & Luli' Proc. Roy. Geogr. Soc. vol. iv, p. 79; map on p. 128.
1882. H. E. O'NEILL.—'A Three Months' Journey in the Makua & Lomwe Countries' Proc. Roy. Geogr. Soc. vol. iv, p. 193.
1884. H. E. O'NEILL.—'Journey from Mozambique to Lakes Shirwa & Amaramba' Proc. Roy. Geogr. Soc. vol. vi, pp. 632, 713.
1885. H. E. O'NEILL.—'Eastern Africa between the Zambesi & Rovuma Rivers' Proc. Roy. Geogr. Soc. vol. vii, p. 430 and Scot. Geogr. Mag. vol. i, p. 337.
1887. J. T. LAST.—'On the Society's Expedition to the Namuli Hills' Proc. Roy. Geogr. Soc. vol. ix, p. 467; map on p. 212.
1900. P. CHOFFAT.—'Sur le Crétacique Supérieur à Moçambique' C. R. Acad. Sci. Paris, vol. cxxxi, p. 1258.
1903. P. CHOFFAT.—'Contributions à la Connaissance Géologique des Colonies Portugaises de l'Afrique: le Crétacique de Conducia' Comm. Serv. Geol. Portugal.
1912. A. HOLMES & D. A. WRAY.—'Outlines of the Geology of Mozambique' Geol. Mag. dec. 5, vol. ix, p. 412.
1913. R. L. REID.—'Notes on Mozambique Exploration' Geogr. Journ. vol. xlii, p. 44; map on p. 112.
1913. A. HOLMES & D. A. WRAY.—'Mozambique: a Geographical Study' (with map). Geogr. Journ. vol. xlii, p. 143.
1914. A. HOLMES.—'The Lateritic Deposits of Mozambique' Geol. Mag. dec. 6, vol. i, pp. 529-37.
1915. E. J. WAYLAND.—'Notes on the Occurrence of Stone Implements in Mozambique' (with map). 'Man,' vol. xv, p. 57.
1915. D. A. WRAY.—'Observations sur la Géologie du District de Moçambique' (with sketch-map). Comm. Serv. Geol. Portugal, vol. xi, pp. 69-84.
1917. A. HOLMES.—(a) Picrite from the Ampwihi River, Mozambique' Geol. Mag. dec. 6, vol. iv, p. 150; (b) 'The Pre-Cambrian & Associated Rocks of the District of Mozambique' Abs. Proc. Geol. Soc. no. 1010, p. 89; & Geol. Mag. dec. 6, vol. iv, p. 380.

Fig. 1.—*Map illustrating the distribution of the volcanic rocks of Mozambique.*

[Based on the topographical survey by the staff of the Memba Minerals Ltd., 1910-11 (Geogr. Journ. vol. xlii, 1913, p. 112) and on geological observations made by Dr. A. Holmes, Mr. E. J. Wayland, and Mr. D. A. Wray.]

Fig. 2.—Section AB, from the Mitikiti River to Mosuril Bay. (Length = 25 miles.)

Fig. 3.—Section CD, from Ibrahino to Conducia Bay. (Length = 11 miles.)

The Volcanic Area.

V. THE DISTRIBUTION AND FORMER EXTENT OF THE LAVAS.

The volcanic rocks of the district of Mozambique occur along a narrow belt of country which extends from Mokambo Bay to beyond the Sanhuti River, following a line approximately parallel to the general direction of the coast (see map, fig. 1, p. 226). The boundary-fault between the sedimentary coastal belt and the Pre-Cambrian complex roughly bisects the volcanic area, although in the north the lavas are more abundant on the western side of the fault. The lava-flows are everywhere horizontal, and are clearly the result of fissure-eruptions, no traces of pyroclastic ejecta having been anywhere encountered.

The flows are now restricted to innumerable small outcrops surrounded, according to the locality, by gneiss and granite, by Cretaceous or Tertiary sediments, or by more recent lateritic earths and alluvium. Small dykes and sills, representing the feeders through which the magmas reached the surface, penetrate the underlying rocks, and are exposed in many places between the much dissected lava-flows. On the accompanying sketch-map (fig. 1), it has been possible to express only the broader outlines of the various formations which enter into this complicated patchwork. No pretence is made to detailed accuracy, for the inherent difficulties of pioneer mapping, topographical as well as geological, were considerably increased by widespread sheets of superficial débris, and in places by a dense undergrowth of tropical vegetation.

Throughout the area the prevailing lavas are basalts of a remarkably uniform type. All are vesicular, and most of them are coarsely amygdaloidal. That similar flows of amygdaloid originally extended northwards as far as Fernão Velloso Harbour is made clear by the presence of abundant pebbles of agate and jasper around the Nakalla River and along the western shores of the Harbour. Pebbles of agate and jasper are still being derived from the amygdaloids, and naturally they occur in great abundance on the coastal side of the exposures, particularly along the lower reaches of the Mitikiti, Monapo, Mikati, and Sanhuti Rivers. Similar pebbles, however, also occur to the west of the exposures, especially in the Monapo district, where the flows appear to have been laterally more extensive than elsewhere. The existence of these relics in places (such as Mitikiti) to which they could not have been transported by the present drainage, makes it certain that the lavas flooded a strip of country from 5 to 10 miles broad, and at least 50 miles long.

Beyond Mitikiti's Kraal, a solitary basaltic dyke, well encrusted with laterite, was met with in Maravi's carefully guarded country. Its position, near Nashologoto, is marked on the map. In a line with this dyke, a few miles away to the south, a series of hot springs breaks through the gneissic surface, providing the Mitikiti River with a small but permanent tributary. We encountered the steaming waters in a dense forest during the dry season, when all

the neighbouring gullies were empty. This fact, together with the comparatively high temperature (about 60° C.), suggests that the springs may be of juvenile origin, representing the last flicker of expiring activity on the border of a volcanic field already much reduced by erosion. Nearly a gallon of the water was evaporated to dryness in a clean prospecting-pan, in order that the residue might be tested by blowpipe reactions. Carbon dioxide was present in just sufficient abundance to be recognized. The residue was very small, and only soda and silica could be detected.

The rocks described in the present paper are confined to a district rather more than 30 miles in length, extending from the Mitikiti River to beyond the Sanhuti River. Amygdaloidal and vesicular basalts are not the only types of lava represented. In

Fig. 4.—*Specimen of amygdaloidal basalt from the Sanhuti-River district. (Photograph by Mr. D. A. Wray.)*

the neighbourhood of the Monapo River—2 miles north-west of Mochelia—a narrow dyke of hornblende-andesite penetrates a sheet of amygdaloid (H.A. in fig. 1, p. 226), and Mr. Wayland found pebbles of pyroxene-andesite on the débris-strewn flats of the same district. Here also fragments of tephritic pumice are found, though again not *in situ*. This rock clearly indicates another line of variation which is more strongly represented in the north, for the late Mr. R. L. Reid discovered an interesting occurrence of phonolite associated with basalt and picrite-basalt in the neighbourhood of the Sanhuti River. Other rocks not found *in situ* are sölsbergite and ægirine-trachyte. Thus, there occur together, within the limits of what is a comparatively small volcanic field, lavas of both alkali and calc-alkali types.

VI. PERIOD OF ERUPTION.

The period of eruption of the amygdaloids cannot be definitely ascertained, but three lines of evidence point to their Tertiary, and almost certainly post-Oligocene, age.

Q. J. G. S. No. 287.

Fig. 5.—Sketch of the Mochelia Dyke penetrating Tertiary sandstones, by E. J. Wayland :
(for diagrammatic purposes vegetation is omitted).

(a) Evidence from Faulting.

In the district north of Mokambo Bay, between the Monapo and Mitikiti Rivers, sheets of amygdaloid are seen to lie successively on a surface of Cretaceous sandstones and limestones, and on far older crystalline rocks. At Mitikiti's Kraal, only occasional pebbles of agate and jasper remain to prove the former extension of the flows. The junctions between sandstone and limestone and between limestone and gneiss are faulted, and it is evident that denudation kept pace with the movement and reduced the various formations to a nearly plane surface before volcanic activity commenced. Unfortunately, it is not easy to determine the period of faulting. The Oligocene deposits of Lumbo, on the southern shore of Mosuril Bay, are probably faulted down against the Cretaceous sandstone, but the movement there may not have been simultaneous with that within the Cretaceous sediments, nor with that between the latter and the Pre-Cambrian complex. If it be conceded that all the faulting is of approximately the same period, the time of extrusion could not be earlier than the Oligocene; but, as this assumption is itself not securely founded, the evidence points to a period no more definite than post-Cretaceous.

(b) Evidence from the Age of Intruded Sediments.

The phonolite of the Sanhuti River and the amygdaloids throughout the area are necessarily post-Cretaceous, since they lie partly on a base-levelled Cretaceous platform. At Mochelia, however, Mr. Wayland found a number of dykes intrusive through sandstone and conglomerate, which he interpreted as

the shore-facies of the Oligocene deposits of Lumbo and Mozambique Island (fig. 5). From this more detailed evidence, a lower limit may be assigned to the period of vulcanicity, determining the age of the vulcanism as late Oligocene or post-Oligocene.

(c) Evidence from the Composition of the Oligocene Limestones.

In the Oligocene deposits of Mozambique Island and Lumbo, fragments of Cretaceous limestone occur that may be easily identified, although their size is small compared with the similar contained fragments in the Mochelia conglomerate. Now, if the conditions of denudation and deposition were such that pebbles of limestone were preserved, it seems reasonable to suppose that, if the amygdaloids had existed at that time, they would also have played some part in building up the Oligocene formations. At the present day, the rock-detritus that is distributed over the littoral plains at high-water level, invariably contains large numbers of agate- and jasper-pebbles; and similar, though less abundant, relics of igneous activity are found among the gravels of the numerous raised beaches which fringe the shore from point to point. Hence, since no trace of basalt nor of its siliceous amygdales have been detected in any of the Tertiary sediments, one may conclude with some confidence that the basalts had not then been extruded, and consequently that the period of their extrusion was late Oligocene or, more probably, post-Oligocene.

The phonolite and associated lavas from the Sanhuti district lie across the boundary between Cretaceous and Archæan rocks. Their age is, therefore, post-Cretaceous; but their relations to the far more abundant amygdaloids are as yet entirely unknown.

VII. ORDER OF ERUPTION, AND CLASSIFICATION.

The lavas from the Sanhuti mentioned above were collected by Mr. Reid during a journey to Mount Meza. In the case of three of his specimens, the order of eruption can be definitely stated. Near the base of the volcanic series, lying on a floor hidden by lateritic earth and gneissic débris, is a dark compact basalt containing rusty amygdales partly occupied by calcite. Both in the composition of the amygdale minerals and in its microscopical aspect, the rock differs conspicuously from all the other basalts of Mozambique. At a higher level a lava of lighter colour was met with. This is the phonolite, and it also contains calcite as the chief occupant of the vesicles. At the top of the series a black vesicular basalt was found. Owing to its extremely mafic character, it is here designated a picrite-basalt (see § XIII, p. 244). The specimens next collected include a fragment of amygdaloidal basalt rich in chaledony and heulandite. This rock is identical with the amygdaloidal basalts occurring elsewhere in the volcanic area, and was found *in situ* on a sedimentary basement.

It is interesting to notice that, in Abyssinia, W. T. Blanford found two equally contrasted series of lavas. The lower consisted

of amygdaloidal basalts remarkably similar to those of Mozambique, while the upper included extensive flows of trachyte and phonolite.¹ Thus in Abyssinia the evidence that the amygdaloids preceded a series of alkali-lavas is complete. Unfortunately, in Mozambique the observations hitherto made do not admit of so definite a deduction.

Of the remaining alkali-lavas described in this paper, none were found *in situ*.

South of the Monapo, the occurrence of a narrow dyke of andesite cutting a flow of amygdaloid leaves no doubt as to the succession.

A complete statement of the sequence of igneous rocks throughout the district cannot be given, but in the following synopsis the associations in three representative districts are enumerated. Names marked with an asterisk are of lavas not yet known *in situ* :—

	<i>Sanhuti District.</i>	<i>Sokoto District.</i>	<i>Monapo District.</i>
A.	Sölsbergite.* Picrite-basalt. Phonolite. Basalt.	Ægirine-trachyte.*	Tephritic pumice.*
B.	Amygdaloidal and vesicular basalts.	Amygdaloidal and vesicular basalts. Basalt sills and dykes.	Pyroxene-andesite.* Hornblende-andesite. Amygdaloidal and vesicular basalts. Basalt sills and dykes.

The amygdaloidal and vesicular basalts (which extend throughout the area) vary but little in respect of their basaltic framework. Such differences as have been noted depend on the proportion of brown glass, the sizes of crystals, and the degree of vesicularity. The amygdaloids are occupied by agate, jasper, and quartz, and by a variety of zeolites; moreover, the composition and the relative abundance of the amygdaloid-minerals constitute a second line of variation.

With the exception of the dyke of andesite already mentioned, all the dykes and sills encountered in the volcanic area are basaltic, and can be closely matched by rocks occurring as surface-flows. The reason for this is clear: the dykes and sills in most cases are exceedingly narrow, and they appear not to have been long separated by erosion from the overlying lava-sheets to which they served as feeders. The larger Mochelia dykes are free from vesicles; but all the other specimens collected contain a residuum of glass, and are minutely vesicular and amygdaloidal. A noteworthy feature is the general absence of zeolites from these small intrusions. Taking the basalts as a whole, a continuous series can be arranged, starting with the compact Mochelia basalt, passing through various vesicular and amygdaloidal types, and finishing with glassy scoriaceous basalts.

The lavas fall naturally into two main groups, designated as A & B in the list of types given below (p. 233). For petrographic description the following order will be adopted. In the cases

¹ 'Observations on the Geology & Zoology of Abyssinia' 1870, p. 182.

determined, the position and symbol of each rock in the quantitative (C. I. P. W.) system of classification is added:—

Rocks of Group A. (Alkali series and associated basalts).

Sölvbergite	Nordmarkose	I, 5, 1, 4.
Ægirine-trachyte	n. d.	
Trachytoid-phonolite	Umptekose	II, 5, 1, 4.
Tephritic pumice	Akerose	II, 5, 2, 4.
Basalt	Camptonose	III, 5, 3, 4.
Picrite-basalt	Auvergnose	III, 5, 4, 4.

Rocks of Group B. (Calc-alkali series).

Basalts: sills and dykes ..	Hessose	II, 5, 4, 4.
Basalts: lava-flows	Tonalose-bandose ..	II, 4, 3-4, 4.
Hornblende-andesite	Bandose	II, 4, 3, 4.
Ground-mass	Lassenose	I, 4, 2, 4.
Pyroxene-andesite	n. d.	

Petrographic Descriptions and Analyses.

Rocks of Group A.

VIII. SÖLVBERGITE. (Pl. XX, fig. 1.)

Two specimens (153¹ & 154) of sölvbergite were collected by the late Mr. R. L. Reid, between Miali and the Sanhuti River; but their source, which was possibly a dyke penetrating gneiss, was not discovered.

The rock has a mottled appearance in the hand-specimen, due to the alternation in ill-defined layers of dark-grey and straw-coloured patches. In this respect it bears a close resemblance to the type-rock of Gran, but it is heavier, darker, and more finely-grained than the latter. Small tabular phenocrysts of clear glassy anorthoclase are sparsely scattered through the rock, reaching 1 cm. in their largest dimension. Under the microscope the following minerals can be distinguished. Their approximate proportions by weight, measured by the Rosiwal micrometric method, are added:—

<i>Minerals.</i>	<i>Estimated Percentage by weight.</i>
Anorthoclase	77
Cossyrite (accompanied in small amount by katoforite and arvedsonite)	13
Ægirine and ægirine-augite	8
Magnetite (and ilmenite?)	2
Hæmatite?	n. d.
Zircon	n. d.
Total	100

Anorthoclase determines the texture of the rock, which is trachytic. The crystals are clear and unaltered, and have a

¹ These numbers in parentheses refer to specimens in the collection of Mozambique rocks studied by the author. The collection is at present in the Geological Department of the Imperial College of Science & Technology. When its investigation is completed, it is proposed to present the collection to the Mineralogical Department of the British Museum (Natural History).

prismatic habit, elongated parallel to the α axis. The three refractive indices are respectively slightly above, equal to, and slightly below 1.526 (monochlor benzol) according to the direction. Carlsbad twinning is common, but the fine striations due to albite twinning often seen in anorthoclase have not been detected. The extinction, however, is mottled and undulose. Small inclusions are present, frequently with a peripheral arrangement. Most of them are minute prisms of ægirine, but a few highly refractive blebs, which exhibit high polarization-colours, are probably zircon.

Cossyrite occurs in ragged patches, and in thin wedges occupying the angles between adjacent feldspars. Except in especially thin sections and near the edges, when the deep-red and brown pleochroism becomes visible, the mineral is practically opaque. Small grains of katoforite and arfvedsonite are associated with the more absorbent amphibole.

Ægirine and ægirine-augite lie among the feldspars in shreds and granular aggregates. The pleochroic scheme of the ægirine is as follows:—

x (nearly= c).....	blue-green.
$y=b$	yellow-green.
z (nearly= a) ...	yellow-brown.

Magnetite, probably titaniferous, is present in masses of about the same size as those of cossyrite. It can readily be distinguished from the latter by observation in reflected light. Red ferruginous stains accompany the amphiboles in some cases, and probably represent an excess of ferric oxide over that required for their crystallization.¹

Chemical Composition.

Analysis of a perfectly fresh specimen (153) gave the following results:—

	Percentages.	Molecular Proportions.		Mineral Composition (Norm).	
SiO_2	61.02	1.017	Quartz	1.74	} Salic =87.62.
Al_2O_3	17.11	.168	Orthoclase	26.69	
Fe_2O_3	4.37	.027	Albite.....	55.02	
FeO	3.42	.047	Anorthite	4.17	
MgO	0.63	.016			} Femic =12.00.
CaO	1.20	.021	Diopside.....	1.40	
Na_2O	6.51	.105	Hypersthene ...	3.28	
K_2O	4.47	.048	Magnetite	6.26	
$\text{H}_2\text{O} +$...	0.31	...	Ilmenite	1.06	
$\text{H}_2\text{O} -$...	0.33	...		99.62	
TiO_2	0.59	.007			
MnO	0.34	.005	Water.....	0.64	
Total	100.30		Total	100.26	
			Class I.....	Persalane.	
			Order 5 ...	Canadare.	
			Rang 1 ...	Nordmarkase.	
			Subrang 4	Nordmarkose.	

$\text{Ra} = 2.26 \times 10^{-12}$ grms. per grm.
Specific gravity = 2.58.

¹ For the primary character of hæmatite and limonite in certain igneous rocks, see G. M. Murgoci, Amer. Journ. Sci. ser. 4, vol. xx (1905) p. 145.

Several analyses of sölvbergite from other localities are tabulated below for comparison with the Mozambique example. All the analyses bear a close family resemblance, indicated in the quantitative classification by their falling into divisions I, 5, 1, 4, or II, 5, 1, 4. The Mozambique sölvbergite is richer in iron-oxides, both ferric and ferrous, than any other hitherto analysed. The abundance of ferrous iron, which is the more noteworthy, is clearly related to the dominance of cossyrite over the more usual ægirine, and in part to the presence of magnetite :—

	A.	B.	C.	D.	E.	F.
SiO ₂	61·02	63·74	65·46	64·28	64·92	58·90
Al ₂ O ₃	17·11	17·86	17·40	15·97	16·30	17·70
Fe ₂ O ₃	4·37	4·27	3·00	2·91	3·62	3·94
FeO	3·42	0·30	1·60	3·18	0·84	2·37
MgO	0·63	0·10	0·09	0·03	0·22	0·54
CaO	1·20	0·83	0·76	0·85	1·20	1·05
Na ₂ O	6·51	7·23	6·51	7·28	6·62	7·39
K ₂ O	4·47	5·19	4·74	5·07	4·98	5·59
H ₂ O	0·64	0·83	0·87	0·20	0·50	1·90
TiO ₂	0·59	tr.	0·24	0·50	...	0·40
P ₂ O ₅	n. d.	...	...	0·08	...	...
MnO	0·34	0·19	...	tr.	0·40	0·55
Totals.....	<u>100·30</u>	<u>100·54</u>	<u>100·67</u>	<u>100·35</u>	<u>99·60</u>	<u>100·33</u>

- A. Between Miali and the Sanhuti River, Mozambique (an. Holmes).
- B. Edda Gijorgis, Abyssinia (an. Prior).
- C. Camel's Hump, Victoria, Australia (an. Bailey, Lewis, & Hall).
- D. Andrews Point, Essex County, Mass., U.S.A. (an. Washington).
- E. Sölvberget, Gran, Norway (an. Schmelck).
- F. Kjøse, Aklungen, Norway (an. Schmelck).

IX. ÆGIRINE-TRACHYTE. (Pl. XX, fig. 2.)

Fragments of a porous lava with small phenocrysts of felspar (anorthoclase) and strongly developed flow-structure were found north of Sokoto Hill (151 & 152). Mr. Starey and I worked in the district for several weeks, but failed to discover the rock *in situ*. The weathered surface of the specimens collected has a rusty-red colour, broken by white-lined vesicles, the contents of which prove to be opal (refractive index between 1·446 = chloroform, and 1·472 = nut-oil). Within, the rock presents a mottled appearance, similar to, but more finely granular than, that of the sölvbergite just described. Specific gravity = 2·33.

Under the microscope the minerals that can be distinguished are anorthoclase, ægirine, cossyrite, magnetite, and opal. In addition, a great deal of an obscure brown alteration-product is present; similar material in the trachytes of the Great Rift Valley has been called 'ferrite' by Dr. G. T. Prior. As in the Rift-Valley rocks, so here, the 'ferrite' seems to be an alteration-product of cossyrite and other soda-amphiboles, for its mode of occurrence

is exactly paralleled by that of the soda-amphiboles in the other rocks of Group A.

Flow-structure is of two kinds, which merge one into the other. The first is determined by parallel laths of anorthoclase accompanied by radial growths of that mineral with ægirine, cossyrite, and 'ferrite,' occupying the wedge-shaped interstices. The second type of flow-structure is that which imparts to the rock its megascopic aspect. It is determined by the alternation of bands rich in prisms of ægirine, with bands containing long drawn-out vesicles now occupied by opal. The opalized bands are further characterized by abundant 'ferrite.' A subsidiary type of band is mainly composed of parallel laths of anorthoclase with cossyrite. Elsewhere the laths of anorthoclase, while presenting a general trachytic aspect, have crystallized in radial aggregates. The lava bears a close resemblance to the phonolitic trachyte from Lake Baringo described by Dr. G. T. Prior in 1903.¹

The radium-content of the rock was determined in 1913, and proved to be 2.83×10^{-12} grms. per gm. The silica percentage was found by the late Lieut. G. Kirby to be 64.51.

X. TRACHYTOID-PHONOLITE. (Pl. XX, fig. 3.)

The phonolites of the Sanhuti-River district (149 & 150) differ from the other lavas of Mozambique in two noteworthy respects. Large phenocrysts of clear glassy anorthoclase, an inch or more in length, are distributed through a grey ground-mass somewhat coarse in grain for a phonolite. Amygdales, averaging half an inch in diameter, are also scattered through the rock, and these are occupied by natrolite and calcite. The former mineral lines the cavities in aggregates of white fibres, leaving the bulk of the interior partly or wholly filled with calcite.

Under the microscope, the minerals recognized and their approximate percentages, determined by the Rosiwal micrometric method, are as follows:—

<i>Minerals.</i>	<i>Estimated Percentage by weight.</i>
Anorthoclase	33.8
Natrolite and isotropic material...	24.7
Nepheline	6.6
Ægirine and ægirine-augite	15.1
Katoforite	11.5
Arfvedsonite }	
Barkevikite }	
Cossyrite	4.3
Calcite	2.0
Magnetite and ilmenite	2.0
Apatite	n. d.
Total	100.0

The phenocrysts of anorthoclase are prismatic, elongated

¹ Min. Mag. vol. xiii (1903) p. 241.

along the *a* axis. Carlsbad twinning is common, but no twin striations can be detected. The refractive indices are the same as those of the sölvbergite feldspars. Small inclusions of the ground-mass are present, in which ægirine and magnetite can be seen. An analysis of the mineral for alkalies, made by Lieut. Angus McIntyre in 1913, yielded the following results:—soda = 6·68 per cent.; potash = 4·51 per cent.

The phenocrysts are surrounded by a narrow zone of kaolinization, which in places penetrates the interior along cleavage-cracks. Wherever kaolin is present, calcite is also found, sometimes in granular crystals, sometimes in crypto-crystalline aggregates with kaolin.

In the ground-mass small laths of anorthoclase are distributed in a mesh, which in texture falls between the trachytic and the intersertal types. Prisms of nepheline of similar dimensions are also present.

Soda-pyroxenes and amphiboles occupy the wedge-shaped spaces between the feldspars, but not completely. The ultimate base of the rock is a mineral, the refractive index of which lies between 1·482 and 1·478, and is identical with that of the natrolite found in the vesicles. Associated with this interstitial natrolite is an obscure isotropic substance. Its refractive index approximates to, but is higher than, that of the natrolite: it contains no chlorine, and is probably analcime or glass.

With the exception of cossyrite, which forms occasional small phenocrysts, the coloured minerals are all of later crystallization than the anorthoclase and nepheline. Grass-green ægirine is very abundant; but in most cases the colour is patchy, indicating association with ægirine-augite, which is pale green and gives a high extinction-angle. A few grains of augite, sometimes zoned, are also present. The pyroxenes are frequently included in the monoclinic amphiboles. Cossyrite, however, itself containing inclusions of ilmenite and apatite, is often surrounded by ægirine.

The pleochroism of katoforite, as exhibited in this rock, is variable; but the following scheme represents the usual distribution of colour (and also the maximum extinction-angle):—

$X \wedge a = 33^\circ$		straw-yellow to colourless.
$Y = b$		smoky red to purple-brown.
$Z \wedge c = 33^\circ$		greenish-yellow.

The birefringence is very low, and the refractive index is approximately that of monobrom-naphthalin, 1·66. Some of the grains and wedges of katoforite pass into arfvedsonite, orientated in parallel growth. Its pleochroism is in tints of lavender-grey X; violet Y; and yellow-green Z. The extinction-angle 16° differs markedly from that of katoforite, while the birefringence remains about the same. A few individuals that look like katoforite in ordinary light are probably barkevikite, for their polarization-colours are high. The extinction-angle could not be measured, but the refractive index was found to lie between those of monobrom-naphthalin = 1·66 and methylene iodide = 1·74.

Owing to the smallness of the grains and the lack of cleavage, the optical orientation of cossyrite could not be determined. The refractive index is near 1·66, but slightly higher. Pleochroism is in tints of deep brown, reddish-brown, and lighter brown, and can only be observed in a very thin section.

The first minerals to crystallize out were magnetite, ilmenite, and apatite, followed by phenocrysts of anorthoclase and cossyrite. After partial resorption of the phenocrysts, during which the anorthoclase suffered peripheral alteration to kaolin, the crystallization of the groundmass began. Nepheline and anorthoclase were followed in order by cossyrite, ægirine, katoforite, and arfvedsonite. Finally, natrolite, a little calcite, and an obscure isotropic substance filled up the still-unoccupied spaces; also natrolite and calcite were deposited in the vesicles.

Chemical Composition.

An analysis of fresh portions of No. 149, free from visible amygdalæ, gave the following results:—

Percentages.		Molecular Proportions.	Mineral Composition (Norm).	
SiO ₂	56·34	·939	Orthoclase	27·80
Al ₂ O ₃	17·86	·175	Albite	46 11
Fe ₂ O ₃	4·43	·028	Nepheline	8·52
FeO.....	3·81	·053	Anorthite	1·95
MgO.....	0·52	·013		
CaO.....	1·97	·036	Diopside	3·07
Na ₂ O.....	7·33	·118	Olivine	1·89
K ₂ O.....	4·72	·050	Magnetite	6·50
H ₂ O+.....	1·22	...	Ilmenite	1·22
H ₂ O-.....	0·82	...	Calcite	1·60
CO ₂	0·71	·016		
TiO ₂	0·67	·008		98·66
P ₂ O ₅	tr.	...		
MnO.....	0·28	·004	Water.....	2·04
Total	100·68		Total	100·70

Salic.

Femic = 14·28.

Ra = $4 \cdot 10 \times 10^{-12}$ grms. per grm.
Specific gravity = 2·47.

BHE

Class II..... Dosallane.
Order 5..... Germanare.
Rang 1..... Umptekase.
Subrang 4... Umptekose.

Analyses of similar rocks from neighbouring regions are quoted below for comparison. The Mozambique example is almost identical with the phonolite from Mount Kenya analysed by Dr. G. T. Prior. The similarity extends equally to the mineral composition. Dr. Prior has kindly allowed me to examine the phonolites from British East Africa in the Natural History Museum, and, except in texture, they bear a striking resemblance to the phonolite from the Sanhuti River. The latter rock, like the associated sölvbergite, is unusually rich in iron-oxides, this being due to the presence of magnetite as an accessory.

	A.	B.	C.	D.	E.	F.
SiO ₂	56·34	54·94	58·37	57·81	58·62	61·49
Al ₂ O ₃	17·86	19·34	16·65	18·74	21·50	18·25
Fe ₂ O ₃	4·43	1·80	4·09	5·76	0·47	1·77
FeO	3·81	4·52	3·03	0·42	3·65	3·13
MgO	0·52	1·11	0·37	tr.	0·56	0·41
CaO	1·97	2·05	1·66	1·28	0·88	1·65
Na ₂ O	7·33	8·39	7·28	9·35	7·95	6·78
K ₂ O	4·72	5·93	5·46	4·52	5·47	5·47
H ₂ O	2·04	0·32	2·36	1·50	1·12	0·26
TiO ₂	0·67	0·67	0·21	...	0·06	0·51
CO ₂	0·71	...	...	...	...	...
P ₂ O ₅	tr.	0·18	0·08	...	...	0·09
MnO	0·28	tr.	0·43	tr.	...	...
Totals.....	<u>100·68</u>	<u>99·90</u> ¹	<u>99·99</u>	<u>99·38</u>	<u>100·28</u>	<u>99·81</u>

¹ Including ZrO₂ = 0·38, and SO₃ = 0·27 per cent.

- A. Phonolite. Near the Sanhuti River, Mozambique (an. Holmes).
 B. Glassy katoforite-phonolite. W. Kibo, B.E. Africa (an. Eyme).
 C. Phonolite. Base of Mount Hohnel, Mount Kenya, B.E. Africa (an. Prior).
 D. Tinguaitite. Edda Gijorgis, Abyssinia (an. Prior).
 E. Phonolite. Nosy Komba, Madagascar (an. Pisani).
 F. Phonolitic trachyte. Ravin des Fleurs Jaunes, Réunion (an. Boiteau).

XI. TEPHRITIC PUMICE.

Among the detritus that litters the northern bank of the Monapo, near its entry into Mokambo Bay, numerous fragments of dark-grey pumice occur. Unfortunately the rock has nowhere been seen *in situ*, although it may be traced for a few miles along the northern bank of the river. It must, therefore, have come from the district between the Monapo and Murimatigri—an area originally covered by flows of amygdaloid, but now greatly dissected by erosion.

In chemical composition, the rock differs strikingly from the basalts and andesites of the neighbourhood, whereas it appears to be closely related to the alkali and associated lavas of the Sanhuti-River district.

Under the microscope, the rock is seen to be made up of a dense brown glass containing in places irregular patches of less intense colour, in which crystallization had just made a beginning. Within these local clearings, very minute crystals of magnetite or ilmenite and microlites of feldspar can just be seen under a quarter-inch objective. The feldspar shows no trace of twinning, but a maximum extinction-angle of 25° points to its identity as andesine. This result suggested that the rock might be an andesite-pumice. Against this view, however, was the fact that the radium-content of the lava was $2·59 \times 10^{-12}$ grms. per grm., a figure which would be surprisingly large for a rock of andesitic composition. In these circumstances it was thought

desirable to have the rock analysed. With the exception of the alkali determinations the analysis was made by my friend Dr. H. F. Harwood (Chemical Department, Imperial College of Science & Technology), and for his assistance I wish to express my grateful thanks.

Chemical Composition.

	Percentages.	Molecular Proportions.		Mineral Composition (Norm).	
SiO ₂	52·27	871	Orthoclase	18·90	
Al ₂ O ₃	17·70	·174	Albite	37·31	} Salic = 75·42.
Fe ₂ O ₃	7·01	·044	Nepheline	6·98	
FeO	4·48	·063	Anorthite	12·23	
MgO	1·79	·045	Diopside	10·90	} Femic = 23·99.
CaO	5·93	·105	Olivine	0·62	
Na ₂ O	5·95	·096	Magnetite	10·21	
K ₂ O	3·20	·034	Ilmenite	1·06	
H ₂ O+	0·37	...	Calcite	1·20	
H ₂ O-	0·43	...			
CO ₂	0·51	·012		99·41	
TiO ₂	0·56	·007			
MnO	tr.	...	Water	0·80	
Total	100·20		Total	100·21	

Ra = $2·59 \times 10^{-12}$ grms. per grm.
Specific gravity = 2·55.

Class II Dosulane.
Order 5 Germanare.
Rang 2 Monzonase.
Subrang 4 Akerose.

	A.	B.	C.	D.
SiO ₂	52·27	52·78	51·80	53·04
Al ₂ O ₃	17·70	19·08	17·90	17·34
Fe ₂ O ₃	7·01	3·63	3·10	2·12
FeO	4·48	3·79	4·36	6·96
MgO	1·79	1·58	3·72	2·49
CaO	5·93	5·09	6·59	5·86
Na ₂ O	5·95	7·95	4·74	5·61
K ₂ O	3·20	3·85	3·65	3·00
H ₂ O	0·80	0·44	2·87	0·37
CO ₂	0·51	0·10	...	...
TiO ₂	0·56	1·50	1·41	2·12
P ₂ O ₅	n. d.	0·63	...	0·83
MnO	tr.	tr.	...	...
Totals	100·20	100·75 ¹	100·14	99·74

¹ Including 0·33 per cent. of chlorine.

- A. Tephritic pumice, Monapo River, Mozambique (an. Harwood & Holmes).
B. Trachydolerite, Mount Meru, British East Africa (an. Maritz).
C. Essexite, Bekinkina, Madagascar (an. Pisani).
D. Olivine-trachyandesite, Vellouve, Réunion (an. Boiteau).

The most notable feature indicated by the analysis is the high

percentage of iron, and especially of ferric oxide. This characteristic distinguishes the rock from the trachyandesites and trachydolerites, and suggests that the name tephrite would be somewhat more appropriate. According to Dr. H. S. Washington,¹ the name trachydolerite should be restricted to rocks containing labradorite or a more basic plagioclase, as well as alkali-felspars; and the name trachyandesite to rocks containing andesine in addition to alkali-felspars: both types of rock, moreover, should be rather rich in potash. But for the high iron-content, the composition of the rock now described would fulfil moderately well the conditions for a trachyandesite. Its close similarity to the trachyandesite from Réunion (analysis D) bears out this opinion, but the chemical characters of the rock are probably expressed more accurately if it be named a tephritic pumice.

XII. BASALT. (Pl. XX, fig. 4.)

The lava-flow represented by specimen 156 was found by Mr. R. L. Reid at the base of the volcanic succession in the Sanhuti-River district. It is exposed on the north side of the river near the boundary-fault, where it lies on a basement of gneiss, and probably extends to the Cretaceous sediments on the east. The basalt is a dense dark-grey rock holding rusty amygdales that average $\frac{1}{8}$ inch in diameter. The amygdales are lined and sometimes entirely filled by palagonite, which in thin section varies in colour from yellowish green to reddish brown, though in the hand-specimen, beneath the rusty shell of iron-oxides, it is nearly black. The specific gravity is about 2.42, thus agreeing closely with that of the palagonite from Cape Flora (Franz Josef Land) examined by Sir Jethro Teall.² The same material occurs in the main body of the rock, wedged in the crystalline network of the ground-mass.

The only other minerals found in the amygdales are thomsonite, easily recognizable by its moderately-high double refraction, and calcite. Thomsonite occurs in radiating aggregates, each acicular crystal giving straight extinction. The refractive index, about 1.52, is low for thomsonite, and points to a high content of soda.

Excluding the amygdales, the mineral composition of the rock, determined by the Rosiwal method, is approximately as follows:—

<i>Minerals.</i>	<i>Estimated percentage by weight.</i>
Labradorite	56
Augite	24
Palagonite	15
Magnetite, ilmenite, ³ and decomposition-products	5
Total.....	100

¹ Journ. Geol. Chicago, vol. v (1897) pp. 366–68.

² Q. J. G. S. vol. liii (1897) p. 486.

³ The percentage of these minerals is greater than 5, for only a few of the inclusions in felspar and augite could be measured.

The rock is for the greater part very fine-grained, but in places small ophitic patches occur, never more than $\frac{1}{4}$ inch long, in which the texture is much coarser (see Pl. XX, fig. 4). On an average, two of these patches may be seen in a section of half a square inch. In the direction of the greatest extension the ophitic texture seems to have been broken up, perhaps by flow, for porphyritic crystals of labradorite and augite stream away into the fine ground-mass. At right angles to this direction similar porphyritic crystals occur, but less abundantly. In the ophitic patches, as usual, the felspar was the first mineral to crystallize (except for a few skeleton-crystals of magnetite or ilmenite which form rare inclusions). The porphyritic crystals are sometimes composite, and here too the felspar preceded the augite. In the ground-mass, on the contrary, the augite began its crystallization before the felspar (and continued beyond the latter), and the texture is minutely intersertal. It is clear, therefore, that two distinct periods of crystallization are represented, and that these took place under conditions sufficiently different to affect not only the grain and texture, but also the order of crystallization of the two chief minerals.

The felspar of each generation is labradorite, but the early crystals are richer in the anorthite molecule than the later. In the former, which are characterized by broad albite twinning and absence of zoning, the average refractive index is 1.57. All the felspars are clear and glassy, and are nearly free from inclusions except around the borders of the smaller laths, where innumerable dark globules associated with tiny green blebs of augite obscure the edges. Only in the neighbourhood of the inclusions is there any trace of alteration, the body of the felspars being perfectly fresh.

Augite also shows a slight difference in composition, according to the time of its crystallization. The ophitic plates and larger crystals are grey-green, while the small granules of the ground-mass frequently exhibit a brown or even a purple madder tint.

Magnetite and ilmenite began to crystallize before the other minerals of the rock, but continued beyond them. They occur in skeleton-crystals and in small irregular masses, and probably the dark globules that border the felspars and fringe the edges of the palagonite wedges represent the final attempts of the same minerals to crystallize: for, where they occur in palagonite, the colour of the latter is paler than elsewhere.

Besides palagonite, there is a small amount of obscure interstitial matter, some of which is colourless and feebly birefringent, thus suggesting that it may be a zeolite or possibly orthoclase. A green alteration-product also occurs, and may be serpentine or chlorite.

There is nothing to suggest that palagonite has been produced by the weathering of an original glass. Glass does not occur in this rock; but, in many of the vesicular basalts belonging to the second stage of eruption, glass occurs abundantly, and when it

weathers it changes in the direction of laterite, not of palagonite. The latter substance appears generally to be associated with amygdaloidal basalts, not with vesicular types. The formation of palagonite, like that of amygdaloidal infillings, is therefore to be ascribed to a concentration of water (and possibly of other volatile fluxes) in the residual liquors left in the crystal network of the nearly consolidated rock. In the present case, the occurrence of thomsonite with palagonite is significant, on account of the light that it throws on the origin of the alkali rocks which succeeded the basalt. Thomsonite may contain as much as 7 or 8 per cent. of soda, and the low refractive index of the present example suggests that it is a soda-rich variety. Moreover, palagonite often contains 4 per cent. of soda or more. In contrast with these figures, the rock itself (including a certain amount of interstitial palagonite) contains only 3·29 per cent. of soda, showing that the progress of crystallization led to an enrichment of the residual liquors in soda. The same conclusion would be deduced from the characters of the two generations of plagioclase. Thus, even within the limits of a lava-flow that has rapidly cooled, it is possible to discern a process of differentiation which, on a larger scale and with slower cooling, should result in the production of a magma relatively rich in soda. It is, surely, more than a mere coincidence that the magma erupted next in succession was that which crystallized as the phonolite already described.

Chemical Composition.

Portions of specimen 156, visibly free from amygdaloes and weathered crust, were crushed and analysed. The results obtained are as follows:—

	Percentages.	Molecular Proportions.		Mineral Composition (Norm).	
SiO ₂	48·82	·814	Orthoclase	8·34	{ Salic =60·57.
Al ₂ O ₃	15·93	·156	Albite	27·77	
Fe ₂ O ₃	7·18	·045	Anorthite	24·46	
FeO	6·63	·092			
MgO	6·02	·151	Diopside	13·79	{ Femic =38·38.
CaO	8·67	·155	Hypersthene ...	7·84	
Na ₂ O	3·29	·053	Olivine	4·79	
K ₂ O	1·41	·015	Magnetite	10·44	
H ₂ O+	0·98	...	Ilmenite	1·52	
H ₂ O-	0·54	...			
TiO ₂	0·83	·010		98·95	
MnO	0·32	·004	Water	1·52	
Total	100·62		Total	100·47	
			Class III ...	Dosalane.	
			Order 5	Gallare.	
			Rang 3	Camptonase.	
			Subrang	Camptonose.	

Ra=1·38 × 10⁻¹² grms. per grm.
Specific gravity=2·78.

	A.	B.	C.	D.	E.
SiO ₂	48·82	47·20	46·36	50·22	49·43
Al ₂ O ₃	15·93	15·29	16·70	16·20	12·73
Fe ₂ O ₃	7·18	9·57	7·53	3·13	5·06
FeO	6·63	6·13	6·23	8·07	8·47
MgO	6·02	5·90	5·84	7·54	6·96
CaO	8·67	8·93	9·77	8·57	8·59
Na ₂ O	3·29	3·61	3·22	3·36	3·50
K ₂ O	1·41	0·85	1·12	1·38	1·21
H ₂ O	1·52	1·12	0·35	0·22	1·84
CO ₂	...	...	...	...	0·28
TiO ₂	0·83	1·14	1·88	1·95	2·26
MnO	0·32	...	...	...	0·08
P ₂ O ₅	...	0·46	0·58	...	0·49
Totals.....	<u>100·62</u>	<u>100·20</u>	<u>99·58</u>	<u>100·64</u>	<u>100·90</u>

A. Basalt, Sanhuti River, Mozambique (an. Holmes).

B. Basalt, Philippi Lake, Kerguelen Island, South Indian Ocean.

C. Basalt, Mount Drygalski, Heard Island, South Indian Ocean.

D. Basalt, Glass, Cockburn Is., Louis-Philippe Land, Antarctica (an. Prior).

E. Basalt, Yandina, Queensland (an. Jensen).

The composition of the basalt is in no way abnormal, and can be closely matched by that of other basalts from many other localities. Some of these are cited above for comparison with the Sanhuti example. The closest resemblance is found in the case of basalts from the islands of the South Indian Ocean.

XIII. PICRITE-BASALT. (Pl. XX, fig. 5.)

Overlying the phonolite, described above, is a nearly black vesicular rock. Most of the vesicles are empty, but a few are occupied by a powdery form of phillipsite. The refractive index of the mineral is 1·53, its double refraction is very low, and the cleavage is good.

In thin section the minerals present and their relative proportions, determined by the Rosiwal method, are as follows :—

	Minerals.	Percentage by volume.
Phenocrysts	Titaniferous augite	21
	Olivine	14
Ground-mass	Labradorite	65
	Titaniferous augite	
	Magnetite and ilmenite	
	Isotropic base	
Total		<u>100</u>

The rock is conspicuously porphyritic, though augite alone is represented in two generations. Olivine, in clear colourless crystals, which have suffered some resorption but practically no serpentization, is present only as phenocrysts. Labradorite,

on the contrary, occurs only in tiny laths distributed sparsely through the ground-mass. Purple-brown augite is the most abundant mineral present, and bears a close resemblance to the augite described by Dr. A. Scott¹ from the Arenig augite-andesites of Bail Hill (Dumfries-shire). The crystals have a tendency to group together in a roughly radial fashion about a central nucleus of olivine. In the ground-mass small grains of deep-purple augite are very abundant. Whether the purple coloration of certain augites is due to the presence of titanium or manganese cannot yet be definitely stated. The usual belief that it is due to the former element is supported by the analyses tabulated in this paper, but the subject is one that still awaits systematic investigation. The ground-mass is very fine-grained, and dark owing to the abundance of magnetite and ilmenite, which are present in well-shaped crystals and in a dendritic network of branching rods. Iron-ores, titaniferous augite, and a sprinkling of labradorite-laths are crowded together in a residuum of grey-brown glass. In sporadic patches labradorite becomes sufficiently abundant to control the texture, which is then not unlike that of the intersertal basalts described below.

Chemical Composition.

Portions of specimen 155, free from phillipsite, were analysed with the following results:—

	Percentages.	Molecular Proportions.		Mineral Composition (Norm).	
SiO ₂	44·05	·734	Orthoclase	4·00	} Salic =46·27.
Al ₂ O ₃	13·39	·131	Albite	16·83	
Fe ₂ O ₃	7·64	·048	Anorthite	25·44	
FeO.....	8·42	·117			
MgO.....	10·51	·263	Diopside	21·06	} Femic =53·10.
CaO.....	10·46	·187	Hypersthene ...	3·79	
Na ₂ O.....	2·01	·032	Olivine	13·46	
K ₂ O.....	0·67	·007	Magnetite	11·14	
H ₂ O+.....	0·44	...	Ilmenite	3·65	
H ₂ O—.....	0·47	...			
TiO ₂	1·93	·024		99·37	
MnO.....	0·25	·003	Water.....	0·91	
Total	100·24		Total	100·28	

Ra=0·47×10⁻¹² grms. per grm.
Specific gravity=2·78.

Class III ... Salfemane.
Order 5 ... Gallare.
Rang 4 ... Auvergnase.
Subrang 4 ... Auvergnose.

The rock is similar, both chemically and mineralogically, to the Hillhouse or picrite type of the Scottish Carboniferous basalts.² Chemically, it bears some resemblance to the camptonite of Kjøse Aklungen (Norway),³ and this is the more interesting because the

¹ Min. Mag. vol. xvii (1914) p. 100.

² G. W. Tyrrell, Trans. Geol. Soc. Glasgow, vol. xiv (1912) p. 228 (Analysis II, p. 250).

³ W. C. Brögger, 'Eruptivgesteine des Kristianiagebietes: III' 1899, p. 51.

frequent association of camptonite and bostonite is in the Sanhuti-River district paralleled by the association of picrite-basalt and sölvbergite. The rock is also very similar to the limburgites of the Macedon District, Victoria¹ (Tertiary alkali series), which, like the Mozambique picrite-basalt, are associated with anorthoclase-bearing rocks. The main outstanding feature of the analysis is the high percentage (for this class of rock) of ferric oxide. This is due to the preponderance in the rock of augite, and to the abundance of magnetite. Titaniferous augites frequently show an excess of ferric over ferrous iron; the Bail-Hill example is a case in point.

Rocks of Group B.

XIV. BASALTS: SILLS AND DYKES. (Pl. XX, fig. 6 & Pl. XXI, fig. 1.)

The specimens collected² are slightly vesicular rocks from the following localities:—

128, 129, 130.	Sill, west side of Sokoto Hill, at the base.	} Dark grey.
142.	Dyke, near Ibrahimo.	
141.	Dyke, Mochelia (reddish brown).	

These rocks are of even grain and fine texture, and consist essentially of a mesh of lath-shaped feldspars, between which groups of granular augites are contained. Olivine has in all cases been altered to serpentine, and the latter is only a minor constituent. Filling up the interstices of the crystalline network is a grey-brown glass swarming with dark globulites, or with branching sprays of magnetite. Examined closely, specimens from Sokoto Hill and Ibrahimo are seen to be pitted with minute green-lined vesicles or amygdales. The first stage in the infilling of the latter is represented by a fibrous green mineral. The same mineral occurs in greater quantity in the amygdaloids; and, since it contains alumina and has a refractive index greater than 1.576, it may be referred to one of the chlorites. The main body of the amygdale occasionally consists of brown or greenish-brown palagonite; but more usually it is occupied by chaledony, with which opal is sometimes associated. The minute amygdales of the Mochelia dyke appear to be free from a chloritic lining.

The feldspar occurs chiefly in small tabular crystals accompanied by a sprinkling of larger individuals, indicating an approach to porphyritic texture. This appearance is intensified by the bunching together of some of the smaller crystals in parallel or divergent series. Extinction-angles, twinning, and refractive index (1.560) show that the species is labradorite. Many of the larger crystals enclose patches and shreds of chlorite, and lines of globulitic glass-inclusions immediately within their outer borders

¹ H. S. Summers, Proc. Roy. Soc. Vict. n. s. vol. xxvi (1914) p. 278.

² A number of dark compact dyke-rocks collected by Mr. Wray (from the district of Fernão Velloso Harbour and from Makulia farther north) were lost during transit to England.

are common. Otherwise, the feldspars are clear and glassy, and show no traces of alteration.

While most of the feldspar came early in the order of crystallization, there is another member of the feldspar family which is allotriomorphic, and was the last of the minerals to crystallize. It is free from twin lamellæ, exhibits lower polarization-colours than labradorite, and has a refractive index of 1.522. Its identity is thus determined as orthoclase, which is further verified by the relatively high percentage of potash contained in the rocks.

Augite is pale yellowish-green (iron-stained round the borders in the Mochelia rock), and exists in rounded grains or sharply-defined wedges determined by the disposition of the feldspar-laths. It is probably a member of the enstatite-augite series. The intersertal texture thus produced is a marked characteristic of nearly all the Mozambique rocks.

Magnetite, perhaps accompanied by ilmenite, is evenly distributed in small octahedra, irregular grains, and skeleton-crystals. It tends to cling round the augite-crystals, but rarely forms inclusions in them, and never does so in the labradorite. In the Mochelia rock, magnetite is very abundant inside dark patches of glass or palagonite. The mineral certainly belongs to a late stage in the crystallization of the rock.

Dark interstitial matter occupies nearly a quarter of the volume of the rocks, being, however, much less abundant than in the lavas. Some of this material is an isotropic glass packed with globulites, or penetrated by a network of iron-ores. In other cases, microlites of feldspar and obscure aggregates of dark augite are buried in a pale glass. Palagonite is also present in deep-brown or greenish patches, which under crossed nicols are seen to have a fibrous cryptocrystalline texture.

By means of a diffusion-column of methylene iodide and benzene, the constituents of the Sokoto-Hill rock (128) were separated into the following groups. The approximate proportions of each mineral, measured by micrometric analysis, are added:—

Mineral Composition of No. 128.

<i>Specific Gravity.</i>	<i>Mineral.</i>	<i>Percentage by weight.</i>
2.20.....	Opal	3
2.35 }	Glass and palagonite	20
2.45 }		
2.56.....	Orthoclase.....	6
2.62 }	Chalcedony and chlorite	7
2.65 }		
2.68 }	Labradorite	40
2.70 }		
3.10 }	Enstatite-augite	18
3.20 }		
Sank	Magnetite and ilmenite with glass.....	6
		Total..... 100

Taking the specific gravity of the material that sank as 5, the specific gravity of the rock should be 2.74. The actual value, 2.70, corresponds with the slightly vesicular character of the rock.

Chemical Composition.

The Sokoto-Hill and Mochelia basalts were analysed with the results tabulated below. The analysis of the former rock was made under my direction by my former students, Lieut. J. L. Harris, M.C., the late Lieut. G. Kirby, and Mr. E. Spencer:—

Sokoto Hill, 128.

		Molecular	Mineral Composition	
Percentages.		Proportions.	(Norm).	
SiO ₂	52.42	.874	Quartz.....	3.75
Al ₂ O ₃	17.40	.171	Orthoclase.....	10.01
Fe ₂ O ₃	4.21	.026	Albite.....	22.53
FeO.....	5.16	.072	Anorthite.....	30.58
MgO.....	5.30	.132	Diopside.....	12.10
CaO.....	9.08	.163	Hypersthene.....	12.66
Na ₂ O.....	2.65	.043	Magnetite.....	6.05
K ₂ O.....	1.77	.018	Ilmenite.....	1.22
H ₂ O.....	1.26	...		
TiO ₂	0.67	.008		98.90
MnO.....	0.24	.003	Water.....	1.26
Total.....	100.16		Total.....	100.16

Ra = 0.98×10^{-12} grms. per grm.
Specific gravity = 2.70.

Class II..... Dosalan.
Order 5..... Germanare.
Rang 4..... Hessase.
Subrang 4..... Hessose.

Mochelia, 141.

		Molecular	Mineral Composition	
Percentages.		Proportions.	(Norm).	
SiO ₂	51.21	.854	Quartz.....	0.99
Al ₂ O ₃	17.99	.176	Orthoclase.....	6.12
Fe ₂ O ₃	4.63	.029	Albite.....	22.63
FeO.....	5.81	.081	Anorthite.....	34.80
MgO.....	6.11	.153		
CaO.....	9.36	.167	Diopside.....	10.96
Na ₂ O.....	2.92	.047	Hypersthene.....	16.75
K ₂ O.....	1.03	.011	Magnetite.....	6.73
H ₂ O+.....	0.32	...	Ilmenite.....	0.76
H ₂ O-.....	0.72	...		
TiO ₂	0.42	.005		99.74
P ₂ O ₅	tr.	...		
MnO.....	0.27	.004	Water.....	1.04
Total.....	100.79		Total.....	100.78

Ra = 0.85×10^{-12} grms. per grm.
Specific gravity = 2.72.

Class II..... Dosalan.
Order 5..... Germanare.
Rang 4..... Hessase.
Subrang 4..... Hessose.

For comparison, the analyses are repeated below with others of the same type. The occurrence of a similar basalt in Somaliland¹ is interesting, for it preceded the eruption of a series of alkali

¹ A. de Gennes & A. Bonard, C. R. Acad. Sci. Paris, vol. cxxxi (1900) p. 196.

rocks of the same type as those found in the north of the Mozambique area. Microscopically, the east-and-west dykes of Northumberland—Crookdene, Collywell, and Tynemouth¹—are very similar to those described here.

	A.	B.	C.	D.	E.
SiO ₂	51·21	52·42	49·47	51·31	51·20
Al ₂ O ₃	17·99	17·40	18·70	14·55	18·89
Fe ₂ O ₃	4·63	4·21	15·05	...	7·57
FeO	5·81	5·16	...	9·02	...
MgO	6·11	5·30	5·34	6·85	6·75
CaO	9·36	9·03	8·90	11·61	10·52
Na ₂ O	2·92	2·65	2·87	1·79	1·71
K ₂ O	1·03	1·77	0·79	0·60	0·51
H ₂ O	1·04	1·26	0·81	1·41	1·70
TiO ₂	0·42	0·67	...	1·00	1·14
P ₂ O ₅	tr.	...	...	...	...
MnO	0·27	0·24	...	0·47	...
CO ₂	...	...	...	1·47	...
Totals	<u>100·79</u>	<u>100·16</u>	<u>101·93</u>	<u>100·08</u>	<u>99·99</u>

A. Dyke, Mochelia (an. Holmes).

B. Sill, Sokoto Hill (an. Harris, Kirby, & Spencer).

C. Basalt, Kallele River, 56 miles from coast, Somaliland.

D. Crookdene Dyke, Northumberland (an. Smythe).

E. Tynemouth Dyke, Northumberland (an. Stead).

Contact-Metamorphism.

The metamorphism of the sediments through which the dykes and sills intrude is everywhere of a simple character. Usually, the changes are restricted to bands extending only a few inches on each side of the contact. Limestones are recrystallized to granular calcite, and in places crystals of quartz are developed, indicating the percolation of silica-bearing solutions from the lavas. Mr. Wayland found that the upper part of a dyke, intrusive into calcareous sandstone near Mochelia, had been removed by weathering, thus exposing the sandstone walls which had enclosed it. Upon these well-marked hexagonal jointing had been superinduced.

Near the contact of this dyke steam-holes have been developed in the sandstone, and these are now filled with opal and chalcedony, the latter being pale brown owing to the incorporation of limonite which was present in the original cement. Examination of the unaltered sandstone in thin section shows that it consists of slightly rounded grains of quartz, orthoclase, and microcline, cemented together by calcite and limonite. Small nummulites are found embedded in the cement. Near the dyke, calcite is replaced by opal, the metasomatism having equally affected the nummulites. In the amygdaloids of the sandstone, opal was first deposited, chalcedony followed, and the infilling was completed by a clear mosaic of quartz. (See Pl. XXI, fig. 2.)

¹ M. K. Heslop & J. A. Smythe, Q. J. G. S. vol. lxvi (1910) p. 3.

XV. BASALTS: LAVA-FLOWS. (Pl. XXI, fig. 3.)

The specimens collected include the following:—

- 124. Brown amygdaloidal basalt, near the bend of the Monapo River, south side.
- 125. Red amygdaloidal basalt, between Mochelia and Mitikiti (penetrated by an andesite dyke).
- 131. Purple vesicular amygdaloidal basalt; half a mile south of Sokoto Hill.
- 132. Purple vesicular basalt; three-quarters of a mile west of Sokoto Hill.
- 133. } Brown amygdaloidal basalt; south-east of Ibrahimio.
- 134. }
- 135. }
- 136. Purple vesicular amygdaloidal basalt; east of Murimatigri.
- 145. Purple-brown amygdaloidal basalt; near the Sanhuti River.
- 146. Grey-black vesicular basalt; near the Sanhuti River.

One of the best and most continuous exposures of amygdaloidal and vesicular basalts is to be found between the Monapo and Mitikiti Rivers. Numerous small streams and long alluvial flats, connected with the sea by way of mangrove swamps, cut up the flows, and sometimes expose the underlying floor of shale or limestone. In places, hard dykes stand out in ridges running nearly due north and south. The basalt is a rough purplish-grey rock, sometimes dull and earthy at the surface, but often glazed by the deposition of a thin film of lateritic constituents. Along the military road (made in 1910) which skirts the northern shore of Mokambo Bay, the freshly-broken rocks could be admirably seen *in situ*. The colour of the unweathered rock is there purple or reddish-brown, variegated by the green linings of the amygdales and brightened by the sparkling cleavage-surfaces of innumerable crystals of zeolites, such as heulandite. Similar exposures were examined east of the forts at Murimatigri and Ibrahimio, and in the Sokoto-Hill district. The thickness of the flows is now very variable and much reduced by erosion, but it was nowhere seen to exceed about 40 feet.

The lavas are characterized by a high proportion of glass—dark red-brown to black—and by a strong development of vesicles and amygdales. The chief minerals present in the latter are chlorite, zeolites, and various forms of silica. It is noteworthy that calcite is extremely rare. Chalcedony is very abundant, and occurs in a great variety of forms including waxy carnelian, red and green jaspers and bloodstones, and beautifully banded agates. The interior of many of the siliceous amygdales is occupied by a mosaic of quartz. In other cases, where a hollow cavity has been left, well-formed crystals of quartz, or zeolites, project from the sides. Among the agates and jaspers found in the alluvium flanking the Monapo, Mr. Wayland discovered a number of worked stones and implements. These are figured and described in an interesting paper, published in 'Man,' July 1915, p. 57.

Under the microscope the minerals seen are identical with those of the dyke-rocks already described. The feldspars in some

specimens are microporphyritic, and the smaller crystals are frequently grouped together in glomeroporphyritic clusters. Where individuals of markedly different size come into contact in parallel positions, the Becke test indicates that the larger crystals possess a slightly higher refractive index than their smaller neighbours. This evidence, implying that crystals of the second crop are slightly richer in the albite-molecule than those of the first, is interesting, in view of the fact that the zeolites of the amygdalae are predominantly lime-bearing varieties. Some of the larger crystals of labradorite—especially in the neighbourhood of well-filled amygdalae—are replaced by chalcedony, and veined and streaked with chlorite. Signs of weathering, however, are rarely met with.

Augite is present in colourless or yellowish-green grains and aggregates, the colour tending to deepen towards the outer borders, which are often ill-defined and merge imperceptibly into the surrounding glass. In the dark reddish- or greenish-brown glass that occupies the interstices of the crystal network, minute dendritic sprays of magnetite and innumerable globulites are present, particularly around the borders of ill-defined felspar- and augite-crystals. It is worthy of notice that the glass around the larger vesicles is frequently very dense and undifferentiated. This effect is doubtless due to the local cooling set up by the sudden expansion of the volatile constituents of the erupted magma.

Only the amygdale minerals remain to be considered. The vesicles in which they occur are of two strongly-contrasted types:—

- (a) Well-shaped and smoothly-lined spaces easily visible to the naked eye in thin sections (Pl. XXI, fig. 4), and in hand-specimens extending in dimensions up to the size of the closed fist.
- (b) Minute branching interspaces with obscure and irregular borders, connecting sometimes with the larger vesicles, and sometimes with small cracks and fissures that cut abruptly across the texture of the rock.

The minerals found in the amygdalae are chlorite, heulandite, laumontite, natrolite, opal, chalcedony, quartz, calcite, and gypsum. In good exposures, such as that on the Mochelia road, it can be seen almost at a glance that zeolites are by far the most abundant of the amygdale minerals, and that of the zeolites heulandite is the chief member. In the associated surface-débris, the zeolites must soon fall a prey to decomposition, and consequently forms of silica greatly predominate, giving the erroneous impression that the parent amygdalae were mainly siliceous. In hand-specimens the order of infilling is found to be (1) chlorite, (which appears also in later stages), (2) zeolites, and (3) silica.

Palagonite sometimes occurs in minute vesicles; but, with the exception that it is occasionally replaced by chalcedony, it is unaccompanied by zeolites or other minerals. Chlorite is the usual lining material, and in vermicular aggregates it is often present in heulandite and chalcedony.

Heulandite ($\text{CaAl}_2\text{Si}_8\text{O}_{16}\cdot 5\text{H}_2\text{O}$), with its bright cleavage-surfaces and pearly lustre, occurs in great abundance throughout the area, from Mokambo Bay to the Sanhuti River. Cleavage-flakes give good biaxial figures, which are optically positive. The refractive index is 1.5 and the extinction-angle practically straight. Heulandite is frequently followed (for instance in 125*a*) by downy sheaves and radiating granules of yellow laumontite ($\text{CaAl}_2\text{Si}_4\text{O}_{12}\cdot 4\text{H}_2\text{O}$). Individual crystals are so small that a qualitative analysis was necessary to complete the identification. The mineral gelatinizes with hydrochloric acid, and contains alumina, iron-oxide, lime, and much water. The refractive index averages 1.52.

In one specimen divergent aggregates of stilbite were found on heulandite, and were distinguished from the latter by the larger extinction-angle, and by the fact that cleavage-flakes do not show a complete biaxial figure. All the zeolites were carefully tested for soda, but of the three already mentioned it was detected only in stilbite; natrolite ($\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} + 2\text{H}_2\text{O}$), on the other hand, is free from lime. Slender needle-like crystals of this mineral are found on heulandite, and in No. 136*b* radiating sheaves of natrolite complete the filling of vesicles already lined with heulandite. The refractive index is 1.47, and the extinction is straight.

Heulandite is frequently replaced by opal, chalcedony, and quartz, and in some sections (as, for example, in 136, Pl. XXI, fig. 4) it is clear that the change began at the walls of the amygdalae and developed inwards. There is no evidence that the other zeolites have been similarly replaced, but both laumontite and natrolite are sometimes succeeded by chalcedony and quartz. Calcite is exceedingly rare, and it has only been found in one specimen (No. 136*b*), in which it was deposited in minute crystals on quartz. Gypsum is also rare, but was met with in some of the sections in narrow veins cutting through everything from heulandite to quartz. The order of deposition in the vesicles may now be stated for a number of typical cases. Chlorite is omitted, as it is liable to appear at any or every stage up to quartz.

No. 125 <i>a</i> .	No. 133.	No. 136 <i>a</i> .	No. 136 <i>b</i> .	No. 125 <i>b</i> .
Heulandite.	Heulandite.	Heulandite.	Heulandite.	
Laumontite.	Stilbite.		Natrolite,	
		Opal.		Opal.
Chalcedony.			Chalcedony.	Chalcedony.
Quartz.			Quartz.	Quartz.
Gypsum.			Calcite.	Gypsum.

The most striking feature of this suite of minerals is the predominance of lime and silica, and the rarity of alkali and carbonate minerals. The sequence in No. 136*b* is significant, for natrolite free from lime follows heulandite free from soda, while finally calcite appears. In the Sanhuti basalt (p. 241), thomsonite rich in soda is followed by calcite. In the phonolite from the Sanhuti district, natrolite is followed by calcite. There is thus a notable

difference, which may be of great significance, between the vesicle-minerals of the Sanhuti lavas and those of the amygdaloids. On the one hand, is a series of lavas including types rich in alkalis in which soda-zeolites and calcite occupy the vesicles; on the other, is a series of typically calc-alkali lavas in which the vesicles are occupied by lime-zeolites and forms of silica. These two associations, which can be matched in other regions, seem to indicate that among the volatile fluxes of the alkali series carbon dioxide was a dominant member, whereas among those of the calc-alkali series water was the chief constituent, carbon dioxide being absent, or of minor importance.

The order of infilling is closely parallel to that determined in many other localities where the same minerals are represented. As long ago as 1849 Breithaupt¹ recognized the sequence from heulandite to stilbite (given in the original nomenclature as stilbit to desmin). In the Watching basalt, New Jersey, C. N. Fenner² shows that heulandite may be followed by laumontite, stilbite, or natrolite. At the well-known locality of Carnmoney Neck (Antrim), the order of infilling is given by J. Strachan³ as (*a*) hullite and dellesite, (*b*) zeolites, (*c*) chalcedony and quartz.

The circulating solutions of the Mozambique amygdaloids appear to have become saturated in alkaline constituents only towards the end of the period of zeolite deposition. C. Doelter has shown⁴ that natrolite is deposited from solutions of soda, alumina, silica, and water at temperatures below 190° C. Above that temperature analcime is formed. The presence of gypsum among the end-products gives another point on the temperature-scale. Van't Hoff⁵ investigated the relations of gypsum and anhydrite, and found that the latter mineral is deposited in place of gypsum if the temperature exceeds 63·5° C. In the presence of alkali salts the temperature of the transition-point is lowered. The stage of silica deposition falls between those of natrolite and gypsum, and at such low temperatures it is difficult to understand why the silica was not all deposited as opal, unless it is assumed that alkalies were present. G. Spezia⁶ has shown that opal is deposited at moderately low temperatures from siliceous solutions, but that, when alkalies are present, quartz forms instead. Opal already deposited may be transformed into quartz by the action of a hot solution of sodium silicate. The order commonly observed in siliceous amygdaloids (opal—chalcedony—quartz) seems, therefore, to imply a growing concentration of soda in the percolating waters. Interesting in this connection is the composition of the hot springs at Nashologoto, for they may be regarded as a feeble

¹ 'Die Paragenesis der Mineralien' Freiberg, 1849, p. 105.

² Ann. N.Y. Acad. Sci. vol. xx (1910) p. 169.

³ Proc. Belfast Nat. Field Club, vol. ii (1906) App. vii & viii.

⁴ Tschermak's Min. Petr. Mitth. vol. xxv (1906) pp. 99, 102.

⁵ Zeitschr. Phys. Chem. vol. xlv (1903) p. 257.

⁶ Atti Accad. Sci. Torino, vol. xxxiii (1898) pp. 289, 876, & Journ. Chem. Soc. vol. lxxvi, pt. 2 (1899) p. 300 (abstract).

solution containing soda and silica in water charged with carbon-dioxide.

In explaining the origin of amygdale minerals, appeal has been made to two chief processes. By some writers they have been regarded as decomposition-products due to weathering; by others they are regarded as hydrothermal products of the final stages of consolidation. The view is now gaining favour that these minerals represent, not the first stage of destruction of the lavas in which they occur, but the last stage in their construction.¹ C. N. Fenner² takes an intermediate position: for, although he concludes that the vesicles of the Watchung basalt were filled while it cooled, he thinks that the water concerned in the process was drawn from the underlying sediments.

In Mozambique the amygdale minerals are clearly not the result of weathering. In the freshly exposed surfaces on the Mochelia road and on the Ibrahimo road, weathering products are typically absent. The feldspars are generally fresh, and, where altered, they are replaced by chalcedony and penetrated by streaks of chlorite—a change clearly to be correlated with the replacement of heulandite by silica and chlorite. If due to atmospheric weathering, the distribution of zeolites and agate should be uniform: on the contrary, it is very irregular. In some localities the basalts are vesicular and free from infillings; in others the walls of the vesicles are lined to a varying depth, while along certain belts the vesicles are all tightly packed. The view suggested by Fenner cannot be adopted, for the amygdales occur as abundantly when the basalts lie on a platform of granite and gneiss as when they cover a sedimentary basement. There seem to be, however, no objections to regarding the minerals and the water that accompanied them as the last products of consolidation. The regular sequence which, so far as can be seen, is one of decreasing temperature and of increasing concentration of soda and silica; the instability of heulandite towards silica; the absence of zeolites from the sills and dykes (because the material that would have formed zeolites was enabled to crystallize as plagioclase); the general absence of calcite, limonite, and other weathering products; the conspicuous freshness of the pyrogenetic minerals; and, finally, the occurrence of hot springs on the border of the volcanic field—all favour the hydrothermal or late magmatic origin of the amygdale minerals.

¹ For a recent discussion and references to many other localities, see W. F. P. McLintock 'On the Zeolites & Associated Minerals from the Tertiary Lavas around Ben More, Mull' *Trans. Roy. Soc. Edin.* vol. li, pt. 1 (1915) p. 13.

² *Ann. N.Y. Acad. Sci.* vol. xx (1910) p. 106.

Chemical Composition of the Sokoto Vesicular Basalt
(No. 132).

	Percentages.	Molecular Proportions.		Mineral Composition (Norm).	
SiO ₂	56·42	·943	Quartz	8·97	} Salic = 73·19.
Al ₂ O ₃	17·33	·170	Orthoclase	9·45	
Fe ₂ O ₃	2·78	·018	Albite	24·89	
FeO	3·23	·044	Anorthite	29·88	
MgO	4·67	·117			
CaO	8·61	·154	Diopside	10·30	} Femic = 25·03.
Na ₂ O	2·95	·047	Hypersthene	10·09	
K ₂ O	1·58	·017	Magnetite	4·18	
H ₂ O+	1·32	...	Ilmenite	0·46	
H ₂ O-	0·44	...			
TiO ₂	0·25	·003	Total	98·22	
MnO	0·17	·002	Water	1·76	
Total	<u>99·75</u>		Total	<u>99·98</u>	

Ra = $0·94 \times 10^{-12}$ grms. per gram.
Specific gravity = 2·43.

Class II..... Persalane.
Order 4..... Austrare.
Rang 3-4 ... Tonalase-Bandase.
Subrang 4... Tonalose-Bandose.

Comparing this analysis with that of the Sokoto sill, the most striking difference lies in the excess of silica in the vesicular lava. This is clearly referable to the presence of chaledony in the microscopic vesicles of the latter. However, even if free silica be subtracted from the analysis, and the remaining figures recalculated to 100, there still remain noteworthy differences. The lava contains a smaller relative proportion of iron-oxides and magnesia than the sill, and the compositions of the normative plagioclase in the two rocks are :—

Sokoto sill	An ₃₈
Sokoto vesicular lava	An ₃₅

It thus appears that the lava is deficient in the constituents of chlorite and of lime-zeolites. The absence of these amygdale minerals from the rock analysed and their abundance in the neighbouring lavas confirm this result. If we regard the Sokoto sill as representing an approximation to the parent magma of the surrounding flows of vesicular and amygdaloidal basalt, then we may follow the progress of differentiation (controlled by the presence of abundant water and perhaps of other volatile fluxes) and reconstruction through various stages that may be represented as follows :—

XVI. HORNBLLENDE-ANDESITE. (Pl. XXI, fig. 5.)

The specimen (No. 126) was collected from a small dyke penetrating a flow of amygdaloid on the south side of the Monapo, about 2½ miles north-west of Mochelia. In the hand-specimen white phenocrysts of felspar (averaging 4 mm. × 2 mm.) are seen distributed in a dark-grey ground-mass. Smaller crystals of hornblende and flakes of biotite can also be distinguished. The rock is compact, but a few very small amygdales containing well-crystallized quartz are present.

Under the microscope the chief minerals seen and their approximate proportions by weight, determined by the Rosiwal method, are as follows :—

Minerals.	Estimated Percentage by weight.	
Andesine and inclusions.....	26	} Phenocrysts = 40.
Hornblende	9	
Biotite	5	
Plagioclase	not determined separately	} Ground-mass = 60.
Orthoclase		
Quartz		
Biotite		
Hornblende		
Total	100	

Part of the rock was crushed, and by means of bromoform, subsequently diluted with benzine, three groups of minerals were separated :—

- Hornblende and biotite sank in bromoform; in Thoulet solution diluted with water, the average specific gravity of the crop was found to be 2·97.
- Plagioclase sank in bromoform diluted with benzine at 2·67.
- The remaining material—mainly ground-mass—was collected for analysis. Its average specific gravity was found to be 2·61.

Mineral Group.	Percentage by weight.	Specific Gravity.
Andesine and inclusions	26	2·67
Hornblende and biotite	14	2·97
Ground-mass.....	60	2·61
Average specific gravity ...		2·67

With the data thus ascertained the specific gravity of the rock is calculated to be 2·67. The value actually found was 2·68.

The phenocrysts of plagioclase average andesine in composition. They are often strongly zoned, and the interior is, as is usual, richer in the anorthite molecule than the outer zones. Inclusions are rare, except for occasional wisps of chlorite. Alteration is common to a microcrystalline aggregation in which kaolin, perhaps sericite, epidote, and a very little calcite can be distinguished. Green hornblende is present in good idiomorphic crystals modified by slight resorption. Patches of ground-mass, shreds of biotite, grains of magnetite, and small crystals of apatite are found as inclusions, and in one case a rounded crystal of zircon. Biotite also exhibits slight resorption, and its fibrous texture suggests a certain degree of alteration. Magnetite and apatite are present sparingly as inclusions. The ground-mass contains small laths of andesine or oligoclase surrounded by fan-like intergrowths of colourless minerals having refractive indices respectively above and below that of Canada balsam. The minerals in question are probably quartz and orthoclase: for the intergrowths exhibit an approach to microgranophyric texture, and the chemical composition of the ground-mass (tabulated below) leads to the same conclusion. Wisps of biotite largely altered to chlorite are distributed through the ground-mass, and irregular grains of hornblende are also present.

Chemical Composition (Hornblende-Andesite).

An analysis of part of specimen 126 was made, with the following results:—

	Percentages.	Molecular Proportions.	Mineral Composition (Norm).	
SiO ₂	60·76	1·013	Quartz	14·16
Al ₂ O ₃	16·81	·165	Orthoclase	14·46
Fe ₂ O ₃	2·07	·013	Albite	27·77
FeO	2·34	·032	Anorthite	23·91
MgO	3·27	·082		
CaO	6·57	·117	Diopside	6·89
Na ₂ O	3·32	·053	Hypersthene ...	7·28
K ₂ O	2·42	·026	Magnetite	3·02
Loss above 110° C. ...	1·19	...	Ilmenite	0·61
Loss at 110° C. ...	0·48	...		
TiO ₂	0·31	·004	Total	98·10
MnO	0·22	·004	Loss on ignition	1·67
Total	99·76		Total	99·77

Salic
=80·30.

Femic
=17·80.

Specific gravity = 2·68.

Class II Persalane.
Order 4 Austrare.
Rang 3 Tonalase.
Subrang 4 ... Tonalose.

The analyses of some other andesites from other East African localities are quoted below (B, C, D, E) for comparison with the

Mozambique example. The high silica-percentage of the latter is probably due to the presence in the specimen analysed of small quartz-bearing amygdalae, and also to the presence of quartz in the microgranophyric groundmass:—

	A.	B.	C.	D.	E.	F.	G.	H.
SiO ₂	60·76	51·32	56·65	51·97	56·14	65·32	66·40	62·07
Al ₂ O ₃	16·81	16·62	22·11	16·21	17·81	16·08	12·91	17·15
Fe ₂ O ₃	2·07	9·28	3·31	3·37	2·69	2·89	3·87	1·87
FeO	2·34			9·51	4·67		2·56	3·57
MgO	3·27	5·36	3·42	3·68	4·15	2·13	0·53	2·39
CaO	6·57	9·62	6·67	7·67	6·81	3·47	2·32	4·84
Na ₂ O	3·32	2·15	1·86	3·41	3·59	4·33	3·30	4·75
K ₂ O	2·42	2·96	4·10	1·75	1·63	3·62	3·09	2·15
H ₂ O	1·67	2·60	2·20	1·97	1·16	1·06	4·25	1·18
TiO ₂	0·31	n. d.	n. d.	0·22	1·23	0·17	0·54	0·21
MnO	0·22	0·55	0·16	n. d.	0·08	n. d.	0·09	0·26
P ₂ O ₅	n. d.	0·25	tr.	n. d.	0·12	n. d.	0·16	tr.
Totals.....	<u>99·76</u>	<u>100·71</u>	<u>100·48</u>	<u>99·76</u>	<u>100·13</u> ¹	<u>99·07</u>	<u>100·02</u>	<u>100·44</u>

¹ Including 0·01 per cent. SrO and 0·04 per cent. BaO.

- A. Hornblende-andesite, Monapo River (an. Holmes).
- B. Olivine-augite-andesite,¹ Mount Meru.
- C. Amphibole-biotite-andesite,² Mount Meru.
- D. Andesite, Kordofan³ (an. Linck).
- E. Andesite, near the Lucalla River, Angola⁴ (an. Harwood).
- F. Base of hornblende-andesite, Monapo River (an. Holmes).
- G. Toscanite, Indulawane Hill, Zululand (an. Prior).
- H. Quartz-porphyry, Kadero, Kordofan³ (an. Linck).

Chemical Composition of the Ground-mass.

The heavy-liquid separation of the ground-mass already mentioned was not quite clean, for a greater proportion of biotite and andesine accompanied the residue than appeared to be visible in thin section. However, it was thought advisable to analyse the material thus obtained, on account of the light that it might throw on problems of differentiation.⁵ The ground-mass would be expected to have the composition of a latite or rhyolite, and although in Mozambique no such rocks have been discovered in association with the basalts, corresponding dyke-rocks are known to exist at Sinjal in the extreme west of Zambesia, among the volcanic rocks south of the Zambesi and the Lebombo, and in Uganda and Kordofan.

The separated material was air-dried at 110° C. Owing to

¹ E. Pinkert, *Földt. Közl.* vol. xxxvii (1907) p. 292.

² *Id. ibid.* p. 296.

³ *Neues Jahrb. Beilage-Band* xvii (1903) p. 428.

⁴ A. Holmes & H. F. Harwood, *Min. Mag.* vol. xviii (1916) p. 69.

⁵ See Sir Jethro Teall, *Q. J. G. S.* vol. lvii (1901) p. lxxxii, for the application of this method to the rocks of the Cheviots.

the lack of material, ferrous oxide was not separately determined, nor were several important minor constituents. The analysis gives a low summation, but is sufficiently full for the immediate purpose.

	Percentages.	Molecular Proportions.		Mineral Composition (Norm.).	
SiO ₂	65·32	1·089	Quartz	16·86	} Salic.
Al ₂ O ₃	16·08	·158	Orthoclase	21·13	
Fe ₂ O ₃	2·89	·018	Albite	36·15	
FeO	n. d.	...	Anorthite	14·18	
MgO	2·13	·053	Diopside	2·38	} Femic.
CaO	3·47	·062	Hypersthene ...	4·20	
Na ₂ O	4·33	·069	Hæmatite	2·72	
K ₂ O	3·62	·038	Ilmenite	0·30	
Loss on ignition...	1·06	...	Total	97·92	
TiO ₂	0·17	·002	Loss on ignition	1·06	
Total	99·07		Total	98·98	

Specific gravity = 2·61.

Class I Persalane.
Order 4 Brittanare.
Rang 2 Toscanase.
Subrang 4 ... Lassenose.

Analyses of African rocks of similar composition and associated in the field with andesites are quoted on the preceding page (G & H).

XVII. PYROXENE-ANDESITE. (Pl. XXI, fig. 6.)

Pebbles of pyroxene-andesite (No. 144) were found by Mr. Wayland in the bed of the Monapo River and on the alluvial flats to the south, at distances of 3 to 4 miles from the mouth of the river. The rock is dark grey in colour, and is speckled with phenocrysts of felspar, some of which are transparent, others being opaque. It lacks the prevailing reddish tints of the basalts, but weathers to a dark brown. The rock is singularly compact and free from vesicles—a feature suggesting that, like the neighbouring hornblende-andesite, it may be derived from a dyke. No known lava from the Mozambique volcanic area is entirely free from vesicles or amygdales. The specific gravity is 2·72.

Under the microscope the rock presents no unusual features. It consists essentially of phenocrysts of andesine, augite, and hypersthene, and occasional pseudomorphs of serpentine after olivine, embedded in a fine-grained ground-mass of hyalopilitic texture, in which tiny laths of oligoclase, shreds of biotite, grains of pyroxene and iron-ores, together with a little interstitial glass, are the chief constituents.

The phenocrysts of plagioclase are generally clear glassy andesine, with characteristic twinning and zoning, and an average refractive index of about 1·556. The opaque felspars of the hand-specimen owe their colour to the presence of large inclusions of

biscuit-coloured glass or of innumerable blebs that suggest a frozen emulsion of felspar and glass. Large pyroxenes are also wholly or partly included by the larger felspars, and apatite, magnetite, and serpentine are accessory inclusions. The glass-filled felspars are surrounded by a clear mantle of oligoclase, which may represent a final period of growth simultaneous with that of the ground-mass. The average refractive index of the outer borders is approximately 1.545; that of the laths in the ground-mass appears to be a little less.

Hypersthene and augite occur in somewhat rounded forms, having rarely retained their idiomorphic outlines. Hypersthene, which is beautifully pleochroic, frequently acts as a nucleus around which augite crystals are built. Both pyroxenes contain magnetite, serpentine, and glass as inclusions. Peripheral wisps of biotite occur around many of the rhombic pyroxenes, and also disseminated sparsely through the ground-mass. In several cases the change from hypersthene to biotite is gradual and continuous, but against felspars the biotite always terminates sharply. Serpentine is not abundant, and is present as pseudomorphs after idiomorphic phenocrysts of olivine, and as confused aggregates in the ground-mass. It is of the golden-yellow variety found in the basalts. Like hypersthene, it is bordered with wisps of biotite which have clearly grown at the expense either of the serpentine or of the olivine which preceded it. The potash-bearing molecules of the magma seem to have reacted with the ferromagnesian silicates already precipitated—hypersthene, olivine, or serpentine—in such a way as to produce biotite.¹

The order of crystallization is as follows:—apatite and magnetite, olivine, hypersthene, augite, andesine, oligoclase, biotite, and, finally, interstitial glass.

Relationships and Origin of the Volcanic Rocks.

XVIII. DISTRIBUTION OF SIMILAR LAVAS IN EASTERN AFRICA.

The outstanding feature of the volcanic district of Mozambique is the development of two strongly-contrasted series of rocks—one mainly composed of amygdaloidal basalts and including andesites, the other including alkali-trachytes and phonolites.

Amygdaloidal basalts similar to those of Mozambique are found in many localities of South and Central Africa, but nowhere else south of Mozambique are they known to be of Tertiary age. At Sinjal, near the border of Nyasaland and Portuguese East Africa, Dr. A. R. Andrew and Mr. T. E. G. Bailey² found basalts, associated with andesites and rhyolites, which they refer to the close of the Karoo Epoch. Dr. Prior has kindly allowed me to see the specimens from this locality (now deposited in the Natural History

¹ N. L. Bowen, Journ. Geol. Chicago, Supplem. to vol. xxiii (1915) p. 46.

² Q. J. G. S. vol. lxvi (1910) p. 220.

Museum), and it is clear that in no essential respect do they differ from the Mozambique examples; even the amygdale minerals and the order of their deposition are the same.

South of the Zambesi, basalts, largely amygdaloidal, are found associated with late Karoo sediments, flanking the plateau of crystalline rocks for hundreds of miles. In the north they have been mapped by Dr. E. O. Teale & Mr. R. C. Wilson.¹ Between the Pungwe and the Sabi (Save) rivers they were traced by Col. A. Freire d'Andrade.² Some 50 miles west of the mouth of the Busi, he collected melaphyres in which chlorite-lined amygdaloids containing zeolites and chaledony and quartz are abundant. Similar flows of melaphyre occur in Lourenço Marques. I have examined specimens from the Komati River that appeared to be identical with the basalt of the Sokoto sill. The Lebombo amygdaloids of Swaziland and Zululand are associated with andesites and rhyolites, and some of these have been analysed.³

Occurring farther from the coast, the Drakensbergen lavas,⁴ the Bushveldt amygdaloid of the Transvaal,⁵ the Tuli lavas of Southern Rhodesia,⁶ the Batoka basalts of the Zambesi,⁷ the basalts of the Forest Vale between Bulawayo and the Zambesi,⁸ and the Ngami amygdaloids of the Kalahari,⁹ all show a marked likeness one to the other and to the Mozambique lavas. Towards the south the resemblances become less marked, though the differences are limited to the incoming of olivine (generally serpentinized) among the pyrogenetic constituents, and of calcite among the amygdale minerals.¹⁰ Throughout this vast region, west and south-west of Mozambique, no alkali series of rocks is known to occur in association with the late Karoo amygdaloids (except doubtfully those of the Bushveldt complex, where the age of the intrusions that preceded the amygdaloids is still uncertain). It seems, however, worthy of remark that the igneous rocks that followed the Upper Karoo amygdaloids and the later dolerites of South Africa are generally melilite-basalt, alnoite, or kimberlite. These rocks occur in the Cape Province, the Orange Free State, the Transvaal, Southern Rhodesia, Northern Rhodesia, and Katanga.

¹ Geogr. Journ. vol. xlv (1915) p. 29.

² P. Choffat, 'Contributions à la Connaissance Géologique des Colonies Portugaises d'Afrique' Comm. Geol. Portugal, ii (1905) p. 33.

³ J. McC. Henderson, Trans. Geol. Soc. S. Africa, vol. xii (1910) p. 24.

⁴ A. W. Rogers & A. L. Du Toit, 'The Geology of Cape Colony' 1909, p. 225.

⁵ E. T. Mellor, Ann. Rep. Geol. Surv. Transvaal, 1901, p. 31.

⁶ A. J. C. Molyneux, Q. J. G. S. vol. lix (1903) p. 266.

⁷ G. W. Lamplugh, *ibid.* vol. lxiii (1907) p. 162.

⁸ F. P. Mennell, *ibid.* vol. lxvi (1910) p. 369; and Spec. Rep. 2, Rhodesia Museum, 1904, p. 15.

⁹ S. Passarge, Zeitschr. Gesellsch. für Erdkunde, Berlin (1904) no. 3, p. 179.

¹⁰ A. W. Rogers & A. L. Du Toit, 'The Geology of Cape Colony' 1909, p. 226; see also P. A. Wagner, 'The Diamond-Fields of South Africa' 1914, p. 99.

Melilite-basalt also occurs among the alkali rocks of the Great Rift Valley, where it appears to stand towards them in a complementary relation, as a mafic end-product of differentiation specially rich in lime and magnesia. In South Africa the 'alkaline affinities' of melilite-basalt and kimberlite have been noted,¹ and it is interesting to find that the amygdale minerals of these rocks include zeolites and calcite, but never chalcedony or quartz.²

Although the lavas of Mozambique, and of the greater part of Africa south of that latitude, are predominantly amygdaloidal basalts characterized by siliceous and lime-zeolite amygdaloids, the lavas known in the north are not commonly of this type, except in Abyssinia. The majority of the lavas belong to an alkali series (accompanied by mafic complementary types), to which those of Mozambique bear a close resemblance.³ The distribution of the various types has been well summarized by Prof. J. P. Iddings in his 'Igneous Rocks,' vol. ii (1913) p. 576 *et seq.*, with references to the literature, and therefore the details need not be repeated here. It will be sufficient to draw attention, as Rosiwal did many years ago,⁴ to the frequent association of a calc-alkali series (including amygdaloidal basalts, andesites, and rhyolites) with a more strongly-developed alkali series.

North of the Songwe River in German East Africa, Bornhardt found basalts, andesites, and trachytes, while south of the river, in the extreme north of Nyasaland, A. R. Andrew & T. E. G. Bailey discovered tuffs containing trachyte and phonolite.⁵ In Masailand, along the Uganda Railway towards Victoria Nyanza, in the Kavirondo country⁶ adjoining the Nyanza, in the islands of Lake Rudolf, in Kordofan, and especially in Abyssinia and Somaliland,⁷ the two series are well represented. Wherever the succession has been noted⁸ the alkali series, often accompanied by normal basalts, is the later. In the islands of Lake Rudolf, in Italian Somaliland, and in Abyssinia, the amygdale minerals of the earlier series are chiefly quartz, chalcedony, and opal, accompanied by heulandite and other lime-zeolites. Blanford draws attention to the striking similarity between the amygdaloids of Abyssinia and those of Southern Arabia and the Deccan. In each of the two last-named regions an alkali series is also present.⁹ No detailed petrographic account of the Deccan traps has yet been published,

¹ P. A. Wagner, 'The Diamond-Fields of South Africa' 1914, p. 106.

² A. W. Rogers & A. L. Du Toit, 'The Geology of Cape Colony' 1909, p. 348.

³ Especially in the presence of such soda-amphiboles as katoforite and coesynite.

⁴ Denkschr. K. Akad. Wissensch. Wien, vol. lviii (1891) p. 465.

⁵ Q. J. G. S. vol. lxxv (1910) p. 222.

⁶ F. Oswald, Q. J. G. S. vol. lxx (1914) p. 140 *et seq.*

⁷ W. T. Blanford, 'Observations on the Geology & Zoology of Abyssinia' London, 1870, p. 180.

⁸ As, for example, in Abyssinia, Lake Rudolf, and the Kavirondo country.

⁹ See J. W. Evans, Q. J. G. S. vol. lvii (1901) p. 38. In Kathiawar the nepheline-bearing rocks appear to be intrusive into the Deccan traps, and therefore of later age.

but several specimens in my possession bear the most detailed resemblance to the basaltic dyke-rocks of Mozambique.

In the adjoining table, the distribution of the two series of lavas is tabulated in as complete a form as the present state

District.	'Calc-Alkali' Series.			'Alkali' Series.			
	Amygdaloidal basalt.	Andesite.	Rhyolite.	Alkali-rhyolite.	Alkali-trachyte.	Nepheline-bearing lavas.	Melilite-basalt.*
Deccan	×	×	×	...	...	×	...
Southern Arabia	×	...	...	×	×	×	...
Somaliland	×	...	...	×	×	×	...
Abyssinia	×	×	...	×	×	×	...
Kordofan	×	×	×	...	...	×	...
Lake Rudolf	×	×	...	×	×	×	...
Kavirondo	×	×	×	...	...	×	...
Uganda Railway	×	×	...	×	×	×	...
Elgon	...	...	...	...	...	×	×
Kenya	...	...	...	...	×	×	...
Naivasha	...	...	...	×	...	...	...
Masailand	×	×	...	×	×	×	...
Kilima Njaro	...	×	...	...	×	...	×
Meru	...	×	...	...	×	×	...
Songwe River	×	×	...	...	×	×	...
Mozambique	×	×	...	...	×	×	...
Katanga	×	...	×	...	...	...	×
Sinjal	×	×	×	...	...	...	...
Batoka	×	...	...	...	...	...	...
Forest Vale	×	...	...	...	...	...	...
Southern Rhodesia	×	...	...	...	...	...	×
Zambesia-Pungwe	×	×	×	...	...	...	×
Lebombo	×	×	×	...	...	...	2
Zululand	×	×	×	...	...	...	2
Drakensbergen	×	×	...	...	...	...	2
Chief amygdale-minerals.	Quartz, chalcedony, opal, and lime-zeolites. (Calcite not common, but becoming more abundant south of Mozambique.)			Soda-zeolites and calcite. (Silica absent, except in the rhyolites and more acid trachytes.)			

* Melilite-basalt is included here, not because of any inherent richness in alkalis, but because it seems often to be a complementary end-product of an alkali series.

1. Southern Rhodesia.

2. Melilite-basalts and kimberlites (of later age than the amygdaloids) occur west of these localities in the Transvaal, the Orange Free State, and Griqualand West. See map in P. A. Wagner's 'Diamond-Fields of South Africa' 1914.

of exploration renders possible. The 'amygdaloidal basalts' of the second column are those in which siliceous amygdales are abundant. Normal basalts are not tabulated, for they appear, in various degrees of abundance, to be common to both series. The table brings out the fact that the association in Mozambique of two contrasted series of lavas is not exceptional, although it is the southernmost locality in Eastern Africa in which that association has yet been noted. The weighty problems that centre about the origin of the Mozambique lavas thus become common to all the African occurrences on the north.

The alkali series of Mozambique can be closely matched by the lavas of Réunion, and by those of the Mid-Atlantic islands.¹ In Angola, near Cambambe, trachytes containing katoforite and cossyrite are associated with augite-andesite.² In none of these localities are amygdaloidal basalts like those of Mozambique known to occur.

XIX. VARIATION-DIAGRAMS.

In the preceding sections, ten analyses have been recorded. These analyses fall naturally into two series (belonging respectively to Groups A & B) characterized in each case by a well-marked serial relationship. The variation-diagram adopted for a graphical comparison of the analyses is that in which silica percentages are taken as abscissæ, and the other oxides plotted as ordinates.³ In order to render the comparison as faithful as possible, the total of the two iron-oxides is expressed as ferrous oxide, and to this manganous oxide is added. The analyses are then recalculated to 100, water and carbon dioxide being omitted (figs. 6 & 7, pp. 266-67).⁴

It will be noticed that the two series of curves are distinctly different, and that no analysis belonging to one series would fit the curves connecting the other series.

Series A is based on analyses of the rocks from the Sanhuti district. The curves were drawn before the tephritic pumice of the Monapo was analysed, but when the analysis was made it fell naturally into its place between those of basalt and phonolite, and very little modification of the curves was found necessary. This seems to indicate that the lava in question belongs to the same series as the Sanhuti rocks, and that it is not immediately related to the amygdaloids of the district in which it was found.

The series is characterized throughout by a high percentage of iron-oxides, and by an excess of soda over potash with a marked parallelism of the two alkali curves. Lime and magnesia occupy a low position on the right (that is, beyond 55 per cent. of silica), but rise rapidly on the left, in antipathy to the alkalis which fall towards the left. It is, therefore, difficult to regard the whole

¹ G. T. Prior, *Min. Mag.* vol. xiii (1903) p. 254.

² A. Holmes & H. F. Harwood, *Min. Mag.* vol. xviii (1916) p. 58.

³ A. Harker, 'Natural History of the Igneous Rocks' 1909, p. 118.

⁴ To avoid confusion, the values for titanium dioxide are not plotted.

series as 'alkaline,' for the high alkalies on the right are compensated on the left by high lime and magnesia. In each direction the curves have been continued beyond the extreme analyses by what seemed to be a natural extrapolation. At the mafic end, the potash-curve meets the base at $\text{SiO}_2 = 38$ per cent. The composition of this mafic limit of the series is that of a melilite-basalt. At the felsic end the lime and magnesia curves meet the base at $\text{SiO}_2 = 70.6$ per cent., and the corresponding composition of the acid limit of differentiation is that of an alkali-rhyolite. Although these two limiting rocks have not been found in Mozambique, they both occur in quite similar series of rocks in British East Africa, and are evidently natural members of the series, although occurring only where differentiation has proceeded to its extreme limits.

In order to demonstrate the similarity of this series of Mozambique rocks to those of other areas, variation-diagrams have been made for the lavas of Abyssinia, British East Africa, Réunion, and Teneriffe (fig. 8, pp. 268-69). Most of the analyses on which these are based can be found in Iddings's 'Igneous Rocks,'¹ or in papers to which references are there given, and in Dr. H. S. Washington's well-known tables.² The curves for each constituent have a strong family likeness throughout. The chief points of dissimilarity are found in British East Africa, where, as Dr. Harker has already pointed out,³ alumina falls rapidly in the more siliceous rocks, and iron-oxide (largely ferric) instead of gradually declining, compensates for the low alumina by ascending. The magnesia-curve for the rocks of British East Africa also differs from those of other localities in its slow ascent towards a mafic limit. The discrepancy is, however, due to subsidiary differentiation among the basic rocks, for melilite-basalts and picrite-basalts occur in British East Africa, which (if analysed) should provide a normal magnesia-curve. The resemblances of the curves for Abyssinia, Mozambique, and Teneriffe are the most perfect, and indicate that similar processes must have been at work on similar deep-seated materials in each of those regions, these conditions being the controlling factors in the development of a petrographic province or of a number of similar provinces in widely-separated regions. Analyses of the alkali-rocks of Madagascar, the Transvaal, Angola, and the Los Islands were also plotted, but in none of these cases was there any resemblance to the Mozambique curves, probably on account of the existence of more than one series of differentiates in those districts.⁴

Series B is based on analyses of rocks from the Monapo-River and Sokoto-Hill districts. The analysis of the ground-mass of hornblende-andesite is included, for it provides a good indication of the course of differentiation towards the felsic end of the series.

¹ Vol. ii (1913) pp. 576-90.

² U.S. Geol. Surv. Prof. Paper 14 (1903).

³ 'Natural History of the Igneous Rocks' 1909, p. 124.

⁴ Such, for example, as occur in the Christiania district; see A. Harker, *op. cit.* p. 123.

Fig. 6.—Variation-diagram of the Tertiary volcanic rocks of Mozambique: Series A.

Fig. 8.—*Variation-diagrams of the post-Cretaceous volcanic
Mozambique, Réunion,*

rocks ('alkali' series) of Abyssinia, British East Africa, and Teneriffe.

A felsic limit is reached at $\text{SiO}_2 = 71.2$, where the lime-curve meets the base-line. The composition of the limit is that of a rhyolite. Alumina is much higher and ferrous oxide much lower than in the corresponding felsic limit of Series A. This contrast is in accordance with the mineralogical characteristics of the rocks of Series A, soda-pyroxenes and amphiboles being present, whereas in Series B the ferromagnesian minerals are augite, hornblende, and biotite. No attempt was made to find a mafic limit to Series B, for the curves do not reach even the ordinate corresponding to 50 per cent. of silica.

Soda is again in excess of potash and the two curves are nearly parallel, but converge as silica increases. The lime-curve is everywhere at a higher level than in the corresponding range of Series A. The iron-oxide curves are similar in the two series, but that of Series B is at a lower level throughout and declines more rapidly. The alumina-curve of Series B is much flatter than that of Series A, because in the latter the place of alumina is partly taken by ferric oxide in the soda-amphiboles and pyroxenes. The general form of the curves in Series B is very similar to those of the volcanic rocks of Lassen Peak (California),¹ and of the San Francisco district of Arizona.²

Regarding each of the series as a whole, it seems doubtful—in the absence of any knowledge of the relative volume of each rock species—whether one can be regarded as more alkaline than the other. The main distinction is that in Series A the antipathy of lime and magnesia to the alkalis is much more marked than in Series B, the separation of these two groups of constituents taking place much sooner and much more completely in Series A than in Series B. Each of the alkalis begins to exceed lime in Series A at about 54 per cent. of silica, whereas in Series B this does not occur until silica has reached 66 per cent.

There seems to be no justification for supposing that the two series of rocks are the result of different processes acting on similar deep-seated materials, for they are both associated with the same meridional system of faulting. We are, therefore, driven to consider the two series as the consequence of similar processes acting on different materials, those materials being in the one case under-saturated with silica, relatively deficient in water,³ and rich in carbon dioxide, and in the other case over-saturated with silica, rich in water, and practically free from carbon dioxide. Whether these two groups of parent materials were derived from a pre-existing common source, is a problem that cannot yet be definitely solved.⁴

¹ A. Harker, 'Natural History of the Igneous Rocks' 1909, p. 126.

² H. H. Robinson, U.S. Geol. Surv. Prof. Paper 76 (1913) p. 181.

³ N. L. Bowen writes: 'It may well be that volatile substances are as abundant in magmas of this [alkali] series as in any others, but that water is relatively an unimportant fraction' Journ. Geol. Chicago, Suppl. to vol. xxiii (1915) footnote 2, p. 78.

⁴ For a suggestion that may apply here, see J. W. Evans, Geol. Mag. dec. 6, vol. iii (1916) p. 189.

XX. ORIGIN OF THE LAVAS.

Four problems, or groups of problems, present themselves for discussion in this section :—

- (a) The differentiation of the alkali-lavas and their associates, Series A.
- (b) The origin of the parent magma of Series A.
- (c) The differentiation of the amygdaloidal basalts and their associates, Series B.
- (d) The origin of the parent magma of Series B.

(a) The serial relationships of the lavas of Series A, disclosed by their variation-diagram, point to some continuous process of differentiation acting on a common parent magma. The sequence of lavas in the Sanhuti district—(1) basalt, (2) phonolite, (3) picrite-basalt—suggests that the first lava to be erupted most nearly approaches the composition of the parent magma, and that the lavas that succeeded it stand in a complementary relation one to the other, the one being rich in alkalies, the other in lime and magnesia. The order of crystallization of the more significant minerals in the series regarded as a whole is approximately as follows: olivine, titaniferous augite, labradorite, diopside, augite, less calcic labradorite (andesine in tephritic punice?), anorthoclase and nepheline, soda-pyroxenes, soda-amphiboles, and opal (in the ground-mass of ægirine-trachyte). It thus appears that magnesia was the first of the main constituents to commence its withdrawal from the parent magma, and that it was closely followed by lime. A concentration of alkali alumino-silicates and of soda ferro-silicates accompanied by increasing quantities of the volatile fluxes thus became possible. Towards the close, water began to exert a controlling influence, shown by the formation of soda-amphiboles and still later by the deposition of natrolite. The close genetic association of rocks like ægirine-trachyte with free silica (opal) and of phonolite with deficient silica (nepheline) may also be due to the high-temperature activity of water. Describing the history of a magma gradually modified by crystallization, Dr. N. L. Bowen¹ says

‘For any given concentration of the molecules KAlSi_3O_8 and $\text{NaAlSi}_3\text{O}_8$, however small, there is a certain corresponding concentration of KAlSiO_4 , NaAlSiO_4 , and SiO_2 ,’

the polysilicate molecules being broken down in the presence of water. Later, he says (*op. cit.* p. 56):

‘The precipitation of KAlSi_3O_8 , $\text{NaAlSi}_3\text{O}_8$, KAlSiO_4 in mica, and SiO_2 as quartz, means the concentration in the liquid of all the other molecules,’

among which nepheline and the volatile fluxes are important members. In preference to supposing that silica can be removed from a magma by crystallization in the presence of water and other

¹ ‘The Later Stages of the Evolution of the Igneous Rocks’ Journ. Geol. Chicago, Suppl. to vol. xxiii (1915) p. 45.

fluxes, even at moderately high temperatures, two suggestions may be made:—

- (i) that the portion of a magma specially rich in water and free silica—and therefore light—tends to move upwards, crystallizing only when water begins to escape, and leaving a desilicated portion in which the crystallization of nepheline would then naturally proceed; or
- (ii) that in the presence of water, nepheline and alkali-felspar could crystallize, leaving free silica in solution, the ratio between nepheline and alkali-felspar depending on temperature and pressure and on the concentration of water in the magma.

For the reasons stated above, it is considered that the various rock-types of Series A could be evolved by a process of crystallization accompanied by a gravitational settling of the heavier crystals and an upward separation of the lighter residual magmas. At intervals the process would be locally brought to an end by the eruption of lavas.¹

(b) Except at the close of the magmatic history described above, the rocks produced were under-saturated with silica. The parent magma must also have shared this characteristic, and other features to be explained (in contrast with the magmas concerned in the production of the amygdaloids) are the comparative poverty in water and the presence of carbon dioxide.

The well-known theory of Prof. R. A. Daly,² who ascribes alkali rocks to the desilication of basaltic magma by absorption of carbonate sediments, is quite inapplicable to the present case. Certainly calcareous bands occur in the Cretaceous rocks of the Sanhuti district, but these are merely a thin veneer on a Pre-Cambrian basement, and can have had no effect on the composition of the lavas. Crystalline limestones occur in narrow bands interfoliated with the gneisses of the basement rocks, but in such small quantity that, if any part of them had been absorbed, a much greater proportion of granite and gneiss would also have been taken up, and the desired effect would thus have been nullified. In one respect only is there a point of contact between Daly's theory and the view here adopted: namely, the belief that carbon dioxide was an important member of the volatile fluxes belonging to the magma from which the alkali lavas were derived.³ Under high pressures calcite and magnesite can exist in the presence of silicate minerals without dissociation if the temperature be not too high. It is therefore possible that at very great depths, and among rocks

¹ The process here suggested is, in principle, not unlike that advocated by Dr. N. L. Bowen (*op. cit.* 1915), except as regards the relationships of silica, nepheline, alkali-felspars, and water.

² Bull. Geol. Soc. Am. vol. xxi (1910) p. 115; and 'Igneous Rocks & their Origin' 1914, chap. xx.

³ Prof. C. N. Smyth has recently discussed the genesis of alkali rocks on the hypothesis that they are segregated from 'normal' magmas by the action of special pneumatolytic agents, Am. Journ. Sci. ser. 4, vol. xxxvi (1913) p. 33.

presumably of basic composition, carbon dioxide may be present in primary calcite and other carbonate minerals. If this were so, then a sufficient relief of pressure, such as may have initiated the Tertiary volcanic activity of East Africa, would inevitably bring about reaction between natural carbonate and silicate minerals—reactions which, if they were of the kind described by Daly, would lead on to the evolution of an alkali series of rocks accompanied by a cafermic complementary series.

Methods of desilication by water and by natural carbonates have now been considered,¹ but there remains a third possibility that has not been previously suggested. There is reason to believe that below the granites and gneisses of the continents rocks of basaltic composition fall naturally into place, and that below these occur rocks of peridotitic composition.² If igneous activity in any region were initiated, at or through such a depth that the magmas formed included one of peridotitic composition, it seems likely that during the upward progress of the latter it would interact with basaltic material, taking up silica to form enstatite or hypersthene, and abstracting lime to form monoclinic pyroxenes. Such minerals, being heavy, would tend to sink (or at least not to rise) leaving above a magma relatively impoverished in silica, but enriched in alkalis and perhaps in a new series of volatile fluxes.

The occurrence of kimberlite pipes in South and Central Africa favours the view that igneous activity may begin in a zone of peridotitic composition; but, as it stands, the theory still throws no light on the origin of the associated melilite-basalts. On the other hand, if melilite-basalt is always a cafermic complement to an alkali series, it is remarkable that no alkali rocks should have been discovered in South Africa. The calciferous dykes of the Premier Mine,³ and the great abundance of calcite in many kimberlite pipes⁴ and in melilite-basalt, again suggest that carbon-dioxide was an important constituent of the deep-seated materials whence these rocks came.⁵ It is difficult to explain the presence of so much calcite, either as an alteration-product or as an infiltration from surrounding sediments, and we are thus led from another point of view to consider the possibility of calcite being present as a primary constituent of very deep-seated rocks. A source for the high percentage of lime in melilite-basalts and of calcite in kimberlite pipes would thus be provided. Moreover, melilite-basalt could then be directly formed by the interaction of

¹ Dr. H. I. Jensen's suggestion of desilication by Pre-Cambrian saline beds, *Proc. Linn. Soc. N.S.W.* vol. xxxiii (1908) p. 522, has obviously no application.

² A. Holmes, *Geol. Mag.* dec. 6, vol. ii (1915) pp. 63–64.

³ P. A. Wagner, 'The Diamond-Fields of South Africa' 1914, p. 98.

⁴ *Ibid.* p. 75.

⁵ *Ibid.* p. 117. Wagner ascribes the initiation of the igneous activity represented by kimberlite pipes to the relief of pressure consequent upon the isostatic uplift of the continent that began in Upper Cretaceous times, and suggests that the rocks must have come from unusually great depths.

calcite and peridotite without necessarily implying the concomitant formation of complementary alkali rocks.

(c) As in Series A, the serial relationships between the rocks of Series B point to a process of differentiation acting on a basaltic magma. In this case, however, the magma must have been well provided with water and over-saturated with silica. Given a magma of the kind suggested, a process of differentiation towards andesite is not difficult to understand. By the sinking of some of the crystals first formed—olivine, labradorite, and augite—the residual magmas would have the composition appropriate to pyroxene- and hornblende-andesites. In turn, the sinking of the phenocrysts of hornblende-andesite would leave a magma having the composition of latite or rhyolite, according to the time during which the process was able to continue. For rocks of this series our knowledge of the kind of differentiation concerned in their genesis has been greatly advanced by recent freezing experiments made in the Carnegie Institution of Washington, and particularly by those of Dr. N. L. Bowen.¹ Prof. Daly has summarized the field evidence in favour of the generally accepted hypothesis that andesite is an early differentiate from basaltic magma.²

The Mozambique lavas suggest that in the presence of water not only silica is held in solution by the magma, but also that calcium silicate is retained, its complete crystallization in plagioclase and, perhaps, in augite being deferred (relatively to increasing silica) to a much later stage than in magmas containing carbon-dioxide. The forms of the two lime-curves in the variation-diagrams demonstrate the later crystallization of lime minerals in Series B than in Series A, and the abundance of lime-zeolites in the amygdaloids points to water as the responsible agent. As soon as means are devised for experimenting with artificial magmas containing volatile fluxes under pressure, the suggestion here advanced could be directly tested. It would only be necessary to compare the course of crystallization in two melts of similar composition, one charged with water, the other with carbon-dioxide.

(d) The question of the origin of the parent magma of Series B is probably one that could be solved only with a complete knowledge of the preceding igneous history of Mozambique. There is no reason to suppose that the excess of silica is due to the absorption of granite and gneiss by an ascending basaltic magma, for the percentage of potash in the lavas is quite normal. Moreover, as will be pointed out more particularly later, the heat-supply can scarcely have been sufficient to allow a margin for the occurrence of any appreciable assimilation.

¹ Am. Journ. Sci. ser. 4, vol. xxxix (1915) p. 175; 'The Crystallization of Haplobasaltic, Haplodioritic, & Related Magmas' Am. Journ. Sci. ser. 4, vol. xl (1915) p. 161; and Journ. Geol. Chicago, Suppl. to vol. xxiii (1915).

² R. A. Daly, Journ. Geol. Chicago, vol. xvi (1908) p. 401; and 'Igneous Rocks & their Origin' 1914, p. 375.

Assimilation not being admitted, there are two ways in which the requisite magma may have been formed. There have been in Mozambique at least three successive periods of granitic intrusion, the first being by far the most extensive, the second and third being almost entirely restricted to small intrusions and pegmatite dykes respectively. It may be that the deep-seated differentiation that gave rise to the early granitic magmas was never quite clean, the result being that a considerable proportion of water accompanied by silica would be retained by the deeper basaltic magmas.¹

On the other hand, even if there had been no free silica in the basaltic magma that formed in Tertiary times, a certain amount may have been liberated by the early crystallization of olivine, the olivine being afterwards separated from the residual liquor by sinking,² the liberated silica being maintained in solution by the activity of water and the crystallization of lime as silicate being deferred by the same agency. No olivine-rich lavas are associated with the basalts, but this may be due to the eruption of the lighter magmas in preference to the heavier crystal-charged differentiates.

XXI. THE RADIOACTIVITY OF THE LAVAS, AND ITS BEARING ON THEIR ORIGIN.

The radium-content of most of the lavas was estimated by Strutt's solution method.³ In the case of the andesites from the Monapo River this could not be done, on account of lack of material. The results obtained, together with those for some other Mozambique rocks, are tabulated below:—

	Rock.	Radium in grms. per gm. of rock.
	Sölvbergite.....	2.26×10^{-12}
Series A.	Ægirine-trachyte	2.83 "
	Phonolite.....	4.10 "
	Tephritic pumice.....	2.59 "
	Basalt (Sanhuti River)	1.38 "
	Picrite-basalt	0.47 "
Series B.	Basalt sill (Sokoto Hill).....	0.98 "
	Basalt dyke (Mochelia).....	0.85 "
	Microvesicular basalt (Sokoto Hill)	0.94 "
	Amygdaloid (mean of four specimens)	0.76 "
Tertiary.	Sandstone (Mochelia Hill).....	0.71 "
	Limestone (Sokoto Hill).....	0.43 "
Cretaceous	Felspathic sandstone (Mount Mesa).....	1.59 "
	Ferruginous sandstone (Mosuril)	1.18 "

¹ The differentiation of granitic magma from basaltic magma has been fully dealt with by N. L. Bowen, Journ. Geol. Chicago, Supplem. to vol. xxiii (1915) p. 46.

² *Ibid.* p. 39.

³ R. J. Strutt, Proc. Roy. Soc. ser. A, vol. lxxvii (1906) p. 472 & vol. lxxviii (1907) p. 150; A. Holmes, Sci. Progress, no. 33 (1914) p. 13; and 'The Age of the Earth' London, 1913, pp. 104-107.

These results correspond in a general way with those obtained by other observers for similar rocks from other parts of the world,¹ and they support two generalizations already admitted² :—

- (a) That rocks belonging to an alkali series tend to be richer in radium than those of corresponding silica content belonging to a calc-alkali series.
- (b) That in alkali rocks the radium-content is roughly proportional to the amount of alkalies and particularly to the amount of soda, rather than to the silica percentage.

In the absence of any knowledge of temperature-gradients in Mozambique, it is not possible to apply the results specifically in their relation to the thermal problems of vulcanism. The radium-content of the basalts (including that from the Sanhuti River) is about 1.0×10^{-12} grms. per grm., and, since this figure agrees closely with the average for other basaltic rocks, it is to be expected that the average thorium-content of the basalts is also normal. I have previously shown³ that, if granite and gneiss continue downwards from the surface to a depth of about 6 kilometres, and if below that depth basaltic rock continues for 47 kilometres, then the temperature at the base of the 'radio-active layer' (about 33 miles below the surface) must be about 1000° C. This calculation assumes that all the earth's heat is maintained by the thermal energy liberated during the disintegration of uranium and thorium. If, on the other hand, part of the earth's heat (say, one quarter) is a remnant of its original thermal condition, then the temperature at the same depth may be a little above 1000° C.,⁴ and the temperature will continue slowly to increase at greater depths. With a capping of granite and gneiss thicker than is assumed above, the basal temperature of the radioactive layer is (given the same temperature-gradient) reduced below 1000° C., whereas, if the thickness is less than 6 kilometres, the basal temperature becomes higher. With no granite and gneiss (that is, assuming the whole radioactive layer to be of basaltic material having a radium-content of 1.0×10^{-12} grms. per grm.) the temperature would be increased to a maximum of 1650° C. at a depth of about 44 miles.⁵

A temperature of 1000° C. at a depth of 33 miles would be barely sufficient to initiate volcanic activity, even if far-reaching relief of pressure by fissuring be admitted. A temperature of 1650° C. at a depth of 44 miles is in this case an impossible maximum, since there is a capping of granite and gneiss, though of unknown thickness. We may, therefore, conclude that the lavas came from depths between 33 and 44 miles. Even so, it is not likely that a basaltic magma could be formed by fusion unless

¹ See, for example, J. Joly, *Phil. Mag.* vol. xxiv (1912) p. 694; and A. Holmes, *Sci. Progress*, no. 33 (1914) p. 15.

² *Ibid.* p. 17.

³ *Geol. Mag.* ser. 6, vol. ii (1915) pp. 68–69.

⁴ *Ibid.* p. 111.

⁵ *Ibid.* p. 67.

there were a considerable relief of the pressure appropriate to such depths. In this connexion, the boundary-fault along which the lavas are aligned is of particular interest, for it seems to mark a zone along which pressure actually was relieved to an extent and depth sufficient to promote fusion.

The boundary-fault system is probably a consequence of isostatic readjustment between the uplifted mainland and the sunken region of Mozambique Channel. Long denudation of the crystalline plateau should, on the hypothesis of isostasy, naturally lead to its uplift, and that such a movement has taken place is demonstrated by the presence of a coastal belt of Cretaceous and Tertiary sediments, and by the existence of still more recent raised beaches at various levels along the coast (see fig. 5, p. 230). Moreover, the heavy denudation of the crystalline rocks implies the removal of an important section of the 'radioactive layer.' This process therefore leads, like uplift, to the cooling and contraction of the lithosphere, and thus additional tension-stresses are developed that can only find relief in fissures and faults. Doubtless the actual formation of fissures was helped by regional movements of a tensional character, associated in a complementary way with the compressive movements of Tertiary mountain-building elsewhere.

In conclusion, I wish to place on record the unfailing courtesy and hospitality with which we were everywhere received by the Portuguese officials in Mozambique, who were always ready to help us in every way that lay in their power. For permission to publish the geological observations made during the expedition, I owe my thanks to the Directors of the Memba Minerals Ltd.; in particular, I have to thank them for placing at my disposal a large collection of rock-specimens, including those collected in the Sanhuti-River district, and many of those collected by the staff of the Company during the 1910 season. From my friends and former colleagues Messrs. E. J. Starey, E. J. Wayland, and D. A. Wray, I have received notes and sketches referring to the districts in which they worked, and I desire to express my indebtedness to them for help thus afforded. In connexion with the investigation of the rocks in the laboratory, I wish to thank Prof. W. W. Watts for granting every possible facility for work at the Imperial College of Science & Technology; Prof. the Hon. R. J. Strutt for continuing to lend me his apparatus for determining radium in rocks and minerals; Prof. C. G. Cullis and Dr. J. W. Evans for examining many of my sections, and offering valuable suggestions; and Dr. G. T. Prior and Lieut. W. Campbell-Smith for looking through my sections, and allowing me to compare the Mozambique lavas with specimens of similar rocks in the Natural History Museum from British East Africa, Abyssinia, Nyasaland, and other African localities. In making the analyses published in this paper I received considerable help from Dr. H. F. Harwood, Lieut. J. L. Harris, M.C., the late Lieut. G. Kirby, Lieut. A. McIntyre, and Mr. E. Spencer, and for their assistance in an

arduous task I am particularly grateful. Finally, I owe my thanks to Mr. G. S. Sweeting, who kindly cooperated with me in the preparation of the photomicrographs reproduced in Plates XX & XXI.

EXPLANATION OF PLATES XX & XXI.

PLATE XX.

- Fig. 1. *Sölvbergite* (153) found between Miali and the Sanhuti River, Mozambique. Chief minerals: *anorthoclase*, *cosryrite*, and *soda-pyroxenes*. $\times 20$. (See p. 233.)
2. *Ægirine-trachyte* (152) north of Sokoto Hill. Chief minerals: *anorthoclase*, *cosryrite*, and *ægirine*. $\times 20$. (See p. 235.)
3. *Phonolite* (150) near the Sanhuti River. Chief minerals: *anorthoclase*, *nepheline*, *natrolite*, *soda-pyroxenes*, and *amphiboles*. The dark phenocryst is *cosryrite* surrounded by a green *chlorite-like* mineral. $\times 20$. (See p. 236.)
4. Basalt with ophitic patches (156) near the Sanhuti River. Chief minerals: *labradorite* and *augite*, with some *palagonite* in the ground-mass. $\times 20$. (See p. 241.)
5. *Picrite-basalt* (155) near the Sanhuti River. Chief minerals: purple *augite* and *olivine*; *labradorite*, purple *augite*, and glass in the ground-mass. $\times 20$. (See p. 244.)
6. *Micro-vesicular basalt* (128) from a sill at the western base of Sokoto Hill. Chief minerals: *labradorite* and *augite*, in a base of dark-brown glass. The vesicles are occupied by *chalcedony* and *chlorite*. $\times 20$.

PLATE XXI.

- Fig. 1. Basalt (141) from the dyke at Mochelia. Chief minerals: *labradorite* and *augite* in a base of dark-brown glass. $\times 36$. (See p. 246.)
2. *Amygdaloidal sandstone* (112) from contact with the Mochelia dyke (text-fig. 5). Grains of *quartz*, *orthoclase*, and *microcline* are present in the sandstone, cemented by *calcite* which is replaced near the dyke by *opal*. In the steam-holes *opal*, *chalcedony*, and *quartz* are present. $\times 12$. (See p. 249.)
3. *Amygdaloidal basalt* (124) south of the Monapo River. Chief minerals: *labradorite* and *augite* in a base of dark-brown glass. $\times 20$. (See p. 250.)
4. *Amygdale* in *amygdaloidal basalt* (136) east of Murimatigri Quartel. Illustrating the replacement of *heulandite* (dark areas) by *chalcedony*. $\times 20$. (See p. 252.)
5. *Hornblende-andesite* (126) from a dyke penetrating amygdaloid south of the Monapo River. Chief minerals: *andesine*, *hornblende*, and *biotite*, in a ground-mass consisting of the same minerals, together with *quartz* and *orthoclase*. $\times 20$. (See p. 256.)
6. *Pyroxene-andesite* (144) found near the Monapo River. Chief minerals: *andesite*, *augite*, and *hypersthene*, in a ground-mass of *hyalopilitic* texture. $\times 20$. (See p. 259.)

DISCUSSION.

Mr. F. P. MENNELL said that he had listened to the paper with the greater interest, in that he had spent more than ten years in a neighbouring part of Africa. He was quite in accord with

[November 23rd, 1917.]

the Author, that alkaline and non-alkaline rocks were to be found along the African coast in intimate association. It was not clear, however, from what had been said, on what principle the Author separated the rocks that he put into his alkaline group from the others with which he had dealt, and it was not easy to see why they should be treated apart. It was interesting to note that, although alkaline volcanic rocks were so often found in the coastal regions, there were no occurrences known in the inland districts of this part of Africa.

Dr. J. W. EVANS congratulated the Author on his presentation of the results of several years' work on some very interesting rocks. He had not confined himself to simple descriptions of structures and minerals, but had endeavoured to ascertain what light the facts disclosed threw on the evolution of igneous rocks, especially those rich in alkalies. The speaker enquired whether there was any evidence that the alkali-rocks were later than those of normal types in this area.

Mr. A. E. KITSON congratulated the Author on the paper. He asked whether there was any general linear arrangement of the dykes, and if so, whether the lines were parallel with the coast. He said that on both sides of Africa, wherever late volcanic rocks occurred, it seemed that they had been extruded along lines of fracture roughly parallel with the coast, or in fracture-zones inland, and that on the Gold Coast volcanic necks and plugs occurred in several places along the Volta River; but he had not found similar evidence in that colony outside of zones of fracture.

The AUTHOR, in reply, thanked the Fellows for their kind reception of his paper, and stated that most of the points raised in the discussion were fully dealt with in the paper itself. Answering Mr. Mennell, he said that the division of the lavas into two series was based on analyses, variation-diagrams, the composition of the amygdale-minerals, and in part on the sequence, so far as this was known. In reply to Dr. Evans, he was sorry to say that there was no definite field-evidence from which the relations of the two series could be deduced. Referring to Mr. Kitson's remarks, he observed that, as in many other of the African coast-lands, the main faults were parallel to the prevailing trend of the coast, and most of the basaltic dykes followed the same direction.

1. $\times 20$

2. $\times 20$

3. $\times 20$

4. $\times 20$

5. $\times 20$

6. $\times 20$

1. $\times 36$

2. $\times 12$

3. $\times 20$

4. $\times 20$

5. $\times 20$

6. $\times 20$