On a series of volcanic rocks from the neighbourhood of the Lucalla River, Angola.

(*With Plate V.*)

By ARTHUR HOLMES, D.I.C., A.R.C.S., B.Sc., F.G.S.
Demonstrator in Geology, Imperial College of Science and Technology, London.
With Analyses by H. F. HARWOOD, M.Sc., Ph.D.

[Read June 20, 1916.]

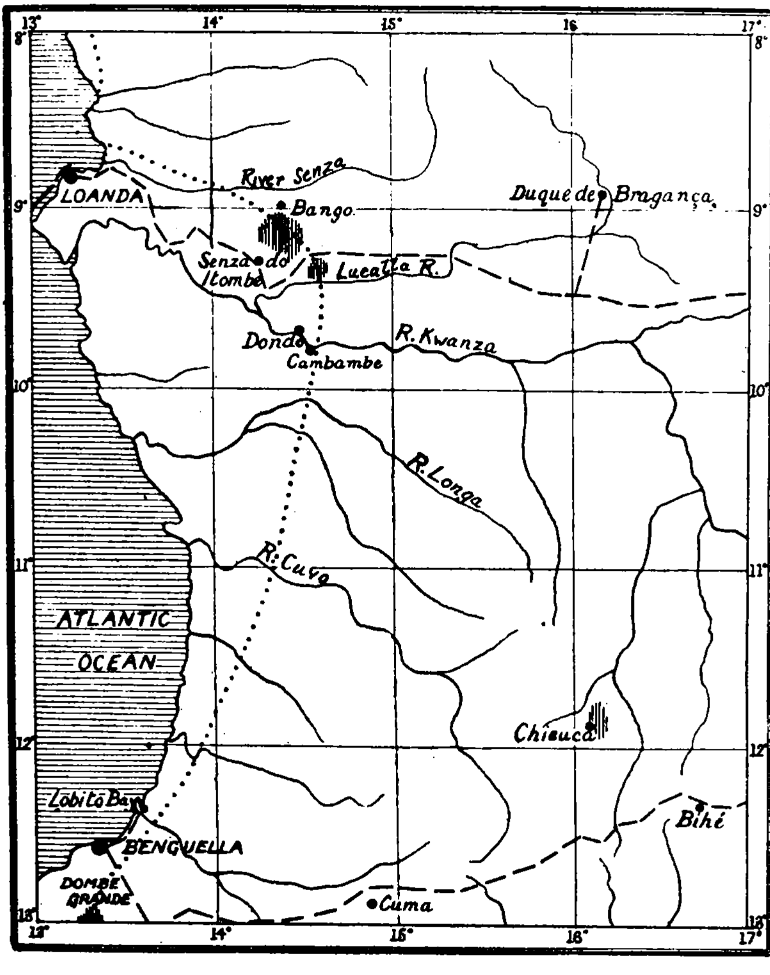
I. *Introduction.*

LAST year, while working through the geographical collection of rocks in the Geological Department of the Imperial College, I found an interesting series of volcanic rocks from the neighbourhood of the Lucalla River in the district of Cambambe, Angola, which hitherto has not been described. The specimens were collected about the year 1860 by J. J. Monteiro,[1] a former student of the Royal School of Mines, who

[1] J. J. Monteiro, 'Angola and the River Congo,' 1875, vol. ii, p. 69, writes: 'A very interesting excursion was one I made [from Cambambe] about thirty miles in a northern direction, where I passed through most beautiful mountain scenery, the formation of the country being trachyte.' On pp. 65 and 70, he mentions the series of lavas lying between Senza do Itombe and Bango, and suggests that the two occurrences are connected.

See also P. Choffat, 'Coup d'œil sur la géologie de la province d'Angola.' Comm. Dir. Trab. Geol. Portugal, 1895-6, vol. iii, pp. 84-91.

devoted many years to the exploration of Angola. The collection, though consisting of only ten specimens, comprises porphyritic basalts, alkali-trachytes, a nephelinite allied to monchiquite, and an augite-andesite. With the permission of Professor W. W. Watts the rocks were investi-



— — — — Railways. Alkaline Igneous Rocks.
· · · · · · · · · Approximate Boundary between the Coastal Belt (Tertiary and Cretaceous formations with local basins of Upper Karroo rocks) and the Archaean Platform.

SKETCH-MAP OF PART OF ANGOLA.

gated by Dr. H. F. Harwood and myself, the results being embodied in the present paper.

A series of igneous rocks of Tertiary age from a neighbouring locality—between Senza do Itombe and Bango—has already been described, briefly by Senhor Pereira da Sousa,[1] and in greater detail by myself.[2] The specimens were collected by my friend Colonel Freire d'Andrade in 1906, and include phonolites accompanied by nepheline-syenite and nepheline-monchiquite.[3]

Unfortunately the age of the rocks collected by Monteiro cannot yet be stated more definitely than that it is post-Karroo. It is significant, however, that they occur, like their neighbours to the north-west (which are known to be of post-Cretaceous age), along the boundary between the sedimentary rocks of the coastal plain and the crystalline rocks of the Archaean belt that lies to the east. On the locality map (see p. 59) the approximate position of this boundary has been sketched in. It will be noticed that volcanic rocks again make an appearance at Dombe Grande, south of Benguella. A collection of rocks from this locality, made by L. Malheiro between the years 1882–6, included two fragments that were determined by J. P. Gomes as 'liparite' and 'nepheline-basalt' respectively.[4] Prof. P. Choffat has kindly sent to me the original sections on which the identifications were based. The 'liparite' is an arenaceous limestone, and the 'nepheline-basalt' is described below as a basanite (p. 73). The lavas of Dombe Grande lie partly on a foraminiferal oolitic limestone of Miocene age and partly on mica-schist belonging to the Archaean belt.

Basaltic rocks are very common between Benguella and Mossamedes, and are responsible for numerous small mesas rising to a height of 200–300 feet never far from the coast. Monteiro describes the lavas as amygdaloids containing heulandite and calcite in great abundance.[5] These again are of Tertiary age and lie over the boundary between the crystalline and sedimentary formations.

[1] Pereira da Sousa, C. R. Acad. Sci. Paris, 1913, vol. clvii, p. 1450.

[2] A. Holmes, Geol. Mag., 1915, dec. 6, vol. ii, pp. 228–232, 322–328, and 366–370. See also G. Berg, Min. Petr. Mitt., 1903, vol. xxii, p. 359.

[3] These are probably the 'trap rocks' encountered by Livingstone almost at the commencement of his journey from Loanda to the Zambesi. 'Travels in South Africa,' 1857, p. 398.

[4] P. Choffat, loc. cit., pp. 89 and 90. J. P. Gomes, Comm. Dir. Trab. Geol. Portugal, 1896–8, vol. iii, p. 289.

[5] J. J. Monteiro, loc. cit., p. 220.

II. Porphyritic Basalts. (Plate V, fig. 1.)

The basalts are dark grey rocks having large porphyritic crystals of labradorite up to 3 cm. in length. The specific gravity of the specimens lie between 2·70 and 2·71, while that of the porphyritic felspar is 2·685. In one case (545) the rock is pitted with nearly spherical vesicles averaging 3 mm. in diameter and carrying a powdery lining of opal. In No. 548 analcime is present, though in small amount. Treated with acid the rocks effervesce slightly, giving off sulphuretted hydrogen, a fact which points to the presence of pyrrhotite. Here and there small tarnished specks of the mineral can be seen in the hand-specimens.

Under the microscope the following minerals are recognized:

Phenocrysts:

- Labradorite, macro-porphyritic and micro-porphyritic: average refractive index, 1·56.
- Olivine, micro-phenocrysts.
- Purple-brown augite (rare), micro-porphyritic.

Groundmass:

- Labradorite: average refractive index 1·56.
- Alkali felspar: average refractive index 1·525.
- Purple-brown augite accompanied by aegirine-augite.
- Titaniferous magnetite and pyrrhotite.
- Analcime and apatite in specimen No. 548.

Vesicles:

- Opal in No. 545: $n=1{\cdot}45$.
- Analcime in No. 548: n between 1·481 and 1·49.

The groundmass makes up rather less than half the rock. In it the three groups of minerals, felspars, pyroxenes, and iron-ores, are present in roughly equal proportions. The structure approaches the intersertal type, laths of labradorite separating grains of pyroxene. Most of the latter display purple tints and are presumably titaniferous, but a few have the colour and pleochroism of aegirine-augite. Between the felspar laths and the pyroxene and iron-ore granules, there are limpid spaces occupied sometimes by untwinned orthoclase which includes minute needles of what is probably apatite, and sometimes (in 548) by an isotropic constituent, the refractive index of which agrees with that of analcime.

Set in this groundmass are large prismatic phenocrysts of labradorite, accompanied by smaller ones that are only visible in thin section.

Extinction-angles (e.g. 18° on brachy-pinakoidal cleavage fragments), refractive index, and specific gravity indicate that the composition is between Ab_5An_5 and Ab_4An_6. Inclusions of iron-ores are common, particularly towards the margins. A few highly refractive blebs are also present, and their high double refraction suggests their identity with either zircon or rutile. Around the borders of the felspars the melanocratic minerals are sometimes noticeably concentrated. Olivine occurs only in one generation, and is remarkably fresh, serpentine being found only along a few microscopic cracks. Micro-porphyritic crystals of augite—pleochroic from purple-brown to straw-yellow—are sometimes moulded around a nucleus of olivine, but otherwise phenocrysts of augite are rare.

An analysis of specimen 548 was made by Dr. Harwood with the following results:

	Per-centages.	Molecular Proportions.
SiO_2	47·98	800
Al_2O_3	21·68	213
Fe_2O_3	0·58	4
FeO	8·28	115
MgO	3·13	78
CaO	8·63	154
Na_2O	3·65	59
K_2O	2·06	22
H_2O	0·73	—
H_2O (at 105° C.)	0·72	—
TiO_2	2·24	28
ZrO_2	0·02	—
P_2O_5	0·06	—
MnO	0·16	2
BaO	0·16	1
SrO	trace	—
S	0·09	3
	100·17	
less O for S	0·04	
	100·13	

Specific gravity 2·71

Mineral Composition ('Norm').		
Orthoclase	12·23	75·91
Albite	22·32	
Anorthite	36·70	
Nepheline	4·66	
Diopside	5·35	22·61
Olivine	11·89	
Magnetite	0·93	
Ilmenite	4·26	
Pyrite	0·18	
Water	1·45	
	99·97	

Class II	Dosalane
Order 5	Germanare
Rang 3	Andase (nearly Hessase)
Subrang 4	Andose (nearly Hessose)

The rock bears a close resemblance to the Markle type of the Scottish Carboniferous basalts, not only in chemical composition, but also in structure and mineral composition.[1] This being the case it is interesting to note that farther south in Angola there is a porphyritic olivine-basalt (Kiticingue, Portichicorcoo) that resembles the Dunsapie type.[2] Speci-

[1] F. H. Hatch, Trans. Roy. Soc. Edinburgh, 1892, vol. xxxvii, p. 119. G. W. Tyrrell, Trans. Geol. Soc. Glasgow, 1912, vol. xiv, p. 241.

[2] Ibid., p. 245.

mens were collected by Mr. R. J. Cuninghame and are now in the British Museum (Natural History), where I was kindly allowed to see them by Dr. G. T. Prior. The rock has a groundmass of labradorite laths with grains of purple augite, much iron-ore, and a little olivine. Phenocrysts are present, generally in glomero-porphyritic masses, consisting of labradorite (with inclusions of augite, iron-ore, and blebs of groundmass); augite zoned in tints of purple and straw-yellow and exhibiting beautifully developed hour-glass structure; and olivine seamed with veins of serpentine.[1]

III. *Nephelinite.* (Plate V, fig. 3.)

This is a dark grey, compact rock (546) speckled with small phenocrysts of pyroxene, and with straw-yellow to red coloured patches that seem to be characterized by the presence of nepheline. Specific gravity 2·85.

The minerals present as seen under the microscope are:

Phenocrysts.	Groundmass.
Nepheline.	Nepheline.
Analcime.	Analcime.
Aegirine.	Orthoclase.
Aegirine-augite.	Calcite.
Purple augite.	
Grey-green augite.	
Barkevikite.	
Sphene.	
Apatite.	
Titaniferous magnetite.	

Pyroxenes, forming a continuous series including the varieties named above, are by far the most abundant minerals present. In many of the largest crystals (1 × 2 mm.), which are idiomorphic, the colours are patchy, and irregular zoning may be seen. Generally the interior is mainly aegirine or aegirine-augite, while the borders, and particularly the terminations (along the *c*-axis), are of a purple colour. On the contrary, the small crystals are largely or even wholly composed of purple augite; aegirine-augite when present is confined to the periphery. Finally, sprinkled among the idiomorphic crystals are irregular grains and blebs

[1] Other basalts and dolerites from the Benguella Plateau have been described by J. P. de Nasciamento, 'A Colonisação de Angola,' Lisbon, 1912, and G. W. Tyrrell, Trans. Roy. Soc. Edinburgh, 1916, vol. li, p. 558.

of grey-green augite. In the larger pyroxenes, apatite and magnetite, probably titaniferous, are present as inclusions.

Ragged shreds of barkevikite—pleochroic from reddish-brown to straw-yellow—may be seen occasionally, the amphibole having grown from the exterior of the pyroxenes, and rarely independently. The extinction angle $Z \wedge c$ is about 10° and the birefringence is moderately high.

Apatite is unusually abundant. It occurs in rounded crystals slightly elongated parallel to the *c*-axis, which are generally crowded with gas pores drawn out parallel to the direction of elongation. For this reason the mineral has a grey or blue appearance in thin section. Similar apatite in a nephelinite from the Little Island of Trinidad has been described by Dr. G. T. Prior.[1] Sphene is present in wedge-shaped crystals of a grey-brown colour. Many of the crystals are twinned and show good pleochroism from greyish-white (X) to light brown (Z). The mineral is often found clinging to the purple terminations of augite crystals or to titaniferous magnetite.

Rounded phenocrysts of nepheline, and isotropic idiomorphic crystals of analcime, sometimes exhibiting a cubic cleavage, are seen in all sections, though they are not uniformly distributed. The same minerals, verified by refractive index measurements and staining methods, are found in the clear transparent groundmass. In addition, however, a certain amount of orthoclase is present. Calcite occurs in small grains as inclusions in analcime and nepheline.

The structure of the rock is far from uniform. Within the main mass of the rock, which is moderately even in texture, and to which the name *nephelinite* is appropriate, there occur irregular patches of two types. The one is finer in grain and darker in colour than the enclosing rock; the other, coarser in grain and lighter in colour. These patches have fairly sharp borders, and are clearly cognate xenoliths or 'enclaves homœogènes' of respectively melanocratic and leucocratic composition relative to that of the surrounding nephelinite. The melanocratic type (fig. 4) consists mainly of pyroxenes with a great abundance of iron-ore; apatite occurs as inclusions, and shreds of biotite and interstitial nepheline are present in small amount. A rock of similar composition would probably be called *jacupirangite*. The leucocratic type is richer in nepheline, altered analcime, and apatite. Aegirine-augite is the chief pyroxene, and sphene and perovskite are present in addition to the

[1] G. T. Prior, Mineralogical Magazine, 1900, vol. xii, p. 322.

iron-ores, which in this case are less prominent. The mineral composition is clearly that of an *ijolite*.

Similar complementary inclusions have been recorded by Lacroix as occurring in the nephelinites of the Oberwiesenthal,[1] and by Stelzner in the nephelinite of Podhorn near Marienbad.[2] Similar leucocratic patches, but including orthoclase, have been found in phonolites from the Little Island of Trinidad[3] and from Fernando Noronha.[4] Although in the present case there is little evidence on which to base an adequate explanation of the origin of the inclusions, the mineral associations of the latter suggest that they are complementary products of differentiation of the magma from which the enclosing nephelinite was crystallized.

IV. Trachytes.

Two varieties of trachyte are represented in Monteiro's collection. Both are characterized by phenocrysts of sanidine, with anorthoclase in the groundmass, but in the one biotite is the chief coloured mineral now recognizable, whereas in the other soda-pyroxenes and amphiboles are abundant, and biotite is absent.

Biotite-Trachyte (560).—The hand specimen is of a cream-grey colour and has a well-marked flow-structure broken here and there by conspicuous prismatic phenocrysts of sanidine, and spangled with shining flakes of biotite.

Under the microscope the only additional minerals that can be determined are anorthoclase, which is present in the groundmass in minute laths, and in radiating groups of needle-like crystals; aegirine, which is developed in minute elongated crystals between the divergent members of groups of anorthoclase needles; and a few grains of magnetite.

The flow-structure is seen in thin section to be controlled by the development of alternate light and dark bands. The former owe their superior transparency to the greater abundance of microliths of anorthoclase. The dark bands are almost opaque on account of the presence of enormous numbers of black globulites, and among these only a few extremely small hair-like felspars can be seen. In each of the bands there are ragged shreds of an obscure reddish-brown alteration product,

[1] A. Lacroix, 'Les Enclaves des roches volcaniques,' 1893, p. 531. For various explanations, see p. 641, et seq.

[2] A. W. Stelzner, Jahrb. k.-k. Geol. Reichsanst. Wien, 1885, vol. xxv, p. 277.

[3] G. T. Prior, Mineralogical Magazine, 1900, vol. xii, pp. 320–321.

[4] O. A. Derby, Amer. Journ. Sci., 1889, vol. xxxvii, p. 185.

and here and there a pleochroic core—reddish-brown to yellowish-green—remains, suggesting a soda-amphibole as the parent material. Similar alteration products represent former amphiboles in the trachytes of Mozambique[1] and the Rift Valley.[2]

The phenocrysts of sanidine are generally corroded by the groundmass, or sharply fractured by flowage. Inclusions of biotite, and grains of iron-ore are present, and many of the crystals are cut through by tongues of groundmass of the dark globulitic type.

Aegirine-Trachyte: (559) (Plate V, fig, 5).—In the hand-specimen of this rock, which is of a pale grey colour, thin prismatic phenocrysts of sanidine twinned on the Carlsbad law, are seen. They vary in length between 5 and 10 mm., and are distributed uniformly through the rock with their long axes parallel.

Under the microscope the following minerals are seen:

Phenocrysts.	Trachytic Groundmass.
Sanidine.	Anorthoclase.
Aegirine and Aegirine-augite.	Aegirine and Aegirine-augite.
Brown alteration products, probably secondary after an amphibole.	Soda-amphiboles.
	Iron-ores.

The phenocrysts of sanidine are idiomorphic and are free from corrosion. Inclusions of soda-pyroxenes and amphiboles, and of magnetite are present, the latter often in strings of small, well-shaped crystals near the periphery. In the groundmass, which has a typical trachytic texture, anorthoclase is by far the most abundant mineral. The laths are beautifully striated by fine lamellar twinning and give a mottled extinction. The extinction-angle is practically straight and the refractive index and double refraction are just perceptibly higher than in sanidine.

Soda-amphiboles are not abundant and, as in the biotite-trachyte, they are largely represented by patches of decomposition products. Around the latter, grains and shreds of aegirine are moulded, and occasionally between the aegirine and the secondary material, cossyrite is present in dark reddish-brown crystals. Elsewhere cossyrite occurs between successive laths of anorthoclase. Sometimes it grows on a nucleus of a katophorite-like amphibole (pleochroic in tints of rose-red, purple-brown,

[1] A. Holmes, Abstr. Proc. Geol. Soc., 1916, No. 994, p. 72.
[2] G. T. Prior, Mineralogical Magazine, 1903, vol. xiii, p. 241.

green, and yellow-green), but in other cases shreds of the latter have grown on cossyrite. It is noteworthy however, that aegirine, wherever the relations can be ascertained, is of later crystallization than either of the amphiboles.

Aegirine, varying to aegirine-augite, is rare as phenocrysts, though occasional idiomorphic crystals diverge the stream of anorthoclase laths. In the groundmass, however, it is abundant in grass-green needles and granular aggregates lying between the felspars. Both amphiboles and pyroxenes appear to have commenced their crystallization before the anorthoclase, and even before sanidine, but to have continued to crystallize beyond the periods of felspar generation.

The rock bears a close resemblance to some of the trachytes of East Africa, the main difference being that most of the latter carry phenocrysts of anorthoclase in addition to those of sanidine. This difference is reflected in the analyses by an excess of soda over potash. In the trachyte from Angola, on the contrary, potash is slightly more abundant than soda. With this exception the aegirine-trachytes of Somaliland, the Höhnel Islands, Lake Baringo, Masailand, and Mt. Meru are closely similar to that here under discussion, especially in the presence of cossyrite and katophorite in addition to the more abundant aegirine. Other similar trachytes are those of São Thomé, St. Helena, the Canary Islands, and the Azores; of Mt. Rotaro, Ischia; of Algersdorf, Bohemia; of the Ravin des Fleurs jaunes, Réunion; and of Mt. Flinders, Queensland.

An analysis of the Angola aegirine-trachyte (specimen No. 559) was made by Dr. Harwood, with the following results:

	Percentages.	Molecular Proportions.
SiO_2	61·02	1017
Al_2O_3	18·88	185
Fe_2O_3	1·98	13
FeO	1·86	26
MgO	0·42	10
CaO	1·34	24
Na_2O	5·76	93
K_2O	6·22	66
H_2O	1·31	—
H_2O (at 105° C.)	0·83	—
TiO_2	0·78	10
P_2O_5	0·007	—
MnO	0·23	3
SrO	trace	—
	100·68	

Specific gravity 2·46

Mineral Composition ('Norm').

Orthoclase	36·70	99·20
Albite	48·78	
Anorthite	6·67	
Corundum	0·20	
Hypersthene	1·66	6·36
Olivine	0.16	
Magnetite	3.02	
Ilmenite	1·52	
Water	2·14	
	100·70	

Class I	Persalane
Order 5	Canadare
Rang 2	Pulaskase
Subrang 3	Pulaskose

This analysis is repeated in the following table for comparison with analyses of some of the trachytes mentioned above. All are conspicuously alkaline types, and except in the Réunion example, potash (by percentage) is in excess of soda. Characteristic features of the analyses are the low magnesia and lime. Titanium and manganese oxides are higher in the Angola trachyte than in average trachyte, most probably on account of the presence of cossyrite.

	A.	B.	C.	D.	E.
SiO_2	61·02	61·49	61·62	64·69	60·58
Al_2O_3	18·88	18·25	18·11	18·34	18·06
Fe_2O_3	1·98	1·77	2·36	—	3·05
FeO	1·86	3·18	1·28	3·44	1·38
MgO	0·42	0·41	0·56	0·50	0·28
CaO	1·34	1·65	1·44	1·72	1·74
Na_2O	5·76	6·78	5·77	4·61	5·01
K_2O	6·22	5·47	7·60	6·46	6·87
H_2O	2·14	0·26	0·78	0·24	1·89
TiO_2	0·78	0·51	0·87	0·81	0·88
MnO	0·23	—	trace	trace	0·04
P_2O_5	0·007	0·09	0·18	0·18	—
BaO	—	—	—	0·09	—
Incl.	—	—	0·15	—	0·07
	100·63	99·81	100·67	100·58	99·75

A. Aegirine-trachyte, near the Lucalla River, 30 miles north of Cambambe, Angola. (Analyst, Harwood.)
B. Phonolitic trachyte, Ravin des Fleurs jaunes, Réunion. (Analyst, Boteau.)
C. Trachyte, Monte Rotaro, Ischia, Italy. (Analyst, Washington.)
D. Trachyte, Algersdorf, Bohemia. (Analyst, Ullik.)
E. Aegirine-soda-trachyte, Mt. Flinders, Queensland. (Analyst, Jensen.)

V. Pyroxene-Andesite. (Plate V, fig. 2.)

This rock (No. 544) is dark grey in colour, and has a well-marked porphyritic texture, the compact groundmass being sprinkled with prismatic phenocrysts of iron-stained andesine averaging 10 × 5 mm. in size.

In thin section the rock is seen to consist of phenocrysts of andesine, hypersthene, and augite, embedded in a coarsely trachytic groundmass, composed of andesine laths, intersertal grains of yellow-green augite, and a dark interstitial glass crowded with black globulites. Iron-ores—mainly titaniferous magnetite and alteration products—occur as inclusions in the phenocrysts and an occasional apatite is enclosed by hypersthene. In places the groundmass is micro-vesicular, the spaces being occupied by iron-stained opal and chalcedony. Apart from the alteration of some of the iron-ores, the rock is remarkably fresh.

The phenocrysts of andesine are generally idiomorphic, clear, and glassy, and exhibit characteristic twinning and zoning. The mean refractive index (nearly the same as that of aniseed oil, 1·556) and the extinction-angles, indicate that the composition is about $Ab_{55}\,An_{45}$. Iron-ores, grains of pyroxene, and patches of groundmass, are present as inclusions, and in a few cases the interior is an emulsion of blebs of dark brown glass and granules of yellow-green augite in a skeleton of andesine, surrounded by a clear mantle of andesine of the same composition. The felspar laths of the groundmass are somewhat richer in the albite molecule, for the mean refractive index is nearly that of nitro-benzol, 1·553, corresponding to a composition of $Ab_{60}\,An_{40}$. The only inclusions present are dark globulites.

The pyroxene phenocrysts occur in slightly rounded idiomorphs. Hypersthene was the first to crystallize, and the smaller individuals frequently serve as nuclei to the later crystals of augite. The latter is of a light greenish-brown colour, notably darker than the yellowish grains of the groundmass.

The order of crystallization is easily determined to be as follows:— Apatite and titaniferous magnetite, hypersthene, greenish-brown augite, andesine ($Ab_{55}\,An_{45}$), andesine ($Ab_{60}\,An_{40}$), yellow-green augite, leaving finally black globulites surrounding a residuum of glass. No biotite or orthoclase, corresponding to the potash, shown to be present by analysis, has been seen in any of the sections.

An analysis of the andesite (No. 544) was made by Dr. Harwood, with the following results:—

	Percentages.	Molecular Proportions.
SiO_2	56·14	936
Al_2O_3	17·81	175
Fe_2O_3	2·69	17
FeO	4·67	65
MgO	4·15	104
CaO	6·81	121
Na_2O	3·59	58
K_2O	1·63	17
H_2O	0 67	—
H_2O (at 105° C.)	0·49	—
TiO_2	1·23	15
P_2O_5	0·12	—
MnO	0·08	1
SrO	0·01	—
BaO	0·04	—
	100·13	

Specific gravity 2·68

Mineral Composition ('Norm').		
Quartz	7·60	75·24
Orthoclase	9·45	
Albite	30·39	
Anorthite	27·80	
Diopside	4·70	23·55
Hypersthene	12·63	
Magnetite	3·94	
Ilmenite	2·28	
Water	1·16	
	99·95	

Class II	Dosalane
Order 5	Germanare
Rang 3	Andase
Subrang 4	Andose

The analysis is in no way exceptional, though its relation to that of the associated basalt is somewhat remarkable. The andesite contains more magnesia than the basalt analysed, and less soda and potash. The latter rock is clearly an alkaline type of basalt, and the association with it of nephelinite and alkaline-trachytes is by no means abnormal. The andesite, however, stands alone, and is no doubt the representative of a totally different series, of which it is as yet the only known member in this part of Portuguese West Africa.

Mineralogically similar andesites (also with alkaline associates) occur on São Thomé, in the Tristan da Cunha group, and near the Monapo River in Mozambique. In the table below, analyses of two other East African andesites are quoted for comparison, and though there is no detailed chemical or mineralogical resemblance, the fact of their occurrence is interesting, for like the Angola example and the rocks mentioned above, they are associated in the field with alkaline types of lavas. For close chemical analogues, it is necessary to compare rocks from western America and Kamchatka.

	A.	B.	C.	D.	E.	F.
SiO_2	56·14	60·76	56·65	56·91	56·47	57·32
Al_2O_3	17·81	16·81	22·11	18·18	15·33	19·79
Fe_2O_3	2·69	2·07	3·31	4·65	2·54	5·33
FeO	4·67	2·34	—	3·61	4·53	1·52
MgO	4·15	3·27	3·42	3·49	5·08	3·48
CaO	6·81	6·57	6·67	7·11	6·93	6·82
Na_2O	3·59	3·32	1·86	4·02	3·81	3·51
K_2O	1·63	2·10	4·10	1·61	1.66	1·62
H_2O	1·16	1·67	2·20	0·36	1·65	0·56
TiO_2	1·23	0·31	—	—	0·99	—
MnO	0·08	0·22	0·16	—	0·18	trace
P_2O_5	0·12	—	trace	0·25	0·54	—
Incl.	0·05	—	—	—	—	—
	100·13	99·44	100·48	100·19	99·71	99·95

A. Pyroxene-andesite, near Lucalla River, Angola. (Analyst, Harwood.)
B. Hornblende-andesite, near Monapo River, Mozambique. (Analyst, Holmes.)
C. Amphibole-biotite-andesite, Mt. Meru, East Africa. (Analyst, Pinkert.)
D. Pyroxene-andesite, Purgatorio, Pasto Volcano, Colombia. (Analyst, Kuch.)
E. Pyroxene-andesite, Munraven Peak, Yellowstone Park. (Analyst, Gooch.)
F. Augite-andesite, Korjaka, Kamchatka.

VI. General Discussion.

Perhaps the most interesting problem suggested by the assemblage of rocks described above is that of the relation of the pyroxene-andesite to the associated alkaline suite of lavas. The analyses, and the mineralogical compositions of the rocks indicate clearly that the andesite could not have been produced by differentiation in the direct line of descent from olivine-basalt to alkali-trachyte. Such an intermediate rock, had it been erupted, should be a trachydolerite or a trachyandesite.[1] The close field association of calc-alkaline and alkaline types is admirably illustrated in eastern Africa (e.g. in Somaliland, Abyssinia, Kordofan, and the islands of Lake Rudolf; along the Uganda Railway and in the Kavirondo country; in the neighbourhood of Mount Meru and Kilima Njaro; along the Songwe River, and in Mozambique). In every case where the relations have been established, it is found that the eruption of the calc-alkaline series preceded that of the alkaline series, and that the andesites belonging to the former series are associated with basalts heavily charged with an excess of silica.[2] On the other hand, the basalts associated with the alkaline lavas are undersaturated[3] in silica.

In Angola, basalts of the oversaturated type have not yet been found. Specimen 545 of Monterio's collection carries a small amount of vesicular opal, but this does not constitute oversaturation, for the rock, like No. 548, contains unaltered phenocrysts of olivine. The andesite is therefore left without a recognized parent and without natural associates of any kind.

It is to be remembered, however, that the lavas from near the Lucalla River may not all be of the same age. By analogy with their neighbours, the rocks of the alkali series are probably of Tertiary age. The andesite may be of similar age or it may be late Karroo, and if the latter it would naturally fall into line with the wide-spread late Karroo basalt-andesite-rhyolite series of South and Central Africa. In this connexion, it is interesting to notice that rhyolites of a distinctly sub-alkaline type occur near Cuma where they were discovered by Professor J. W. Gregory during his recent journey through Benguella. In Benguella (near Chieuca and Ochilesa) the igneous rocks subsequently erupted were alkaline types[4] including nepheline-sodalite-syenite, shonkinite, ouachitite, and sölvsbergite. The basalts and dolerites occurring elsewhere in the same district were probably of the same or later age. The Benguella sequence—calc-alkaline succeeded by alkaline—thus conforms to that followed in many localities of eastern Africa. Whether this is also the

[1] See H. S. Washington, Journ. Geol., 1897, vol. v, p. 366.
[2] A. Holmes, Abstr. Proc. Geol. Soc., 1916, No. 994, p. 72.
[3] S. J. Shand, Geol. Mag., 1913, p. 508; 1914, p. 485; 1915, p. 339.
[4] G. W. Tyrrell, Trans. Roy. Soc. Edinburgh, 1916, vol. li, p. 550.

Rocks Characterized by:		Between Senza do Itombe and Bango [1]	Near Lucalla River, 80 miles N. of Cambambe [3]	Near Chieuca and Ochilesa.[4]	Near Dombe Grande.[5]	Between Cachanga and Cantiates.[6]
Alkali-Felspars	L.		Biotite-trachyte Aegirine-trachyte*	Sölvsbergite Akerite		Alkali-syenite
	M.			Shonkinite*		
Alkali-Felspars and Felspathoids	L.	Nepheline-phonolite Nepheline-syenite Nepheline-sodalite-syenite[2]		Tinguaite-vitrophyre Nepheline-sodalite-syenite Sodalite-syenite		
	M.	Olivine-ulrichite				
Calc-alkali-felspars and Felspathoids M.			Olivine-basalt* with Analcime		Basanite	
Felspar absent or accessory M.		Nepheline-monchiquite*	Nephelinite (Jacupirangite and Ijolite)	Ouachitite		
L = Leucocratic M = Mesocratic or Melanocratic			Associated with Olivine-basalt		Associated with Olivine-basalt	Associated with Gabbro

[1] A. Holmes, Geol. Mag., 1915, dec. 6, vol. ii, p. 369. [2] G. Berg, Min. Petr. Mitt., 1903, vol. xxii, p. 357. [3] This paper.
[4] G. W. Tyrrell, Trans. Roy. Soc. Edinburgh, 1916, vol. li, p. 550. [5] This paper. [6] P. da Sousa, C.R. Acad. Sci. Paris, 1916, vol. clxii, p. 692.
* Signifies that the rock has been analysed.

case farther north, in the Lucalla River area, can only be disclosed by future field work.

Alkaline rocks of late geological age are now known from several eruptive centres in Angola, and while there are distinct signs of consanguinity connecting them all, it is a curious fact that with one exception no individual type is represented at more than one locality. In the accompanying table the various assemblages are summarized (p. 72).

VII. Note on a Basanite from Dombe Grande, near Benguella. (Plate V, fig. 6.)

As already stated, this rock was collected by L. Malheiro, and was determined by J. P. Gomes as a nepheline-basalt. Since, however, the rock contains numerous laths of bytownite, it is here described as a basanite. The hand-specimen is at first glance barely distinguishable from that of the nephelinite described in § III. It is, however, more finely grained than that rock and is sprinkled not with pyroxene phenocrysts, but with serpentinized olivine and grains of iron-ore. Unlike the nephelinite, the basanite carries a few small amygdales occupied mainly by iron-stained analcime. Specific gravity 2·87.

The minerals identified under the microscope are as follows:

Small Phenocrysts.

Pseudomorphs after Olivine.
Titaniferous magnetite.
Apatite.
Bytownite (rare).

Amygdales.

Chlorite (lining).
Analcime.
Calcite.

Groundmass.

Bytownite.
Nepheline and Analcime.
Grey-green and purple augite.
Aegirine-augite.
Barkevikite.
Apatite and Iron-ores.
Calcite.

Among the phenocrysts, olivine pseudomorphs are the most abundant. None of the original mineral now remains, alteration to red or reddish-brown iddingsite—sometimes with a core of leek-green serpentine—having been complete. Rectangular sections of titaniferous magnetite are sprinkled plentifully through the slide, in company with others of less regular outline. The presence of titanium is revealed by frequent alteration to leucoxene. Next in order of abundance come well-formed crystals of blue and smoky apatite, the haüyne-like appearance being due (as in the nephelinite of the Lucalla River district) to the presence of innumerable gas pores drawn out parallel to the long axis. Small clear rods of apatite occur as inclusions in some of the titaniferous magnetite crystals, and the latter in turn are found in the olivine pseudomorphs. Bytownite in rectangular sections with broad twin-lamellae occurs sparingly. All the preceding constituents of the rock occur in it as inclusions, and the order of crystallization among the phenocrysts is thus clearly established.

In the groundmass, olivine is not represented. Laths of bytownite; hexagonal rods of apatite, some blue and smoky, some zoned, and others perfectly clear; grains of augite varying in colour from purple through brown and grey-green to the light green of aegirine-augite; shreds of barkevikite; and innumerable small rectangles of iron-ore, are distributed in a base of iron-stained analcime and nepheline. Analcime is sometimes present in approximately circular spaces with occasional sharp angles controlled by the disposition of dark minerals around the periphery. Among the latter, short wisps of reddish-brown barkevikite are generally present. Occasional traces of cubic cleavage, and a refractive index between 1·481 (castor oil) and 1·491 (toluol), together with the isotropic character, determine the identity of the mineral. Much of the colourless base of the groundmass has exactly the same appearance as the mineral of the open spaces, and there is therefore no reason to regard it as glass rather than analcime. In places blebs and patches of granular calcite are associated with the interstitial analcime. The same pair of minerals occupies the tiny amygdales of the rock, which are lined by a minutely banded variety of chlorite. Here and there the base contains plates of clear glassy nepheline, distinguishable from the neighbouring analcime by its superior refractive index, low double refraction, and uniaxial character. The mineral forms vaguely outlined plates in which the heavier minerals of the groundmass are poikilitically included.

The general order of crystallization for the various stages of consolidation may be stated as follows:—

Phenocrysts:

Apatite, titaniferous magnetite, olivine, bytownite.

Groundmass:

Apatite, titaniferous magnetite, bytownite, augite, aegirine-augite, barkevikite, nepheline, analcime (and calcite?).

Amygdales:

Chlorite, analcime, calcite.

Explanation of Plate V.

Figs. 1–5.—Near the Lucalla River, 80 miles north of Cambambe, Angola.

Fig. 1.—*Porphyritic Basalt* (No. 548). Ordinary light (× 18). Phenocrysts of labradorite and purple augite in a base of labradorite, pyroxenes, and iron-ores.

Fig. 2.—*Pyroxene-Andesite* (No. 544). Ordinary light (× 18). Phenocrysts of andesine and hypersthene in a groundmass of andesite laths, granular augite, and interstitial glass.

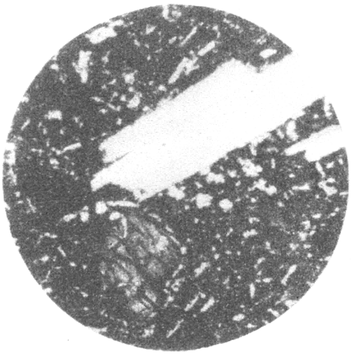
Fig. 3.—*Nephelinite* (No. 546). Ordinary light (× 80). Phenocrysts of nepheline, pyroxenes, sphene, and iron-ores, in a base of nepheline, analcime, and orthoclase.

Fig. 4.—*Jacupirangite*. Ordinary light (× 25). Cognate xenolith of melanocratic type in nephelinite (No. 546). Pyroxenes and iron-ores, with interstitial nepheline.

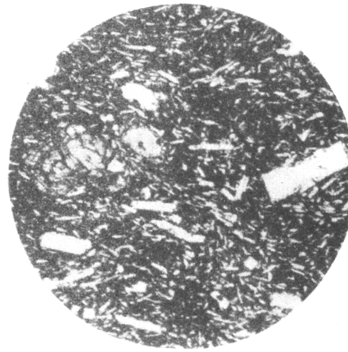
Fig. 5.—*Aegirine-Trachyte* (No. 559). Ordinary light (× 18). Phenocrysts of sanidine and aegirine in a trachytic groundmass of anorthoclase laths, soda-pyroxenes and amphiboles, and iron-ores.

Fig. 6.—*Basanite, Dombe Grande, near Benguella.* Ordinary light (× 25). Phenocrysts of olivine (altered to iddingsite and serpentine) and titaniferous magnetite, in a groundmass of bytownite, apatite, pyroxenes, barkevikite, nepheline, and analcime.

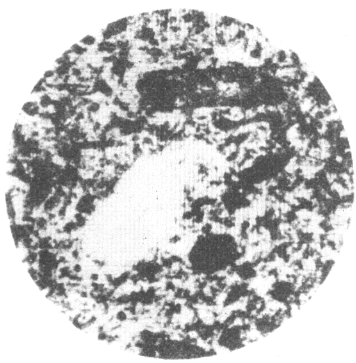
The photomicrographs are the work of Mr. G. S. Sweeting (of the Geological Dept., Imperial College), to whom I owe my thanks for the care with which he has prepared them.



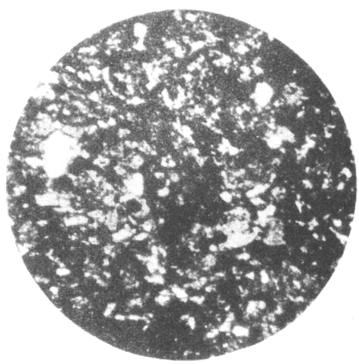
1



2

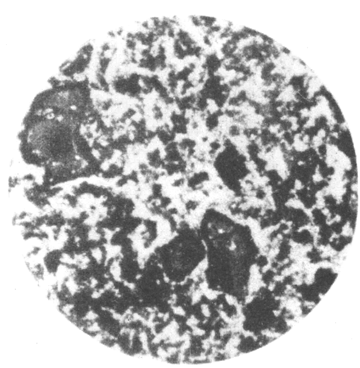


3



4

5



6

A. HOLMES: VOLCANIC ROCKS FROM ANGOLA.