THE AMERICAN MINERALOGIST, VOL. 51, SEPTEMBER-OCTOBER, 1966

THE PETROLOGY OF THE KARROO BASALTS OF BASUTOLAND

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Abstract

An account is given of the petrography and petrochemistry of the Karroo basalts of Basutoland, a horizontal flood-basalt sequence 5000 feet thick. With few exceptions the rocks are tholeiitic basalts poor in olivine and either slightly quartz or slightly olivine-normative. A few flows towards the base of the sequence are richer in olivine.

A chemical comparison is made between the basalts and the Karroo Dolerites, which cut the sediments below the basalts, and it is concluded that the two suites are closely related members of the same series of magmas.

The basalts on extrusion carried microphenocrysts of olivine and plagioclase and a comparison is made between the compositions of the lavas and the liquids in equilibrium at 1 atmosphere with forsterite and anorthite in the synthetic system Fo-Di-An-Qz. The very close match between the lavas and the synthetic liquids leads to the conclusion that the rocks owe their phase and residual liquid compositions to fractional crystallization at or near atmospheric pressure.

Fractionation is more advanced in flows from higher stratigraphic horizons and a brief discussion is given of the problem of whether this indicates progressive fractionation with the increasing height of the magma column or progressive fractionation with time in a static and steadily fractionating chamber.

Introduction

The Karroo basalts of Basutoland form an isolated remnant of an originally more extensive lava field which may have covered much of southern Africa at the end of the Karroo period (approximately during the Jurassic). General accounts of the geology and extent of the lavas are given by du Toit (1954) and Haughton (1963). The principal areas now covered by Karroo igneous rocks in southeastern Africa are shown in Fig. 1. The lavas of the central part of the continent including the Basutoland, Springbok Flats and Kalahari areas are preserved as relatively thin sequences (*e.g.*, 5000 ft in Basutoland) and are rather uniform and monotonously tholeiitic in character. In the strongly warped eastern monoclinal area, however, (including the areas of Lupata, Nuanetsi and the Lebombo) the sequence locally includes nephelinites and large volumes of so-called limburgite at the base. The latter are largely-glassy olivine-tholeiites and are overlain by more oversaturated rocks broadly akin to the normal tholeiites of the central area. In Lupata, Nuanetsi, and the Lebombo, the basalts are succeeded by rhyolites, and the total thickness of volcanics is very great, *e.g.* 26,000 ft is estimated as a minimum thickness in the Nuanetsi area (Cox *et al.*, 1965).

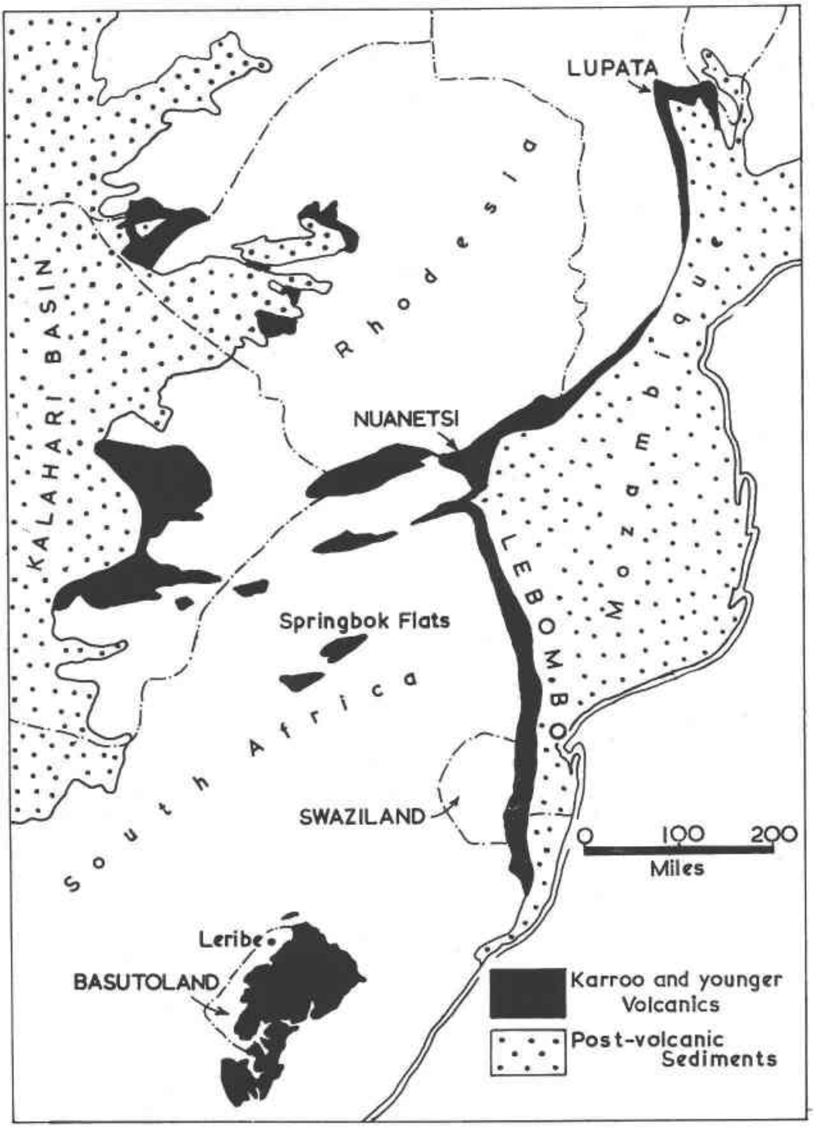

FIG. 1. Locality map showing principal areas of Karroo volcanics in southeastern Africa.

SAMPLING

The Basutoland basalts build up a large dissected plateau, the northeastern and southeastern margins of which form part of the South African Drakensberg. The main part of the highlands (known as the

Maluti Mountains), lies within Basutoland and rises to a general level of somewhat over 10,000 ft. An account of the geology of Basutoland is given by Stockley (1947).

The basalts analyzed in the present study were collected along the track running from Leribe to Kao mine (Fig. 2) and from between Kao and the summit of Thaba Bosiu to the southeast. Samples were located on the 1:50,000 contoured maps published by the Directorate of Overseas Surveys and heights above sea-level were converted to heights above the base of the basalt succession (Table 1). Mapping revealed a very gentle southeastward dip west of the Letele pass for which corrections were made in the conversion. East of Letele the basalts are essentially horizontal.

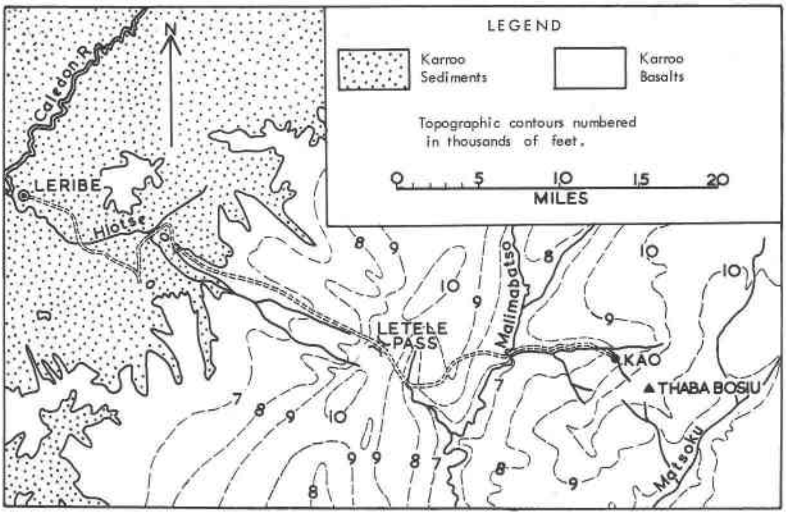

FIG. 2. Geological sketch map of part of northern Basutoland showing localities of areas sampled.

The 5,000-foot basalt succession was sampled on the average every 70 vertical feet, the average thickness of individual flows being estimated at 35 feet. Twenty-four rocks were analysed, each collected from the massive central portion of a flow. It is probable that this collection is typical enough of the whole Basutoland outcrop since earlier workers (*e.g.* Stockley 1947) have often commented on the monotonous uniformity of the lavas. In addition, Dr. D. R. Workman kindly made available a large number of thin sections of basalts from the Sani Pass, on the eastern boundary of Basutoland, and these are petrographically indistinguishable from the Letele-Kao specimens. During the present work the basalts

TABLE 1. LOCALITIES AND HEIGHTS ABOVE BASE OF SUCCESSION OF ANALYZED BASALTS

Spec. No.	Locality	Height above sea level (ft)	Height above base of succession (ft)
B. 1	C	7,675	2,400
B.19	C	8,750	3,250
B.21	C	8,335	2,835
B.31	D	10,650	5,150
B.32	D	10,600	5,100
B.33	D	10,500	5,000
B.36	D	10,350	4,850
B.37	D	10,275	4,775
B.39	D	10,060	4,560
B.42	D	9,850	4,350
B.47	D	9,600	4,100
B.59	B	7,350	1,750
B.61	B	6,880	1,380
B.62	B	6,975	1,475
B.63	B	7,075	1,575
B.66	A	5,875	25
B.67	A	5,890	40
B.69	A	5,775	275
B.70	A	5,850	340
B.71	A	5,900	380
B.72	A	5,900	420
B.74	A	6,200	650
B.76	A	6,150	550
B.78	A	6,650	1,150

Localities

A—On track from Leribe between base of basalt succession and Letele Pass (see Fig. 2).
B—On track between Malimabatso R. and Kao mine.
C—Vicinity of Kao mine.
D—Between summit of Thaba Bosiu and stream junction 1 mile to WNW.

of Mont-aux-Sources in the Natal Drakensberg were also examined briefly without any notable difference becoming apparent.

PETROGRAPHY

The uniformity of the basalts is little less striking in thin sections than it is in the field. The rocks are typically tholeiitic in appearance, containing little olivine and substantial amounts of interstitial glass. Although the rocks rarely appear porphyritic in the field, microphenocrysts of plagioclase and altered olivine are almost always present in chilled basalts from flow bases. The central, massive portions of flows are generally rather coarse, tabular groundmass plagioclase crystals often reaching 1 mm across, with the result that the microporphyritic texture is somewhat obscured. Clinopyroxene generally has an ophitic to subophitic relation to the plagioclase in the coarser rocks, which consequently have a doleritic appearance in thin section. Fine-grained specimens have typical microporphyritic basaltic textures.

In the majority of the basalts examined, small pseudomorphs after *olivine* make up 1–2% of the rock but it is occasionally difficult to distinguish altered olivine from altered glass and the original presence of olivine cannot always be substantiated. No fresh olivine has been found in any of the normal basalts. A few olivine-rich flows are, however, found at the base of the succession on the Letele track and these contain about 12% of olivine, some of which is still unaltered. The crystals tend to be euhedral and have compositions in the range of Fa_{28}-Fa_{32} as determined from measurements of 2V. A similar olivine-rich flow is found 955 feet above the base of the succession on the Sani Pass Road where the lowermost 2,500 ft of the whole succession is present.

Augite is the dominant pyroxene and has optical properties: $\beta = 1.693 \pm .002$ and $1.695 \pm .004$ in two separated samples. $2V_z$ is generally 50°–54° for crystal centres and 42°–45° for crystal margins. The augite is accompanied in many rocks by *pigeonite* ($2V_z$ *ca* 8°) which makes up about a quarter of the total pyroxene. Both pigeonite and augite appear as nearly colorless anhedral crystals which are indistinguishable in general appearance.

Plagioclase is the most abundant mineral of the rocks and includes sparse microphenocrysts which may be up to 2 mm across, not uncommonly arranged in a glomeroporphyritic fashion. Zoning is common in both phenocryst and groundmass plagioclases and is in places oscillatory in the phenocrysts.

A study of the optic orientation of some microphenocrysts following the system used by Muir (1955) suggests that the plagioclases have high-temperature optics (Fig. 3). Determinations were made where possible on the external parts of normally zoned microphenocrysts where compositions were sufficiently sodic for plots of the position of (010) poles to fall in the area where the low and high temperature migration curves are at least moderately divergent. Compositions were then determined from the maximum extinction angles in the zone normal to (010) using the high-temperature curves of Tobi (1963). Many microphenocrysts were found to have centers of bytownite (commonly An_{72-73} and locally as high as An_{80}) and to be zoned marginally to An_{45-50}. When a distinction can be made between groundmass and phenocryst plagioclases the former are more sodic with centers of An_{60-65} and margins down to An_{45}.

Glass is relatively abundant in most of the rocks and may reach 25% by volume. It is mainly dark brown and crowded with minute granules of *ore*. The latter is concentrated in the glass and can appear in an elaborate dendritic form or as somewhat larger anhedral crystals. In many of the rocks examined much of the glass is altered to a variety of radiating micaceous mineraloids ranging from a clear bright orange to an almost opaque dull green appearance. Qualitative *x*-ray fluorescent study shows these to be iron-rich, but diffraction studies were unsatisfactory and gave little more than an indication of a montmorillonite-group peak in some specimens.

Zeolites are very widely present in amygdules. Natrolite, heulandite, phillipsite and apophyllite have been identified but no systematic study has been made.

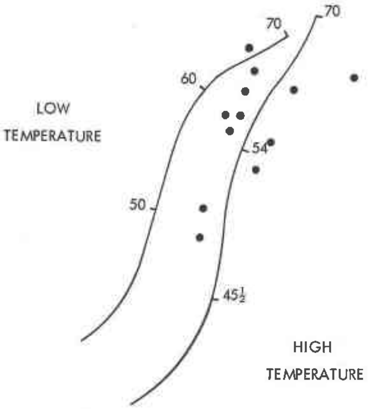

FIG. 3. Partial stereogram showing positions of (010) poles of plagioclases relative to the high-temperature and low-temperature migration curves of Muir (1955).

ANALYTICAL METHODS

Analysis of Si, Ti, Al, Fe, Mn, Ca, Mg, K, and P was by *x*-ray spectrometry, using a Siemens-Halske Kristalloflex 4 unit. Specimens were prepared in duplicate from minus 50 micron rock-powder diluted 4:1 with cellulose binder and briquetted in a $1\frac{1}{2}$ inch diameter mold against a highly polished stainless steel disc (Hornung, 1963, 1965).

Calibration curves of *x*-ray intensity against weight percentage of each of the analyzed elements were prepared from 10 analyzed basalts and before analyzing the Basutoland specimens, W_1 was treated as an unknown and analyzed from these working curves. The results so obtained fell within the range of preferred values for W_1 quoted by Fleischer and Stevens (1962).

The Basutoland analyses were then obtained by direct comparison with these working curves, counting unknown rocks and a reference standard (W_1), alternately to minimize potential errors due to electronic changes. Each element was determined from duplicate briquettes, all the measurements being made for one element in all the samples before resetting goniometer and detector conditions, in order to reduce as far as possible any mechanical or human errors.

Precision in terms of relative deviation is better than 5% for Si, Al, Mg and better than 3% for other elements. The accuracy depends to a large extent upon the accuracy of the analyses of the standards (Welday *et al.* 1964).

Water was determined by Penfield's method, ferrous iron by titration with potassium dichromate, and sodium by flame photometer.

Dr. J. M. Rooke kindly determined the trace element contents of the same basalts, using the methods described by Rooke and Fisher (1962).

The results of major and minor element analyses are given in Tables 2 and 3.

COMPARISON WITH THE KARROO DOLERITES

One object of the investigation of the Basutoland basalts was to check the degree of correspondence between them and the Karroo Dolerites, the widespread series of sills penetrating the sedimentary rocks below the basalts. The establishment of the connection between these two, the extrusive and intrusive aspects of igneous activity in the Karroo basin, was regarded as of particular interest because of the importance the sills have had in petrological thought as a result of their study by Walker and Poldervaart (1949).

In Table 2 the new analyses are compared with those analyses from Walker and Poldervaart (1949) which cover the same range of Fe/Mg index. Table 3 shows a comparison of trace element data from Nockolds and Allen (1956) with the new data.

In both major and minor elements there is a close agreement between the analyzed basalts and the analyzed dolerites. Dr. J. M. Rooke (pers. comm.) made a statistical study of the minor element data and concluded that the differences between the average values for the basalts and dolerites were "highly significant" (*i.e.*, could only arise less than 1 in 1000 times by chance) for Ga and V. The differences between the values for Ba and Sr were "probably significant" (*i.e.*, could only arise less than 1 in 20 times by chance) and the differences between all other elements were "insignificant". It may of course be possible that a comparison of the Basutoland basalts with quite unrelated theolitic suites from other parts of the world would also yield insignificant differences between many ele-

TABLE 2. MAJOR ELEMENT ANALYSES OF BASUTOLAND BASALTS

	B.1	B.19	B.21	B.31	B.32	B.33	B.36	B.37	B.39	B.42	B.47	B.59	B.61	B.62	B.63	B.66	B.67	B.69	B.70	B.71	B.72	B.74	B.76	B.78	A	B
SiO_2	49.4	51.0	49.5	51.3	50.5	52.5	49.9	48.5	51.1	50.2	50.0	47.9	51.4	51.5	50.8	50.0	49.0	51.9	50.9	50.0	51.7	51.4	51.2	50.4	51.8	52.7
TiO_2	.93	1.35	1.12	1.28	1.20	1.29	1.29	.93	1.36	1.17	1.12	.98	.99	.97	.93	.92	.89	1.00	.93	.87	1.02	1.36	.92	.95	1.13	1.16
Al_2O_3	14.1	13.1	13.9	14.1	14.1	13.8	13.5	14.2	14.3	14.2	14.8	15.3	14.7	15.2	14.7	12.3	11.6	14.5	14.6	11.6	14.1	15.1	14.4	14.9	14.8	15.4
Fe_2O_3	5.00	6.10	3.33	3.70	4.54	6.38	5.53	3.70	5.96	5.26	4.32	3.82	3.67	3.41	3.48	2.56	2.80	1.54	1.62	5.10	1.50	2.21	2.68	2.72	3.92	1.38
FeO	6.17	6.05	7.94	8.19	7.01	5.10	6.29	6.74	6.48	6.25	7.43	7.11	6.15	7.07	7.10	10.03	9.88	8.53	8.12	7.84	7.82	9.06	7.07	7.22	7.26	9.35
MnO	.16	.16	.15	.19	.16	.14	.17	.14	.22	.18	.17	.17	.17	.18	.14	.20	.16	.17	.12	.17	.18	.22	.13	.15	.17	.22
MgO	7.7	6.4	7.4	5.7	7.4	6.4	6.0	6.5	5.7	6.2	6.0	6.9	7.1	6.5	7.9	10.6	11.8	8.1	7.6	11.5	7.7	6.6	7.7	7.7	7.1	6.6
CaO	10.43	9.65	10.26	10.70	10.03	9.26	9.20	10.17	9.81	10.08	10.47	11.72	10.44	10.87	10.86	8.62	8.12	10.39	10.35	8.24	10.33	10.65	10.18	10.95	10.57	9.96
Na_2O	2.26	2.48	2.56	2.35	2.19	2.36	2.37	2.34	2.53	2.55	2.43	1.88	2.42	2.43	2.31	2.07	1.85	2.18	2.06	2.19	2.27	2.63	2.20	2.28	2.40	2.22
K_2O	.66	.84	.74	.60	.62	.67	.79	.70	.88	.87	.71	.48	.68	.74	.37	.66	.59	.60	.55	.58	.60	.87	.66	.52	.74	.87
H_2O^+	3.54	3.26	2.71	1.14	2.79	1.84	4.33	5.01	3.11	3.45	3.85	4.12	2.72	.94	1.86	2.40	3.23	1.01	2.13	1.29	1.88	.83	2.49	1.54	—	—
P_2O_5	.11	.13	.17	.15	.13	.13	.14	.10	.16	.14	.13	.13	.15	.13	.12	.09	.06	.17	.10	.05	.08	.17	.10	.12	.13	.16
Total	100.46	100.52	99.78	99.40	100.67	99.87	99.51	99.03	101.61	100.55	101.43	100.51	100.59	99.94	100.57	100.39	99.98	100.09	99.08	99.43	99.18	101.10	99.73	99.45		
Fe/Mg Index	58.4	64.8	59.9	67.1	60.2	63.1	65.5	61.0	67.8	64.2	65.6	60.7	57.6	61.2	56.7	54.1	51.3	55.3	56.1	51.7	54.6	62.9	55.5	55.9		

Analyst: G. Hornung

The Fe/Mg Index is calculated as $\frac{(FeO+Fe_2O_3)\times 100}{FeO+Fe_2O_3+MgO}$ after recalculating to an oxidation ratio $\left(\frac{Fe^{3+}}{Fe^{2+}+Fe^{3+}}\right)$ of 0.1

Column A—Average of the basalts excluding B.66, 67 and 71 (olivine-rich types).

Column B—Average of 44 Karroo Dolerites (Walker & Poldervaart, 1949) covering the same range of Fe/Mg index as the basalts.

TABLE 3. TRACE ELEMENT ANALYSES OF BASUTOLAND BASALTS (OPTICAL SPECTROGRAPH). (p.p.m.)

Element	B.1	B.19	B.21	B.31	B.32	B.33	B.36	B.37	B.39	B.42	B.47	B.59	B.62	B.63	B.66	B.67	B.69	B.70	B.71	B.74	B.76	B.78	A	B
Ba	260	290	260	320	300	310	250	350	300	300	240	190	240	180	220	200	160	200	200	300	210	210	256	200
Be	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	
Co	30	30	30	35	30	30	30	30	30	35	40	40	30	35	50	55	45	40	40	40	35	35	34	38
Cr	350	210	200	230	220	180	170	220	190	200	260	220	350	500	550	550	500	650	550	230	350	800	317	293
Ga	16	18	18	18	18	15	15	13	15	16	14	13	17	13	17	14	17	21	19	20	19	13	16	24
Li	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	9
Mo	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	3	3	< 3	< 3	
Nb	10	10	15	15	15	15	15	10	25	10	15	<10	<10	<10	<10	<10	15	<10	<10	15	15	<10		
Ni	90	70	60	60	50	50	45	25	65	45	55	70	45	80	260	350	130	130	100	70	95	150	73	70
Pb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Rb	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<30	<50	<50	<30	<50	<50	<50	17
Sc	50	25	30	55	25	40	20	40	25	25	30	30	40	30	25	40	30	45	45	35	25	50	34	38
Sr	260	250	240	270	220	240	180	260	230	230	150	120	270	200	140	120	140	150	190	220	110	310	190	168
V	350	300	300	400	300	300	250	300	250	350	350	250	300	300	250	250	300	300	300	350	200	250	300	225
Y	15	15	20	30	25	25	35	25	40	15	25	15	15	10	10	<10	35	10	15	40	25	10	23	22
Zr	80	75	90	110	85	100	85	95	90	100	100	60	75	55	85	75	90	70	80	130	65	55	85	88

Column A—average of Basutoland basalts (19 samples) excluding the olivine-rich basalts, B.66, B.67 and B.71. Analyses by J. M. Rooke.
Column B—average values for Karroo Dolerites (16 samples) covering the same range of Fe/Mg index as the basalts (Nockolds and Allen, 1956).

Trace element analyses for the basalts obtained by x-ray fluorescence.

Ba	250	255	255		230	275	260	260	255	250	245	275	180	250	250	130	250	100	250	265	220	140
Rb	8	16	18		30	25	37	33	40	45	30	37	42	25	35	42	38	36	40	35	28	15
Zr	109	156	90	122		128	142	106	127	142	111	95	103	82	124	112	72	82	107	133	92	84

Analyst—G. Hornung

ments, but the present results must encourage the belief that the Basutoland basalts represent the same series of magmas as the Karroo dolerites. Such differences as are observed are as likely to be due to differing analytical methods as to any real difference between the two groups.

The similarity of the basalts and dolerites in the Basutoland region is well worth establishing, however, because in the Nuanetsi province of Karroo volcanics there is, in contrast a very marked discrepancy between the geochemistry of the basalts and the geochemistry of the gabbros which penetrate them (Cox *et al.*, 1965, 197).

Finally it is worth noting that the main compositional difference between the Basutoland basalts and the Karroo dolerites lies in the greater range of Fe/Mg index covered by the sills, when all the analyses of the latter are considered. A relatively small number of dolerite analyses (Walker and Poldevaart, 1949) have higher indices than the basalts while a rather large proportion have lower indices than the basalts (*i.e.*, show less iron enrichment relative to magnesium). The possible significance of this point will be discussed in a later section.

Discussion of the Compositions of the Basalts

Plotting data. To study variation in a rock-series effectively it is useful to consider simultaneously as many variables as possible. Accordingly, the analyses have been re-cast in terms of normative olivine, plagioclase diopside and quartz and plotted in a tetrahedron using these molecules as apices. This is similar to the method of Coombs (1963), except that in the present study weight per cents are preferred to molecular per cents because of the greater ease of comparison with experimental data.

In the calculation of the norm following the CIPW rules, however, the degree of oxidation of iron has a considerable influence on other quantities, particularly on the allocation of silica. Any oxidation which takes place after solidification of a lava or at a very late stage during crystallization is not petrologically significant for our present purposes and it will disguise the degree of silica saturation which the magma had attained as a result of normal fractionation processes. Comparison of the analyzed basalts with Walker and Poldervaart's data (1949) for the Karroo dolerites shows that the former are considerably more oxidized and do not show a constant oxidation ratio. The dolerites in contrast show a low degree of oxidation and the ratio of Fe_2O_3 to FeO is much less variable.

The higher degree of oxidation of the basalts is probably largely due to weathering or to alteration during the zeolitization of the lava pile. There may also perhaps have been some oxidation during the eruption of the lavas, a process which did not affect the sill rocks.

TABLE 4. NORMS OF BASUTOLAND BASALTS

		B.1	B.19	B.21	B.31	B.32	B.33	B.36	B.37	B.39	B.42	B.47	B.59	B.61	B.62	B.63	B.66	B.67	B.69	B.70	B.71	B.72	B.74	B.76	B.78
Quartz		—	2.16	—	2.52	.78	4.74	2.22	—	.96	—	—	—	1.14	.42	—	—	—	1.62	2.22	—	1.98	—	1.56	—
Orthoclase		3.89	5.00	4.45	3.34	3.89	3.89	5.00	4.45	5.56	5.56	4.45	2.78	3.89	4.45	2.22	3.89	3.34	3.34	3.34	3.34	3.89	5.00	3.89	3.34
Albite		19.91	21.48	22.53	20.44	18.86	20.44	20.96	20.96	22.01	22.53	20.96	16.77	20.96	20.96	19.91	17.29	16.24	18.34	17.82	18.86	19.91	22.01	19.39	19.91
Anorthite		27.24	23.07	25.02	26.69	27.52	25.85	25.30	28.08	25.30	25.30	28.08	33.08	28.08	28.63	28.91	23.07	22.52	28.63	30.02	20.57	26.97	26.97	28.08	29.19
Diopside	Wo	11.02	11.02	11.45	11.48	9.86	8.82	9.51	10.79	10.21	11.02	10.56	11.48	10.44	10.90	10.79	8.58	8.00	9.74	9.63	8.93	10.79	10.79	9.78	11.02
	En	6.00	5.40	6.10	5.40	5.20	4.50	4.60	5.60	4.70	5.40	5.00	6.00	5.80	5.70	6.00	4.90	4.80	5.60	5.40	5.20	6.10	5.50	5.70	6.20
	Fs	4.62	5.41	5.02	5.94	4.36	4.09	4.76	4.88	5.41	5.41	5.41	5.15	4.22	4.88	4.36	3.30	2.77	3.70	3.83	3.30	4.22	5.01	3.83	4.36
Hypersthene	En	10.90	11.10	7.80	9.20	13.80	11.90	11.20	10.80	9.80	9.60	10.20	9.70	12.40	10.80	13.50	17.20	18.70	14.90	14.20	16.50	13.70	9.10	14.10	11.90
	Fs	8.45	11.09	6.34	10.30	11.35	11.09	11.62	9.37	11.22	9.24	10.69	9.50	9.24	9.50	9.90	11.88	11.35	10.16	9.90	9.90	8.71	8.05	9.77	8.45
Olivine	Fo	2.10	—	3.64	—	—	—	—	.70	—	.70	.14	1.40	—	—	.42	3.50	4.90	—	—	5.46	—	1.40	—	1.12
	Fa	2.04	—	3.26	—	—	—	—	.61	—	.82	.20	.61	—	—	.20	2.24	3.26	—	—	3.88	—	1.22	—	.82
Magnetite		1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.62	1.62	1.62	2.09	2.09	1.62	1.62	2.09	1.62	1.86	1.62	1.62
Ilmenite		1.82	2.58	2.28	2.43	2.28	2.43	2.58	1.82	2.58	2.28	2.13	1.56	1.98	1.82	1.82	1.82	1.82	1.98	1.98	1.67	1.98	2.58	1.82	1.98

In order to try and remove the effects of such accidental oxidation a standard degree of oxidation of 10%, close to the average value for the Karroo Dolerites (*i.e.*, $Fe^{3+} \times 100/Fe^{2+} + Fe^{3+} = 10$) was used in calculating the norms of the basalts. The justification for this depends on the acceptance of the equivalence of the basalts and dolerites.

The norms calculated in this way are given in Table 4. It is of interest to note that a substantial number of the rocks thus become olivine-normative, whereas calculations of the norms in the ordinary way makes a higher proportion quartz-normative. The norms calculated before adjusting the oxidation ratio are not given here and it is sufficient to note that the data projected into Fig. 4 using the unadjusted norms is a little more scattered and displaced slightly away from the Ol apex, while still projecting largely into the Fo+An+L field.

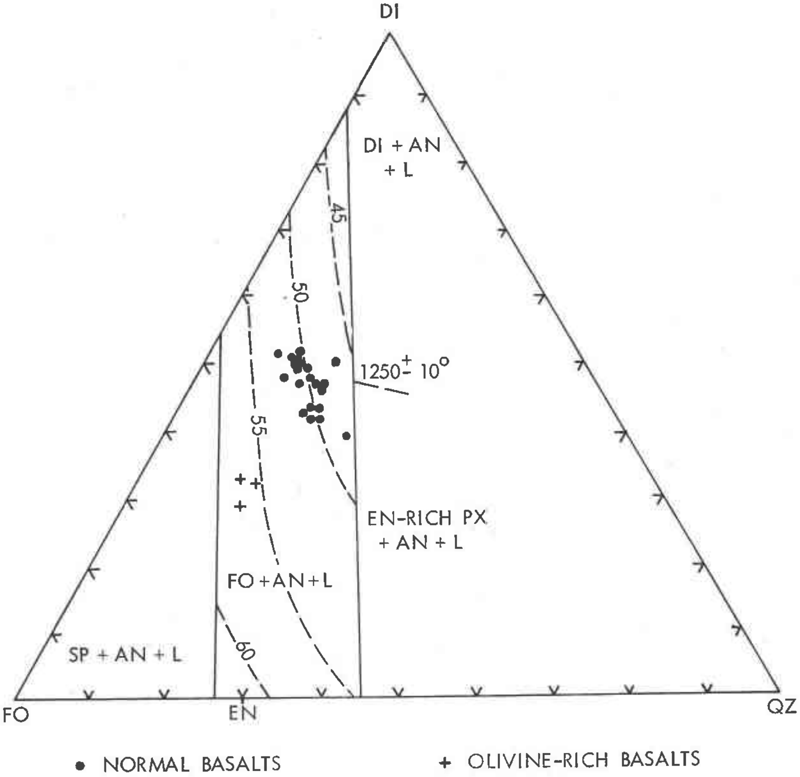

FIG. 4. Analyzed Basutoland basalts projected from plagioclase into the tetrahedron Ol-Di-Pl-Qz. Phase relationships are shown for the synthetic system Fo-Di-An-Qz.

The adjusted norms were converted to plotting co-ordinates by the following method:

1. Normative hypersthene was distributed between olivine and quartz.
2. The totals of plagioclase, olivine, diopside and quartz were then recalculated to 100% to give the four co-ordinates.

The method ignores normative or, il, mt and ap but includes on average 91% of the original anhydrous analysis. The main limitation is that iron and sodium cannot be separately represented, though as will be seen this apparently causes no serious difficulties in the comparison with the synthetic, soda- and iron-free system. An alternative to *grouping* ferrous iron with magnesium, and sodium with calcium (in the feldspar) is to *project from* these constituents by calculating the four co-ordinates simply as Fo, Di as Wo plus En only, An and Qz. Which method is preferable on theoretical grounds is debatable, but we have chosen the grouping method for practical reasons, mainly that there is a much closer correspondence both in composition and actual amount between the phases considered theoretically in the diagram and the phases actually present in the rocks under study.

Application of experimental results for the synthetic system forsterite-diopside-anorthite-silica. Since the four co-ordinates to which the basalt analyses were converted coincide closely with the components of the system Fo-Di-An-Qz, the phase boundaries determined experimentally were added to the diagram. The data used in construction of these boundaries were derived from Osborn and Tait (1952) for the Fo-Di-An join, Hytönen and Schairer (1961) for the En-Di-An join and for the location of the univariant point[1] Fo+Di+En+An+liquid, and from Anderson (1915) for the join Fo-An-Qz.

Figure 4 shows the basalt analyses plotted in the tetrahedron Ol-Di-Pl-Qz with the experimental data from Fo-Di-An-Qz appended. The projection is from the plagioclase coign of the tetrahedron and the phase boundaries shown mark the junctions of the forsterite, diopside and enstatite primary phase volumes where they intersect the boundary of the primary phase volume of anorthite. Each of these lines represents a divariant equilibrium of the type An+2 solid phases+liquid, and they meet at the univariant point Fo+Di+En+An+liquid.

The trivariant surface Fo+An+liquid is shown contoured in anor-

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[1] This "point" is invariant under isobaric conditions but nomenclature will be used throughout to refer to the more general case where pressure is also a variable, *e.g.*, the equilibrium Fo+Di+An+liquid which is isobarically univariant will be referred to as divariant.

thite percentages, and it is encouraging that the plotted points for the normal basalts (plagioclase co-ordinates of which fall between 49.1% and 54.3%) lie very close to this surface, since their petrography shows the assemblage olivine+plagioclase (as microphenocrysts)+groundmass. Ideal perfect fractional crystallization would give rise to non-porphyritic rocks the bulk composition of which would represent original liquid-compositions. In most natural examples, however, microporphyritic rocks in which the total amount of phenocryst material is low are likely to be the products of near perfect rather than ideal fractionation. The bulk composition of such a rock is near a liquid composition but may be slightly displaced towards the bulk composition of the combined microphenocrysts. The analyses of the Basutoland basalts probably approach liquid compositions fairly closely, and the liquids concerned were clearly in equilibrium with olivine and calcic plagioclase at atmospheric pressure. In the synthetic system, liquids of similar normative composition are in equilibrium with forsterite and anorthite. Thus it can be concluded that the basalts almost certainly owe their present phase and residual liquid compositions to processes involving crystal-liquid equilibria at or near atmospheric pressure. Fractional crystallization of a wide variety of more basic liquids is obviously capable of producing bulk compositions of the required type, a conclusion essentially in agreement with the results obtained by O'Hara (1965) in studying Hawaiian basalts using the projection from diopside in the same system. The Basutoland lavas having been erupted in the two-phenocryst state are however somewhat more primitive in terms of atmospheric pressure fractionation than the three-phenocryst rocks discussed by O'Hara.

For convenience above we have used the term "at or near atmospheric pressure", but it should be possible to define this a little more closely. It can be seen from Fig. 4 that the analyzed basalts have compositions which, considered as a group, penetrate the An-Di-En join. The work of Boyd and England (1961) and Kushiro (1964) suggests that, as far as the ternary system Fo-Di-Qz is concerned, the join Di-En becomes a thermal barrier at about 10 kb. It seems likely therefore that the join An-Di-En will also become a barrier in the quaternary system Fo-Di-An-Qz at much the same pressure. Since the analyzed basalts lie athwart this plane, the implication is that they achieved their present compositions under pressure conditions such that the thermal barrier did not exist, *i.e.*, at less than about 10 kb, or at a depth of less than about 30 km.

As O'Hara (1965) has argued, two possibilities exist for the generation of such magmas, either they are formed by partial or complete fusion of crustal materials, or they are formed as residual liquids following the fractional crystallization within the crust of more basic, mantle-derived, liquids. The latter explanation seems more likely in view of the commonly accepted origin of basaltic magmas within the mantle. Thus despite the fact that the Basutoland basalts are as uniform and voluminous a suite of tholeiitic lavas as could be found, we are forced to conclude that they are not representatives of "primary" basaltic magma, but are themselves derived from some more basic parental liquids.

Some more detailed comment is however called for concerning the distribution of the points in Fig. 4. In an ideal situation if the rocks concerned were completely fresh and there were no errors in the analyses it would be expected that rocks formed by the fractionation of olivine and plagioclase only, from a more basic parental magma, would plot on a single olivine-plagioclase control plane, *i.e.*, in the projection would all lie on a straightline passing through the olivine composition point. The analyses presented here do not show this behavior but show a slight tendency to scatter across the direction of olivine-plagioclase control planes. A detailed discussion of this point will be given in a subsequent paper. Preliminary studies suggest the possibility that the lavas are not derived from a unique parent magma but from a range of magmas which had become available as a result of fractionation at an earlier stage in a higher pressure regime. A careful study of the possible effects of analytical error and alteration of the basalts on the position of points in the diagram will however be necessary before this hypothesis can be tested.

THE OLIVINE-RICH BASALTS

The bulk chemistry of the 3 analyzed olivine-rich basalts collected near the base of the succession shows that they are essentially related to the normal basalts by the addition of olivine. With the present evidence, however, it is impossible to decide objectively whether the olivine-rich rocks are more primitive than the normal basalts (*i.e.*, in a loose sense, parental to them) or whether they are derived from the normal basalts by the addition of cumulus olivine.

The chemical relationships are shown in Fig. 5 where the system Ol-Di-Pl-Qz is viewed both in the projection from plagioclase and the projection from quartz. In both cases the olivine-rich rocks plot near a tie-plane joining the normal basalts with the olivine composition point, a demonstration that the bulk composition of the two groups could be related to each other essentially by the addition or subtraction of the chemical components of olivine only.

VARIATION WITH STRATIGRAPHIC HEIGHT

In Fig. 6 the Fe/Mg index, used as an approximate gauge of the degree of fractionation in the near-atmospheric pressure environment, is plotted against height in the stratigraphic sequence. It is clear that there is a slight tendency for the more fractionated rocks to be found stratigraphically higher. Two possible interpretations may be placed upon this:

1. The fractionation stage depends upon the *height* the magma column reached before extrusion.
2. The fractionation stage depends upon the *time* elapsed since the beginning of the volcanic episode.

Walker and Poldervaart's (1949) evidence suggests that the approximate relationship between fractionation stage and height may also include the Karroo dolerite sills intruding the sediments below the basalts.

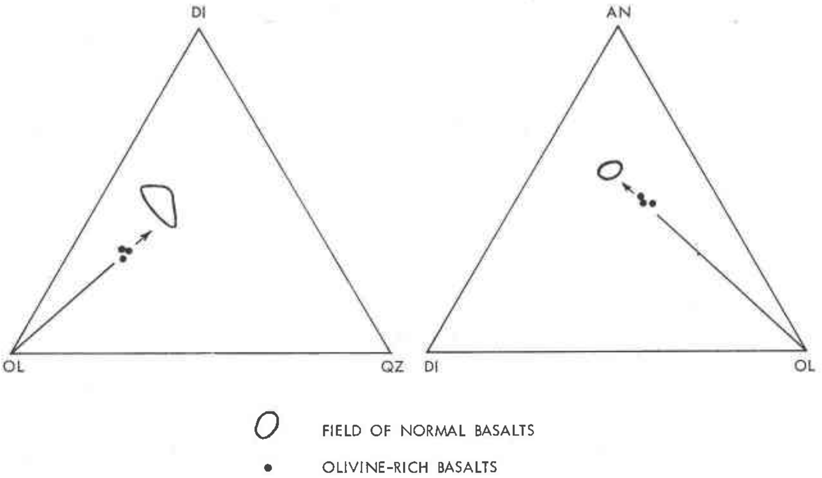

FIG. 5. Relationship between the normal and the olivine-rich basalts showing that the two groups are related by the addition or subtraction of olivine only.

Certainly many dolerites are found which are more magnesian and have lower ratios of iron to magnesium than any of the analyzed basalts and only relatively few dolerites have a more fractionated aspect than the analyzed basalts.

Thus, much depends on the ages of the dolerites relative to the basalts. If it can be shown by future research on absolute ages and paleomagnetism that the dolerites are broadly contemporaneous with the basalts it follows that the degree of fractionation may depend largely on the height of the magma column. This result would be of considerable importance petrologically because it would indicate to what extent fractionation could take place within the conduit of a rising magma. If this effect is at all marked it might be possible to confirm it by the study of lateral variation in individual flows.

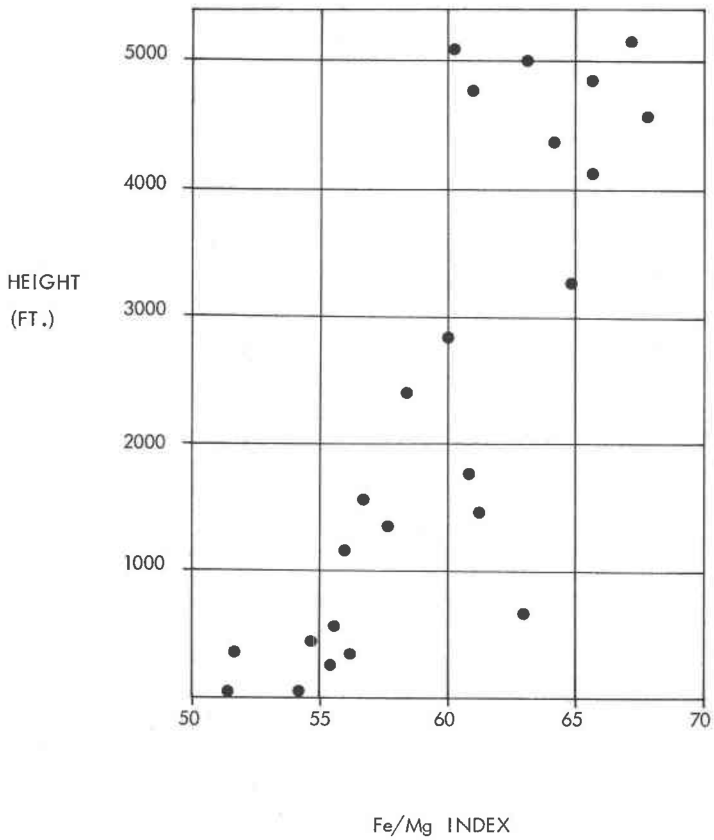

FIG. 6. Variation of Fe/Mg index with height in the stratigraphic succession.

Conversely if the dolerites are generally older than the basalts, both could be derived by successive tapping of a continuously fractionating, possibly static, magma chamber, without significant subsequent fractionation in the conduits.

CONCLUSION

The Basutoland basalts appear to the writers to provide an excellent example of the close correspondence it is possible to obtain between the predictions of experimental petrology and the phase relations of natural basaltic rocks. Because of the low content of phenocrysts (olivine and plagioclase) the analyses can be taken to represent liquid compositions fairly closely and a considerable similarity can be observed between these compositions and the compositions of liquids in equilibrium with forsterite and diopside in the synthetic system Fo-Di-An-Qz at 1 atmosphere.

The implication that the basalts owe their bulk compositions and phenocryst compositions to crystal fractionation processes operating within the crust seems clear.

Finally, it is hoped that the analytical data presented will further the study of geochemical provinces within the Karroo rocks of southern Africa as a whole. Work is currently in hand on the basalts of Swaziland and western Rhodesia (Hornung and MacDonald, in prep.), and on the Tuli syncline (Hornung and Vail, in prep.) and Nuanetsi areas (Jamieson, in prep.) of the southern part of Rhodesia.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Anglo-American Corporation of South Africa whose endowment of Oppenheimer Fellowships in the Research Institute of African Geology, The University of Leeds, has made this work possible. Thanks are also due to Col. J. Scott of Johannesburg and his associates at Kao Mine and Leribe for their material assistance in the field work, and to Dr. J. M. Rooke who kindly made available the results of her trace element analyses.

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Manuscript received, February 3, 1966; accepted for publication, May 5, 1966.