MINERALOGICAL MAGAZINE, DECEMBER 1979, VOL. 43, PP. 487-95

The Karroo dolerites of southern Malawi and their regional geochemical implications

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SUMMARY. The field relationships, petrography and mineralogy, including probe analyses of olivines, pyroxenes, and plagioclases, of the Karroo dolerite dike swarm of southern Malawi, are described. Rock analyses are given and define a typical tholeiitic trend of iron enrichment. The most magnesian rocks are thought to represent fairly picritic liquids. A number of authors have shown that there are significant geochemical differences between the basaltic rocks of the northern and southern parts of the Karroo outcrop in southern Africa, notably for elements such as Al, P, K, Ti, and Ba. The Malawi data presented here, however, show trends that are the reverse of those found hitherto, the Malawi dolerites being closely comparable with the rocks of the central Karroo basin of South Africa and Basutoland. The striking regional variation in the geochemistry of the Karroo basaltic rocks over southern Africa is independent of the tectonics or position *vis-à-vis* the central Karroo basin, and so probably reflects mantle heterogeneity.

ROCKS assignable to the Karroo system occur in northern Malawi and in the south along the border with Mozambique. The northern outcrop comprises sedimentary rocks only, but in the south the youngest rocks of Karroo age are basaltic lavas, and dolerite dikes and sills. The lavas cover about 100 km^2 within Malawi and there is a somewhat greater area, including rhyolites, in adjacent areas of Mozambique. Apart from a brief field and petrographic account (Habgood, 1963) no detailed work has been done on the lavas, or on the dolerite sills which are emplaced in Karroo sediments.

Brief field and petrographical accounts of Karroo dolerite dikes are given in regional reports on the geology of southern Malawi (e.g. Bloomfield, 1958 and 1965; Garson, 1962; Habgood, 1963), and two rock analyses have been published (Garson, 1962; Bloomfield, 1965), but there is no account of the swarm as a whole, although, as can be seen from fig. 1, it is a considerable geological feature.

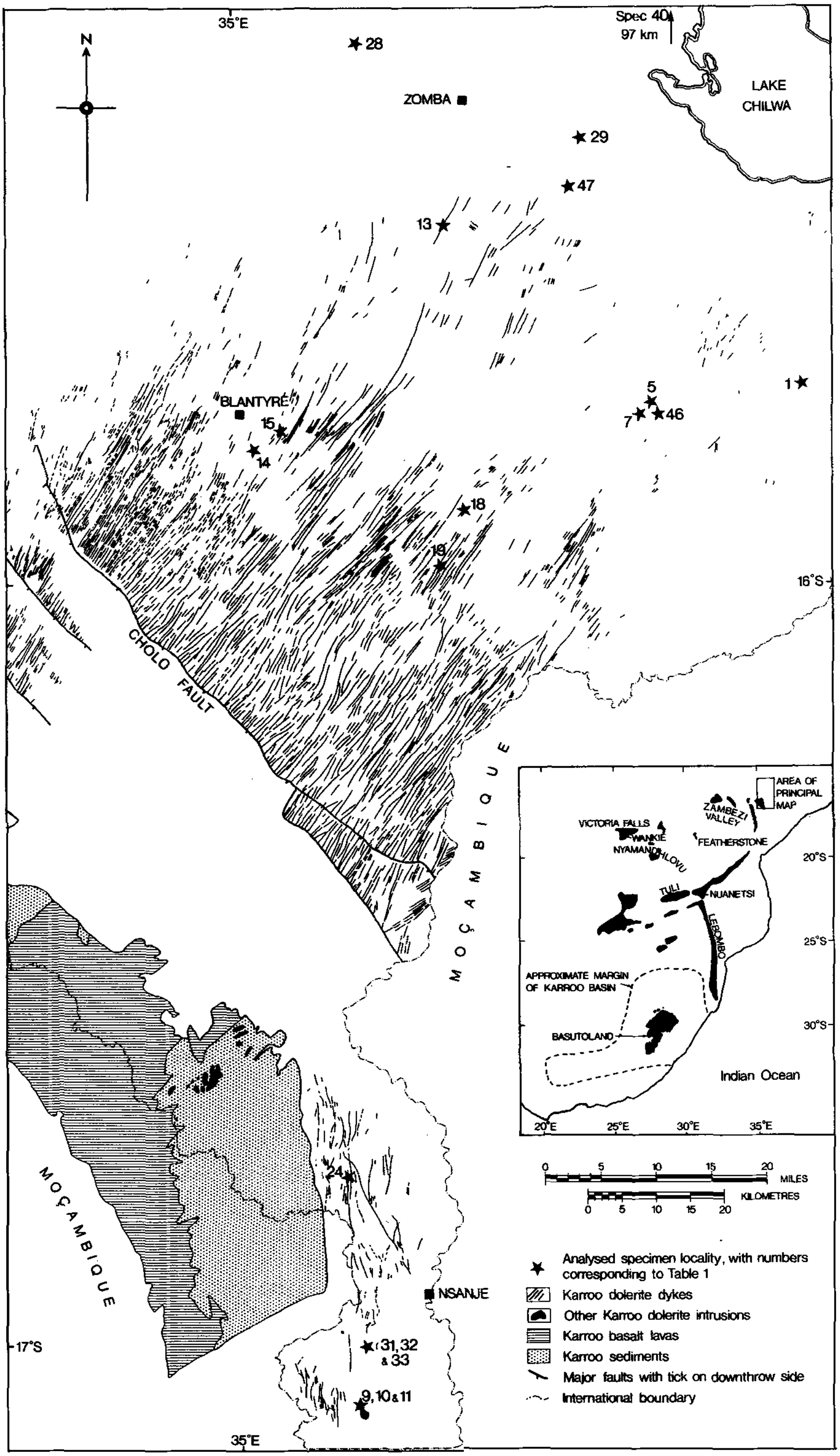
The general trend of the dike swarm is NE-SW, though with some local variations, particularly in the extreme south where it is N-S (fig. 1). The NE-SW trend is parallel to the principal faults which define the rift system in this part of Malawi. The swarm is most dense immediately north of the Cholo fault: in the area just south of the fault dikes are not exposed because they are covered by more recent sediments. Dolerite was also emplaced in parts of the Cholo fault, and in faults parallel to it which extend into a fault system bounding the Zambezi Valley (Woolley and Garson, 1970, fig. 2). The swarm gradually dies out to the NE, only a few dikes being found in the areas immediately south and west of Lake Chilwa. Some 70 km north of the Lake a few dolerites again occur and extend sporadically as far as Lake Malawi.

In the densest part of the swarm there are six or seven dikes to the mile (Habgood, 1963): they usually produce marked ridges and individual dikes can sometimes be followed for many miles. The 'Border Dike' just north of Nsanje, for instance, is some 65 m thick and can be followed for about 50 km (Bloomfield, 1958).

The majority of the specimens on which this account is based were kindly selected for us by Dr R. D. Walshaw from the collection of the Malawi Geological Survey Department. They were collected during regional mapping by K. Bloomfield, M. S. Garson, R. K. Evans, and A. King. These specimens were supplemented with material from the collection of the British Museum (Natural History).

Petrography. All the rocks studied are tholeiitic dolerites, but some contain abundant modal olivine and are perhaps appropriately termed picritic dolerites. Grain-size varies from fine to coarse with plagioclase laths up to 2-3 mm in length. Porphyritic variants occur with glomeroporphyritic aggregates of plagioclase and clinopyroxene, and some olivine-rich rocks contain subhedral olivine phenocrysts up to 2 mm across. Most of the dolerites have an ophitic to sub-ophitic texture, but in the coarsest rocks pyroxene occurs as isolated angular patches between plagioclase laths.

Olivine is usually mantled by clinopyroxene, but in some of the more olivine-rich rocks which occur in the extreme south of the country (fig. 1) there is


35°E
N
28
Spec 40
97 km
LAKE CHILWA
ZOMBA
29
47
13
BLANTYRE
15
14
5
7
46
1
18
19
16°S
CHOLO FAULT
MOÇAMBIQUE
VICTORIA FALLS
WANKIE
NYAMANDHLOVU
ZAMBEZI VALLEY
FEATHERSTONE
AREA OF PRINCIPAL MAP
TULI
NUANETSI
LEBOMBO
APPROXIMATE MARGIN OF KARROO BASIN
BASUTOLAND
Indian Ocean
20°S
25°S
30°S
20°E
25°E
30°E
35°E
0 5 10 15 20 MILES
0 5 10 15 20 KILOMETRES
MOÇAMBIQUE
24
NSANJE
17°S
31, 32 & 33
9, 10 & 11
35°E
Analysed specimen locality, with numbers corresponding to Table 1
Karroo dolerite dykes
Other Karroo dolerite intrusions
Karroo basalt lavas
Karroo sediments
Major faults with tick on downthrow side
International boundary

no obvious reaction relationship, though in others a fine palisade of fibrous orthorhombic pyroxene surrounds the olivine. Olivine is generally fresh but in the more differentiated rocks it is partly or wholly serpentinized.

Clinopyroxene is ubiquitous, and bronzite or pigeonite have been identified in about 10% of the samples studied. In porphyritic rocks clinopyroxene forms euhedral to subhedral phenocrysts and glomeroporphyritic aggregates, but in more equigranular rocks it shows an ophitic or interstitial relationship to plagioclase. Calcium-poor pyroxene forms euhedral phenocrysts in some porphyritic rocks, but in more equigranular types it is subhedral to euhedral and invariably mantled by clinopyroxene.

Plagioclase forms stubby euhedral phenocrysts and glomeroporphyritic aggregates in porphyritic rocks, but in the more usual equigranular types develops subhedral laths which, in the olivine-rich rocks from the extreme south of Malawi, have a length to width ratio of up to 10:1. In these rocks the plagioclases commonly have a central core of pyroxene and opaque minerals, which presumably represents trapped liquid. Zoning is common from bytownite cores, which are invariably sericitized, to labradorite rims.

Hornblende occurs in about one-third of the samples studied, usually in accessory amounts, but in a few rocks is a major constituent. Two types are present. In more highly differentiated rocks an olive green to pale brown hornblende rims and replaces clinopyroxene as well as crystallizing as a primary phase. In other rocks green, but occasionally brown, amphibole occurs as sparse xenocrysts up to 3 mm across, which in some instances are rimmed by clinopyroxene.

Magnetite is ubiquitous and a little brown biotite is sometimes present. A micrographic intergrowth of quartz and alkali feldspar is abundant in more highly differentiated types, and needles of apatite are invariably associated with this texture.

Mineralogy. Olivines from seven rocks have been analysed and they vary from Fa_{12} to Fa_{28}. The rims of crystals are commonly richer in fayalite than the cores, in contrast to the observations of Walker and Poldervaart (1949, p. 633) who found that in South African dolerites the olivines are usually of uniform composition. The olivines are plotted on fig. 2*a* and tied to co-existing calcium-rich pyroxenes.

Calcium-rich pyroxenes from eleven rocks were analysed (fig. 2*a*), and compositions of both cores and rims were obtained for seven of these. They proved to be augites in all samples except for one in which the cores were endiopside. These data are plotted on fig. 2*b* from which the increase in Fe and decrease in Ca in the rims is apparent for the more magnesian pyroxenes, but in the two most iron-rich pyroxenes iron enrichment in the rims is accompanied by a slight Ca increase also.

There are surprisingly few chemical analyses of pyroxenes from Karroo dolerites or basalts: Walker and Poldervaart (1949), for instance, relied on optical determinations. However, there are probe data for pyroxenes of the Birds River Gabbro, South Africa (Eales and Booth, 1974); they form a Ca-rich series (fig. 2*a*), and, unlike the Malawi dolerites, show extreme iron enrichment, though compositions are clearly comparable for the augitic pyroxenes.

Three Ca-poor pyroxenes were analysed. The most magnesian, a bronzite, forms phenocrysts co-existing with phenocrysts of augite and plagioclase in a markedly porphyritic rock. The other Ca-poor pyroxenes are a magnesian pigeonite and an intermediate pigeonite. They are plotted on fig. 2*a*, tied to co-existing augites, and show a typical iron-enrichment trend. A pyroxene pair from the Birds River Gabbro (Eales and Booth, 1974), also plotted on fig. 2*a*, shows more marked iron enrichment than is found in the Malawi dolerites.

Amphiboles from two rocks were analysed. In one rock (Table I, no. 24) the amphibole forms phenocrysts or xenocrysts, and in the other (Table I, no. 19) it occurs as rims on pyroxene, as well as forming subhedral prisms and interstitial patches. Both are ferro-hornblendes, according to the nomenclature of Leake (1968), and the phenocrysts are the more magnesian. They are plotted on fig. 2*a* and tied to co-existing pyroxenes. It is apparent that as the pyroxenes become unstable the amphiboles continue the iron-enrichment trend, and in terms of Ca content are intermediate between the two pyroxene series. The relatively flat amphibole-pyroxene tie-lines probably reflect the fact that, at the time of crystallization of the amphiboles, the pyroxenes were in a strong disequilibrium with the melt. The relative abundance of amphibole in the more differentiated dolerites indicates that water pressures were comparatively high, and it may have been the crystallization of

FIG. 1. Map of southern Malawi and some adjacent parts of Mozambique to show the distribution of the Karroo dolerite dike swarm (Malawi only) and Karroo lavas and sediments. The location of analysed specimens is indicated, the numbers corresponding to those in Table I. The inset map indicates the areas of outcrop of igneous rocks in south and south-east Africa of Karroo age.

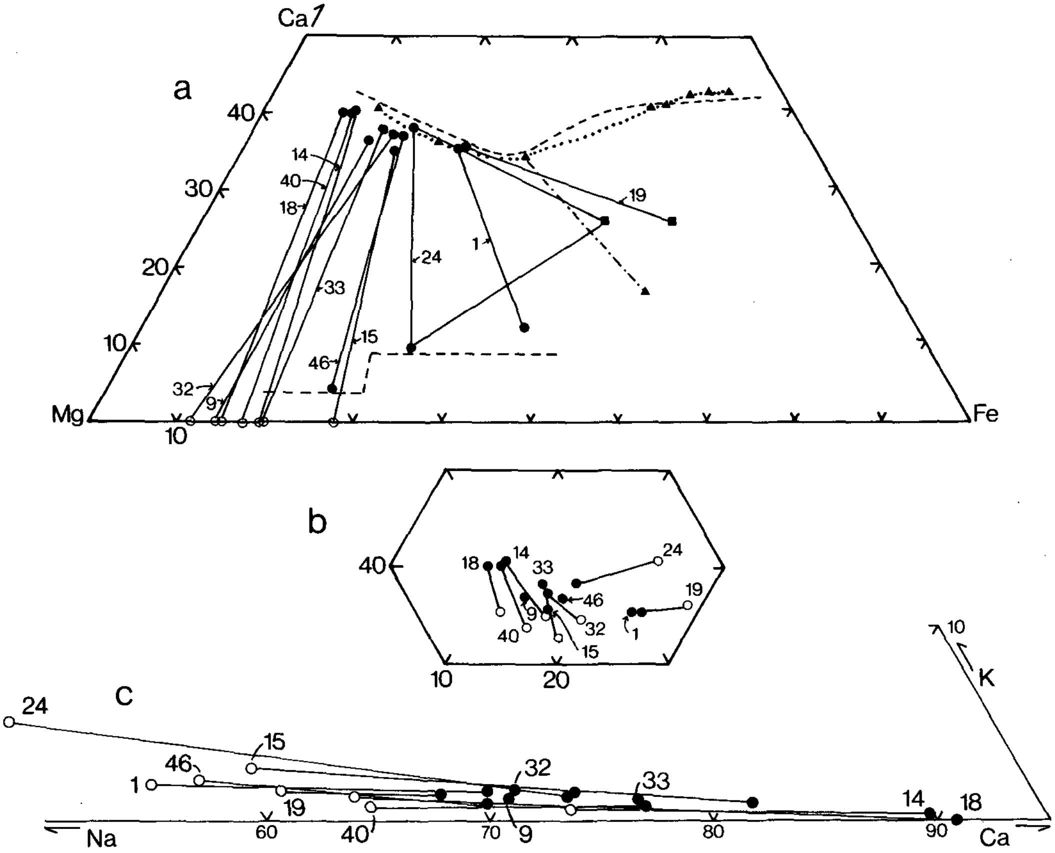


FIG. 2*a*. Compositions of pyroxenes (filled circles), olivines (open circles), and amphiboles (filled squares) plotted in terms of atomic Ca, Mg, and Fe^{2+}. Tie-lines join co-existing phases. Also shown are the crystallization trends of Skaergaard pyroxenes (Brown and Vincent, 1963)—dashed lines, and of the Birds River Gabbro pyroxenes (Eales and Booth, 1974)—dotted line, filled triangles, and dot-dash tie-line. Numbers correspond to host rocks given in Table I. *b*. Part of the Ca-Mg-Fe^{2+} plot showing compositions of cores (solid circles) and rims (open circles) of Malawi dolerite clinopyroxenes. Note the change of trend with increasing iron enrichment. *c*. Core and rim compositions of plagioclases plotted in terms of atoms of Ca, Na, and K.

amphibole, together with the continuing separation of pigeonite, that caused the early Ca-enrichment in the Ca-rich pyroxene trend.

The plagioclases are strongly zoned from cores ranging from An_{91} to An_{67} through rims up to An_{48} (fig. 2*c*).

Rock chemistry. Specimens from twenty-one dikes, from a wide area of southern Malawi (fig. 1), were analysed for major and some trace elements using the methods described in Vartiainen and Woolley (1976, p. 7). These data are given in Table I. All the rocks are hypersthene normative and about half are olivine- and the other half quartz-normative. Three of the rocks have notably high contents of MgO (15.20—12.76 %) and should, therefore, be called picritic dolerites. The data are plotted on an AFM diagram (fig. 3) on which is also shown, for comparison, the trend of the strongly differentiated Karroo Elephant's Head dike and the New Amalfi sheet of South Africa (Poldervaart, 1944), and it is apparent that the Malawi dolerites have a similar general trend, although over a more restricted composition range.

On fig. 4 the major and some trace elements are plotted against weight per cent MgO, the three picritic dolerites being readily apparent. Also plotted on fig. 4 are the values for SiO_2, FeO, and CaO of olivines from two of the picritic dolerites, to which they are tied in the diagram, and an average of clinopyroxene from the same two rocks. It is apparent that initial differentiation of the suite is probably controlled by olivine, plus possibly chrome spinel, and not by clinopyroxene, and the series 9, 32, 11, 10, 33, and 31 (Table I) forms such

TABLE 1

CHEMICAL ANALYSES AND NORMS OF MALAWI KARROO DOLERITE DYKE ROCKS

	9	32	11	40	28	14	10	33	31	18	47	24	13	15	29	90	7	1	5	46	19
SiO_2	48.31	47.98	48.11	49.97	48.85	49.07	48.56	48.31	48.87	50.78	52.13	53.77	50.19	49.59	52.31	51.73	51.64	52.45	53.17	50.72	51.46
TiO_2	0.69	0.68	.78	0.60	0.53	0.51	1.15	1.15	1.17	0.61	0.73	1.03	0.73	1.06	0.89	0.79	0.93	0.86	0.93	0.82	1.13
Al_2O_3	12.55	12.63	13.44	14.70	14.78	15.03	15.02	14.62	15.45	14.71	14.04	14.50	16.19	17.69	14.33	14.14	13.93	14.10	14.14	14.14	15.28
Fe_2O_3	.75	0.67	0.75	2.46	2.16	1.98	0.54	0.58	0.68	1.76	2.95	0.86	2.66	1.02	2.05	2.97	1.91	2.44	1.80	2.58	2.53
FeO	9.30	9.32	9.36	7.18	7.64	7.60	9.40	9.49	9.45	7.76	7.56	8.20	7.76	8.25	8.60	7.32	9.18	8.54	8.85	9.46	8.74
CaO	8.65	8.52	8.89	12.25	12.51	12.87	9.62	9.56	9.75	11.19	10.27	8.53	10.96	10.31	10.01	9.40	9.94	9.13	9.28	9.32	8.90
MgO	15.20	14.20	12.76	10.30	9.93	9.58	9.84	9.49	9.47	8.42	7.33	6.88	6.76	6.48	6.97	6.88	7.15	6.59	6.31	5.87	5.13
MnO	.20	0.19	0.20	0.19	0.19	0.19	0.20	0.20	0.20	0.19	0.21	0.17	0.18	0.18	0.20	0.19	0.21	0.21	0.20	0.23	0.20
Na_2O	1.39	1.39	1.49	1.63	1.50	1.52	1.91	1.93	1.96	1.81	1.92	2.40	1.92	2.17	2.02	2.16	2.05	2.16	2.00	2.60	2.54
K_2O	0.37	0.35	0.42	0.18	0.15	0.21	0.62	0.65	0.67	0.37	0.63	1.46	0.53	1.02	0.86	0.96	0.78	1.08	1.11	1.13	1.00
P_2O_5	0.12	0.11	0.13	0.07	0.05	0.05	0.27	0.23	0.28	0.08	0.10	0.18	0.11	0.22	0.14	0.12	0.15	0.14	0.16	0.20	0.21
H_2O^+	1.99	2.05	1.90	0.60	0.88	0.65	1.20	1.14	1.37	0.71	0.91	0.87	0.97	0.88	0.64	0.80	0.89	1.38	1.00	0.91	1.28
H_2O^-	0.24	0.11	0.35	0.17	0.18	0.19	0.40	0.18	0.28	0.16	0.32	0.36	0.18	0.25	0.33	1.05	0.15	0.17	0.24	0.04	0.33
CO_2	0.81	0.80	0.61	0.26	0.65	0.55	0.25	0.32	0.25	1.30	0.91	1.18	1.86	1.45	1.49	0.53	1.22	0.75	1.16	1.16	0.44
F	0.16	-	0.16	0.08	-	-	-	0.14	-	.09	0.11	-	0.12	-	-	0.07	.01	-	.01	0.07	-
S	0.11	0.11	0.10	0.04	0.03	.05	0.09	0.09	0.09	.06	0.08	0.13	0.08	0.10	0.08	0.04	.08	0.09	.10	0.04	0.09
Others	0.28	0.25	0.21	0.17	0.15	.16	0.20	0.23	0.23	.31	0.11	0.19	0.14	0.17	0.14	0.13	.13	0.15	.14	0.14	0.19
Sub total	101.12	99.36	99.66	100.85	100.18	100.21	99.27	98.31	100.17	100.31	100.31	100.71	101.34	100.84	101.06	99.28	100.35	100.24	100.60	99.43	99.45
O≡F,S	0.12	0.06	0.12	0.05	0.02	.03	0.05	0.10	0.05	.07	0.09	0.07	0.09	0.05	0.04	0.05	.04	0.05	.05	0.05	0.05
Total	101.00	99.30	99.54	100.80	100.16	100.18	99.22	98.21	100.12	100.24	100.22	100.64	101.25	100.79	101.02	99.23	100.31	100.19	100.55	99.38	99.40
Trace elements (ppm)																					
Cr	1370	1095	820	602	480	540	750	750	780	500	90	410	270	410	200	70	140	180	90	140	50
Li	28	23	23	23	23	23	23	23	23	20	23	23	20	-	23	23	28	23	23	23	23
Ni	310	320	270	230	200	200	160	160	170	180	130	160	150	110	140	120	150	140	125	125	110
Cu	10	15	15	25	25	40	20	10	10	20	15	10	25	5	15	100	15	15	40	25	15
Zn	250	250	250	240	250	220	280	300	300	250	270	300	270	300	300	280	280	270	300	320	300
Sr	85	85	110	40	35	42	170	170	170	40	60	170	80	230	110	75	85	90	100	100	110
Ba	<90	30	70	30	30	30	90	90	100	50	27	180	70	125	70	45	100	100	125	100	100
Rb	130	120	130	120	120	120	120	120	120	120	120	120	120	110	120	120	120	120	120	120	120
S.I.	56.3	54.8	51.5	47.4	46.4	45.9	44.1	42.9	42.6	41.9	35.9	34.7	34.4	34.2	34.0	33.9	33.9	31.7	31.4	27.1	25.7
CIPW norms																					
Q	-	-	-	-	-	-	-	0.1	-	2.3	5.2	9.8	3.0	4.1	6.1	6.3	4.7	6.5	8.6	3.4	7.2
C	-	-	-	-	-	-	-	-	-	-	-	-	1.5	3.3	-	-	-	-	0.2	0.3	2.9
or	8.2	8.2	8.8	9.6	8.9	9.0	11.3	11.4	11.6	10.7	11.4	14.2	11.4	12.8	11.9	12.8	12.1	12.8	11.8	15.4	15.0
ab	1.7	1.6	1.7	1.6	1.6	1.6	1.7	1.7	1.7	1.6	1.8	1.4	1.5	1.5	1.7	1.6	1.8	1.8	1.7	2.0	1.7
an	29.2	29.5	31.4	34.5	35.1	35.7	34.4	33.3	35.5	33.9	31.7	31.7	33.5	32.2	32.2	31.4	31.0	31.2	31.3	29.1	25.5
di	37.8	33.6	26.2	13.5	11.5	9.6	11.7	11.3	9.4	6.4	3.8	2.0	-	-	1.9	2.3	3.7	1.3	-	-	-
hy	11.2	16.3	22.1	34.2	31.7	33.6	33.6	34.7	34.6	40.2	41.0	34.3	43.7	39.8	40.8	38.7	40.9	40.4	40.3	43.1	40.7
ol	6.2	3.8	2.9	4.7	7.5	7.3	0.5	-	1.0	-	-	-	-	-	-	-	-	-	-	-	-
mt	1.5	1.4	1.1	0.4	1.1	0.9	0.5	0.6	0.5	2.0	1.4	1.8	2.8	2.2	2.2	0.8	1.8	1.2	1.7	1.7	0.7
il	1.3	1.3	1.5	1.1	1.0	1.0	2.2	2.2	2.2	1.2	1.4	2.0	1.4	2.0	1.7	1.5	1.8	1.6	1.8	1.6	2.1

Specimen numbers all refer to British Museum (Natural History) collection 1970,P23, except for specimen 90 which is from collection 1911,331. Localities are indicated on fig. 1. Rock types are as follows: 9, 32 and 11, picritic olivine dolerite; 40, 28, 14, 10, 33, 31 and 18, olivine dolerite; 47 and 29, dolerite; 24, 13, 90, 7, 1 and 19, quartz dolerite; 15, feldsparphyric dolerite; 5 and 46 porphyritic dolerite.

$$\text{S.I.} = \frac{100\ \text{MgO}}{\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O}}$$

a trend almost perfectly. Because the more basic rocks do not appear to contain olivine phenocrysts in sufficient abundance to account for this by accumulation, this is presumably a fractional crystallization path. Therefore, specimen 9 represents a somewhat picritic liquid, and Dr K. G. Cox (pers. comm.) points out that these are probably the first Karroo rocks derived from picritic magmas to have been found outside the Lebombo.

The three rocks 40, 28, and 14, although very similar to 10, 33, and 31 in terms of MgO, are higher in CaO and lower in incompatible elements. Their petrogenesis must be rather different, and it is noteworthy that these three rocks derive from the more northerly part of southern Malawi (fig. 1), whereas the rocks in the series 9, 32, 11, 10, 33, and 31 are all from the extreme south of the country (fig. 1).

For the rest of the suite it appears that plagioclase and clinopyroxene, as well as olivine, were important in determining the path of crystallization. Specimen 15 with high Al_2O_3 and Sr and low total iron probably involved some degree of plagioclase accumulation.

Regional geochemical variation. Walker and Poldervaart (1949) showed that there are significant geochemical differences between the rocks of the northern and southern parts of the Karroo outcrop and more detailed studies were made by Cox *et al.* (1965), Cox and Hornung (1966), Cox *et al.* (1967) and Vail *et al.* (1969). The southern province, comprising essentially the basalts of Lesotho and Swaziland and the dolerites of South Africa, has a typical tholeiite chemistry, whereas the northern province, consisting principally of the Karroo lavas of Rhodesia, is abnormal by virtue of high values for K, Ti, P, Ba, Sr, and Zr, and probably Nb and Y, and low values for Ca and Al (Cox *et al.*, 1967).

Rhodes and Krohn (1972) confirmed statistically that there is considerable regional variation in the chemistry of Karroo lavas. However, they interpreted their data as indicating the presence of a central Karroo basin (outlined on fig. 1, inset map) and a chemically distinct area marginal to the

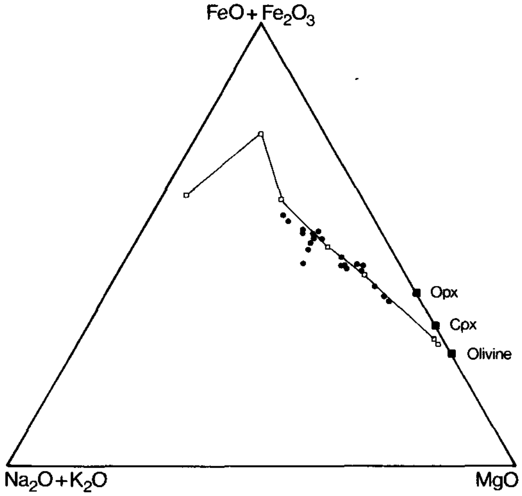


FIG. 3. AFM diagram (wt. per cent) of Malawi Karroo dolerites (solid circles). The open squares are for rocks from the differentiated Elephant's Head dike and New Amalfi sheet (Poldervaart, 1944). The compositions of olivines (average of six most magnesian values—see fig. 2), orthopyroxene, and average clinopyroxene of the Malawi dolerites are indicated.

TABLE II. *Average analyses of Karroo basalts*

	Northern province		Southern province		Malawi dolerites
wt. %	1	2	3	4	5
SiO$_2$	51.71	50.6	52.04	52.0	50.38
TiO$_2$	3.00	2.6	1.31	1.0	0.85
Al$_2$O$_3$	12.50	13.8	15.18	15.5	14.54
Fe$_2$O$_3$	4.23	4.1	2.58	2.0	1.72
FeO	8.18	8.7	8.69	8.7	8.52
MnO	0.16	0.2	0.18	0.2	0.20
MgO	7.14	6.3	6.42	7.2	8.64
CaO	8.42	9.5	10.27	10.3	10.04
Na$_2$O	2.45	2.5	2.53	2.1	1.93
K$_2$O	1.68	1.3	0.66	0.8	0.69
P$_2$O$_5$	0.51	0.4	0.14	0.2	0.15
ppm					
Ba	757		213		86
Sr	737		207		121
Cr	400		255		677
V	258		268		215
Ni	217		76		221
Rb	44		17		130

1. Average of twenty-nine basalts from the northern part of the Karroo outcrop including Nyamandhlovu (8), Featherstone (6), Wankie (2), and Nuanetsi (13) (Cox *et al.*, 1967, Table 3). For localities see fig. 1, inset diagram.
2. Average basalt (seventy-one analyses from twenty-two localities) from margin of the Karroo basin north of latitude 26° S. (Rhodes and Krohn, 1972, Table 1).
3. Average of seventy-three basalts from the southern part of the Karroo outcrop, including Swaziland (Cox *et al.*, 1967, Table 3), Basutoland (Cox and Hornung, 1966, Table 2), and South Africa (Walker and Poldervaart, 1949, Table 15).
4. Average basalt (119 analyses from thirty-eight localities) from the central Karroo basin (Rhodes and Krohn, 1972, Table 1).
5. Average of the twenty-one Karroo dolerites of southern Malawi.

basin. A glance at the map (fig. 1, inset) shows that the area to the south of the basin is very much smaller than the area to the north, and as analyses from the southern margin are relatively few their similarity to analyses of rocks from the northern marginal area was missed by earlier workers. However, because the available analyses come overwhelmingly from the central basin and areas to the north of the basin, it is simpler and more practicable to divide the Karroo outcrop into northern and southern areas at a latitude of 26° S (see fig. 1, inset map).

Because of lack of data all previously published regional geochemical studies have only extended northwards as far as the Victoria Falls to Featherstone line of outcrops of central Rhodesia (fig. 1, inset diagram), but there was extensive Karroo volcanic activity in the central Zambezi Valley, in Mozambique, east and south of Tete, and in southern Malawi. The Karroo dolerites of southern Malawi described here are perhaps the most northerly manifestation of the Karroo igneous episode, and extend considerably the area which must now be included in any regional geochemical study.

Table II (col. 5) shows average analyses for the twenty-one Malawi Karroo dolerites analysed during this work and, for comparison, averages are also given for representative areas of the northern and southern (essentially central Karroo basin of Rhodes and Krohn, 1972) provinces. The differences between northern and southern province areas identified by earlier workers are readily apparent from Table II, notably for TiO$_2$, Al$_2$O$_3$, CaO, K$_2$O, P$_2$O$_5$, Ba, and Sr. It is also apparent that the Malawi data for all these oxides and elements match closely those of the southern, not the northern, areas.

In fig. 5 values for TiO$_2$, Al$_2$O$_3$, K$_2$O, P$_2$O$_5$, and Ba are plotted against MgO, for a number of northern and southern province areas, together with the Malawi dolerite data. These plots indicate variable degrees of overlap between the provinces, for all five elements, but the distinction between the two provinces is clearly significant. In each case the Malawi data plot with the southern province distributions, a fact which radically changes the regional geochemical pattern described hitherto.

Discussion. The Karroo dolerites of southern Malawi are chemically and mineralogically typical tholeiites and, therefore, unremarkable. However, when considered in the context of the regional geochemistry of the Karroo basaltic province they are important because they differ from regional chemical trends which have been recognized and interpreted by a number of earlier workers. The simple division of the Karroo outcrop into chemically contrasting northern and southern provinces now no longer holds, and neither does the division into a central Karroo basin with contrasting basin marginal areas.

None of the many mechanisms which have been

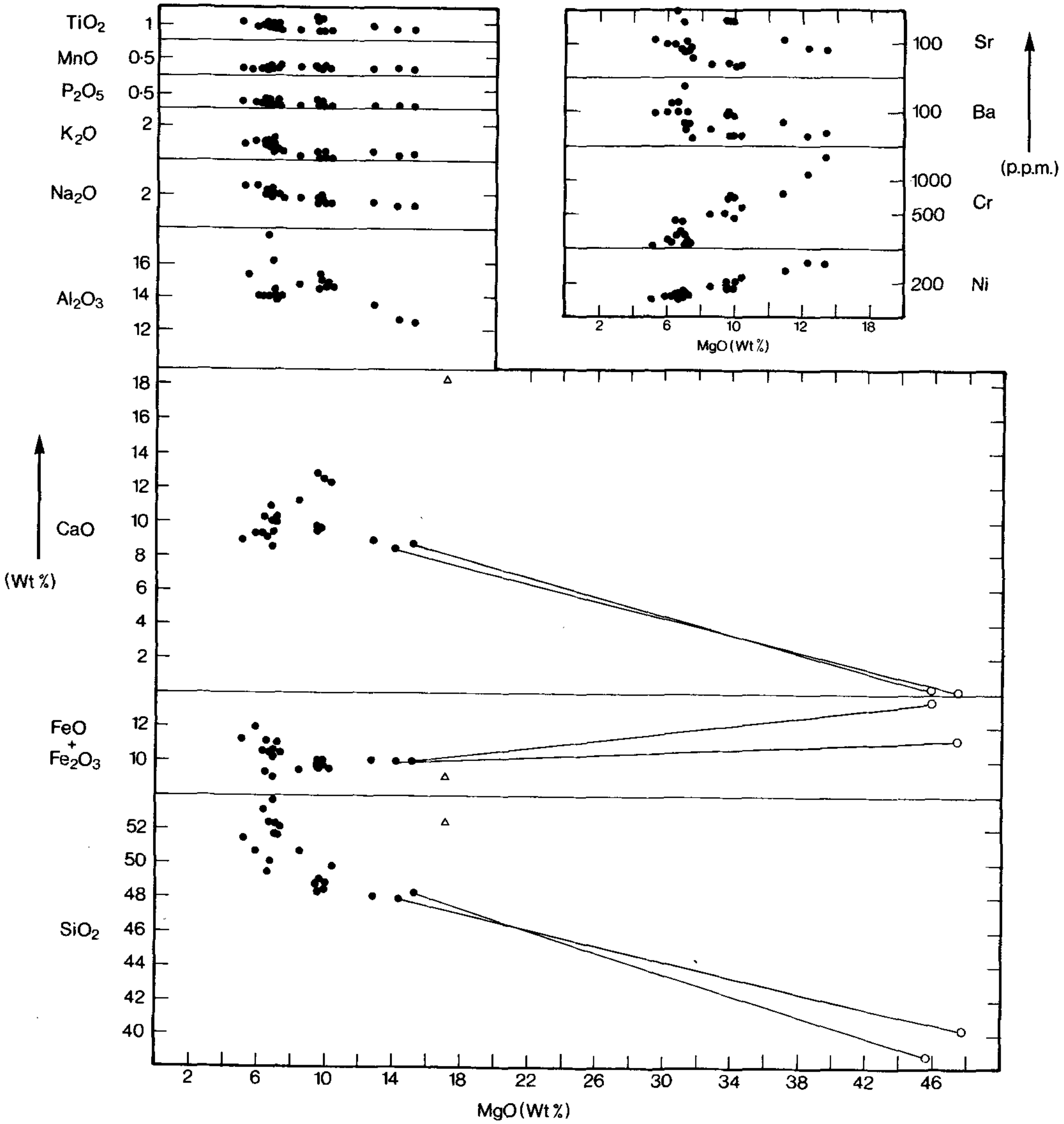


FIG. 4. Plot of wt. per cent oxides, and ppm for five elements, against wt. per cent MgO for the Malawi Karroo dolerites (see Table I). Also plotted are olivine compositions (open circles) for the two most magnesian rocks, to which they are tied, and an average augite (open triangle) from the same two rocks. It is apparent that initial differentiation of the suite was strongly controlled by olivine, not pyroxene.

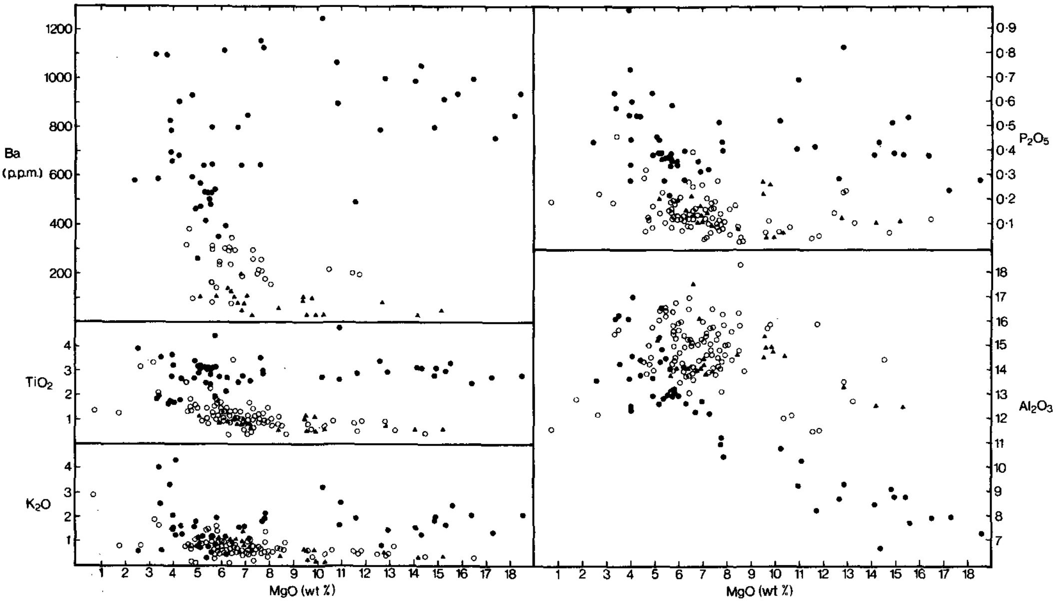


FIG. 5. Plot of selected oxides and barium against MgO (wt. per cent) to illustrate some chemical differences between the northern and southern parts of the Karroo outcrop. Filled circles, Karroo basalts and dolerites from areas north of latitude 26° S (see fig. 1, inset map); open circles, Karroo basalts and dolerites from south of latitude 26° S; filled triangles, Malawi dolerites. The Malawi dolerites have a strong tendency to correlate with rocks from the southern part of the Karroo. Data from Cox and Hornung (1966), Cox *et al.* (1967), Vail *et al.* (1969), and this paper.

suggested to explain the Karroo regional chemical variation, and which are summarized in Rhodes and Krohn (1972), is wholly satisfactory. The variation seems to be generally independent of most major tectonic and structural features, and the Malawi data do not fit the idea of a thermal regime peripheral to a central Karroo basin, unless a similar basin existed in the area of NE Rhodesia, central Mozambique, and southern Malawi, and there is no evidence for this. The Malawi data are consistent with the hypothesis of Cox (1972) that Karroo magmatism was due to a single complex cycle, initiated by the breakup of Gondwanaland, and involving the rise of a potassium-rich magma body in the approximate area of Rhodesia. Magmatism peripheral to this area 'was characterized by more normal magmatism derived from only moderate depths in the mantle and caused only by increased heat flow' (*op. cit.* p. 330). Although the depth of origin of magmas was probably an important factor in accounting for some of the variation among Karroo igneous rocks, particularly of some of the more extreme alkaline types (Woolley and Garson, 1970), the present authors feel that the general regional chemical variation across the Karroo province is best explained by heterogeneity in the mantle, and rather than one particularly large mantle plume beneath Rhodesia suggest that there were numerous mantle perturbations the volcanic products of which reflect the composition of that particular area of mantle. The large scale of the variation and the fact that the Karroo province was truncated along the line of the present SE African coast by plate movements suggest that the same pattern of regional variation should be present in the equivalent provinces of Antarctica, and possibly India.

Acknowledgements. Dr R. D. Walshaw kindly made available a selection of dolerites from the collection of the Geological Survey of Malawi, and Mr S. Mwabile was very helpful in providing background information on these samples. We are most grateful to Dr K. G. Cox who made a number of very significant suggestions for improving the paper, and we are also grateful to him and Dr P. Henderson for critically reading an earlier version of the manuscript.

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[*Manuscript received 7 March 1979;*
revised 2 August 1979]