# Karroo basalts of southern Malawi and their regional petrogenetic significance

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ABSTRACT. Karroo basaltic lavas of southern Malawi are divided into two groups on the basis of stratigraphy, petrography, and the data from 20 newly analysed rocks. A lower group of porphyritic lavas is notably rich in plagioclase phenocrysts and has contents of K, Ti, P, Ba, and Zr unusually high for tholeiitic basalts. They are overlain by an upper group of aphyric or sparsely microphyric lavas whose chemistry is more normal for tholeiites and is comparable with that of the Karroo dolerite dykes in Malawi. Though they outcrop in the northern part of the Karroo province, the lavas and dykes have chemical characteristics more similar to southern province rocks, adding some complexity to the concept of geochemical provinces established by earlier workers. Inter-suite variations in incompatible trace element contents and ratios indicate that the basalts of each group were derived from heterogeneous mantle sources.

THE concept of geochemical provinces within the volcanic rocks of the Karroo system was first clearly established by Cox *et al.* (1967). They distinguished a southern province comprising the basalts of Lesotho (see Cox *et al.* (1967) and Woolley *et al.* (1979) for Karroo locality maps), Swaziland and the dolerites of S. Africa, and having a typical tholeiitic chemistry, from a northern province comprising mainly the lavas of Rhodesia and containing in the mafic members, values of K, Ti, P, Ba, Sr, and Zr abnormally high for tholeiitic rocks.

A more complicated pattern of chemical variation was described by Cox (1972). In the Nuanetsi area of Rhodesia, part of the northern province of Cox *et al.* (1967), rocks from the uppermost part of the sequence, in particular the Inter-bedded Basalts, were recognized as having southern province character, thus negating any simple relationship between magma chemistry and geographical or tectonic situation. This was confirmed by studies of Woolley *et al.* (1979) on the dolerite dykes of southern Malawi in the northern part of the Karroo outcrop. They showed that these rocks apparently have southern province chemistry. Woolley *et al.* (1979) suggested that regional geochemical variations reflect heterogeneity in the mantle sources.

Erlank *et al.* (1980) also invoked mantle heterogeneity, in the horizontal and perhaps vertical senses, as the explanation for compositional variability in the Karroo basalts. On trace element and isotopic evidence they proposed that such heterogeneity resulted from complex pre-Karroo metasomatic events which enriched some areas of mantle in incompatible elements and depleted others.

Continuing studies (Erlank *et al.*, 1980) are attempting to document fully the range of chemical variation in the Karroo rocks as functions of geographical location and stratigraphical position within sequences. Such studies will eventually place some constraints on the mechanisms generating northern and southern province chemistries. As a contribution, this paper presents chemical and petrographic data for a hitherto poorly known northern part of the Karroo sequences, the lavas of southern Malawi.

The fact that both northern and southern province chemistries can be found in one area makes an explanation of the use of the provincial terminology necessary. Cox (1972) preferred such terms as potassic and potassium-poor (or sodic) types while Erlank *et al.* (1980) informally used enriched and
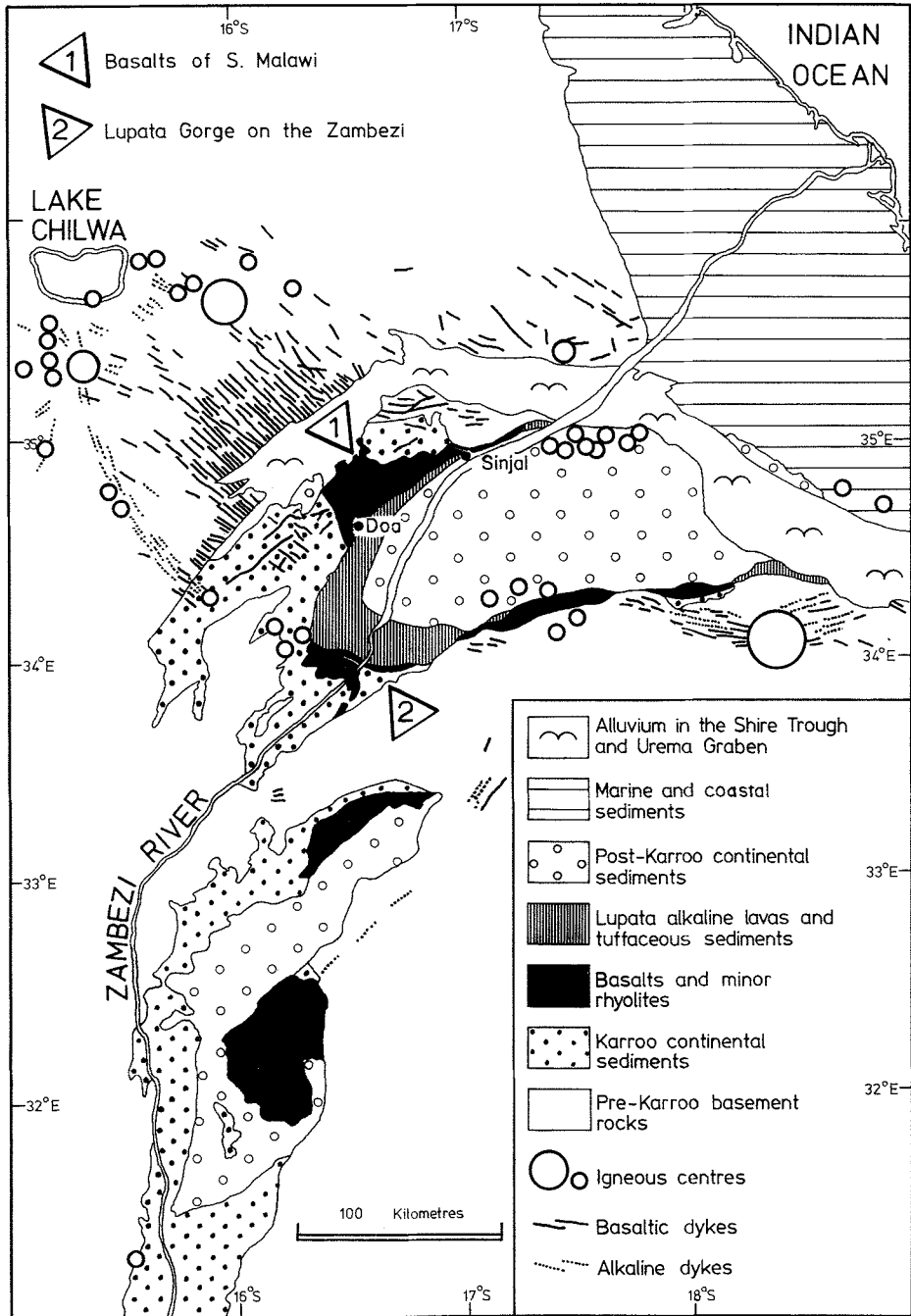
FIG. 1. Simplified geological map of southern Malawi and adjacent areas of Mozambique, to show the relationships between the Karroo lavas studied here (Triangle 1) and related lavas and the dolerite dyke swarm.

normal to describe Karroo basalts, with particular reference to incompatible trace element contents. Such terminology is, of course, imprecise unless some reference datum is specified. The terms 'enriched' and 'normal' are used here to describe the potassic and less-potassic (sodic) varieties of Karroo tholeiite, except where reference to earlier papers is being made and the terms northern and southern provinces are also given to avoid ambiguity.

## Geology

Southern Malawi lies on the SW margin of the Zambezi trough and the stratigraphic units are in a general way tilted away from Malawi towards the Zambezi (fig. 1). Erosion has stripped away many of the younger units from the uplifted margin so that in southern Malawi the older units are found whereas the younger sequences are incomplete or missing. A generalized Mesozoic stratigraphy for southern Malawi is given in Table I; for completeness, the stratigraphy at Sinjal-Doa, some 20 km SW of the Malawi basalt outcrops, and at Lupata gorge, some 70 km to the west, are also shown in Table I. The great thickness of Karroo lavas at Sinjal-Doa suggests that no more than the lower third of the full Karroo volcanic sequence is preserved in southern Malawi.

The lowermost 130 m of the basalt sequence, the *porphyritic group* of this study, is notably plagioclase-phyric and crops out in poorly exposed terrain along with purple-red basaltic pyroclastic rocks. The indifferent exposures make it almost impossible to define stratigraphical relationships within the group and accordingly as wide an area as possible, some 30 km$^2$, was sampled in the hope of collecting the full petrographic range. Among the analysed samples (Table II), the only relative age known is that M4-2 overlies M4-3. The fragments in M4-2 belong petrographically to the porphyritic group but the rock is chemically akin to the overlying aphyric group. It is taken to mark the transition between the two, thus establishing M4-3 as the highest member locally of the porphyritic group.

The overlying basalts of the *aphyric group* form a 300 m thick sequence, with individual flows ranging between 3 m and 25 m. The local vent agglomerate noted by Dixey (1930) near the top of this sequence is somewhat exceptional since pyroclastic rocks are much less common amongst the aphyric lavas than the porphyritic group. The aphyric rocks form higher ground and are rather better exposed than the underlying group. Nine of the analysed specimens were collected in two stratigraphical sequences on Murukanyama Hill and a hill 3 km away; from bottom to top in each case, they are

TABLE I.   Generalized Mesozoic stratigraphy of S. Malawi, with comparative sequences.

| | | SOUTH MALAWI | | SINJAL-DOA | LUPATA GORGE | |
|---|---|---|---|---|---|---|
| | | sandstone | | Sena sandstone | Sena sandstone | 300 m+ |
| CRETACEOUS | | | | unconformity | PHONOLITE LAVAS | 300 m  115 ± 10 m.y. |
| | | | | sandstone with | TUFFACEOUS SANDSTONE | 50 m |
| | | | | some ASH        150 m | conglomeratic sandstone | 100 m |
| | | | | | unconformity | |
| | | | | | RHYOLITE LAVA | 80 m        166 ± 10 m.y. |
| | | | | | sandstone | 90 m |
| | JURASSIC | unconformity | | unconformity | unconformity | |
| | | | | BASALT LAVAS        200 m | BASALT LAVAS   600 m ± | |
| | | | | RHYOLITE LAVAS and | | |
| | | | | TUFFS             130 m | | |
| K A R R O O | | BASALT LAVAS (aphyric) | 300 m | BASALT LAVAS   1100 m | | |
| | | BASALT LAVAS (porphyritic) and PYROCLASTICS | 130 m | | | |
| | | sandstones (upper) | 800 m | | | |
| | TRIASSIC | unconformity | | | | |
| | | red beds | 300 m | Karroo sandstones | Karroo sandstones | |
| | | Mwanza grits and shales | 1000 m | | | |
| | | sandstones (lower) | 1300 m | | | |
| | | coal shales | 600 m | | | |
| | PERMIAN | unconformity | | | | |
| | | basement complex | | | | |

Sources of information:  Dixey and Campbell Smith (1929);  Dixey (1930);  Flores (1964);  Habgood (1963).

M11, M12, M14, M15, M16, and M27, M28, M29, M30 (Table II). M18 is probably from near the base of the aphyric sequence, while M16 is a dyke intruding the porphyritic group, which presumably once fed aphyric extrusives subsequently stripped off. The only leucocratic rock found is a rhyolite dyke (M31) cutting the porphyritic group. While not directly relevant to the main aims of this study, the dyke is of some interest for its likely magmatic affinity. While the only ferromagnesian phase in the rock is magnetite (in various stages of oxidation to hematite) and the dyke itself is corundum-normative (c = 1.4 %), the low $Al_2O_3$ and high $Fe_2O_3$, Ce, Nb, Y, Zn, and Zr contents are more consistent with peralkaline chemistry. It seems probable that during emplacement and crystallization of this body, loss of $Na_2O$ occurred, which caused precipitation of magnetite rather than Na–Fe silicates. This effect has been described from peralkaline intrusions in SW Greenland by Macdonald (1969) and Larsen and Steenfelt (1974). Peralkaline Karroo rhyolites have been recorded in the upper part of the sequence in the southern Lebombo (Assunçao *et al.*, 1962).

*Relationships with the dolerite dyke swarm.* The NE-trending dolerite dyke swarm can be seen on fig. 1 on the shoulder of the alluvium-filled trough opposite the basalt lava outcrops. The representation of the dykes on this map is necessarily diagrammatic; for a better illustration of the intensity of the swarm see Woolley *et al.* (1979).

There are no radiometric dates for the dykes but they are considered to be of Jurassic age because dykes and sills of dolerite intrude sediments of late Triassic to early Jurassic (Stormberg) age in the Chikwawa area and the swarm is cut by intrusions belonging to the early Cretaceous Chilwa alkaline province. It would seem likely therefore, on the basis of age, geographic proximity and rock type, that the dolerite dyke swarm and basalt lavas are representatives of the same phase of igneous activity.

## Petrography

*Lavas of the porphyritic group.* Two types may be distinguished on the basis of phenocryst assemblages (specimen numbers in brackets): olivine-augite-plagioclase-phyric basalts (5, 4-3, 23, 25, 3) and olivine–plagioclase-phyric basalts (9, 22). Chemical data (Table II) indicate that the latter type is more evolved, less magnesian, than the former. All the rocks are characterized by a relative abundance, 8 % to 25 % modally, of plagioclase phenocrysts up to 8 mm long and commonly occurring in glomeroporphyritic aggregates or stellate clusters. Olivine phenocrysts are fresh in specimen 23 but in other rocks are pseudomorphed by iddingsite or serpentine. Their maximum dimension is 1 mm and abundance varies from < 1 % to 5 %. Colourless augite phenocrysts (up to 8 %) occur as discrete, subhedral crystals up to 2 mm across but more often are found in glomeroporphyritic aggregates.

In some specimens, the phenocryst phases grade down in size to a holocrystalline matrix dominated by laths of plagioclase, intergranular augite and pigeonite and Fe–Ti oxides ranging in shape from rod-like to equant. More commonly, the matrix contains variable, up to 30 %, amounts of glass, normally heavily charged with reticulate ore and occasionally devitrified.

*Lavas and dyke of the aphyric group.* While the 'aphyric' designation is convenient in the field, many rocks in this group are actually sparsely microphyric. The following microphenocryst assemblages, listed approximately in order of decreasing MgO contents of the host rocks, have been recognized: olivine (18, 6); olivine–augite (12); augite–plagioclase (27); augite–plagioclase–Fe–Ti oxides (11). The aphyric rocks (14, 15, 16, 28, 29, 30) are the most evolved rocks in the group; textural relationships indicate that oxides were the earliest crystallizing phase. The aphyric rocks and the matrices of the microphyric types consist of plagioclase, augite, pigeonite, Fe–Ti oxides and small amounts of glass. The most common texture is ophitic or subophitic, which has not been seen in the lavas of the porphyritic group. This compares with the general relationship noted by Cox *et al.* (1967, p. 1471), that subophitic relationship had not been observed in northern province rocks but was common in southern province lavas. Some Malawi specimens (11, 12, 14, 27) contain coarser patches of doleritic texture which may contain carbonate ocelli.

## Petrochemistry

Seven specimens from the porphyritic group, 12 from the aphyric group and a rhyolite dyke were analysed for major and 15 trace elements (Table II). All the mafic specimens are hypersthene + quartz normative, even after adjustment of the oxidation ratio $100Fe^{3+}/(Fe^{2+} + Fe^{3+}) = 10$ (Cox and Hornung, 1966, p. 1425), indicating that on a chemical basis, the Malawi basalts are quartz tholeiites. None of the rocks is notably magnesian, the highest MgO content being 8.44 %. No extrusive equivalent of the picritic Karroo dykes of Malawi noted by Woolley *et al.* (1979) has thus been recorded. The relatively low MgO mafic Karroo volcanic rocks have traditionally been termed basalts yet, as Wilkinson and Binns (1977)

TABLE II. Analyses of Malawi Karroo lavas and dykes

| | Porphyritic group | | | | | | | Aphyric group | | | | | | | | | | | | Rhyolite |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | 4.3 | 23 | 25 | 3 | 9 | 22 | 4-2 | 18 | 11 | 12 | 14 | 15 | 16 | 27 | 28 | 29 | 30 | 6 | 31 |
| $SiO_2$ | 51.9 | 51.3 | 50.5 | 50.3 | 50.8 | 50.3 | 49.8 | 57.8 | 51.2 | 52.8 | 50.8 | 50.4 | 52.3 | 52.4 | 52.4 | 52.8 | 52.5 | 52.7 | 49.0 | 72.7 |
| $TiO_2$ | 1.40 | 1.62 | 1.89 | 1.93 | 1.81 | 2.03 | 2.02 | 0.63 | 0.54 | 0.72 | 0.68 | 0.90 | 0.98 | 0.97 | 0.71 | 0.77 | 0.88 | 1.00 | 1.00 | 0.44 |
| $Al_2O_3$ | 15.20 | 14.33 | 14.51 | 15.07 | 16.65 | 15.99 | 16.59 | 11.08 | 14.87 | 14.41 | 14.13 | 14.42 | 13.98 | 14.05 | 14.96 | 14.38 | 14.06 | 13.89 | 16.28 | 10.05 |
| $Fe_2O_3$ | 5.12 | 6.14 | 6.98 | 10.22 | 8.17 | 10.40 | 9.75 | 6.66 | 3.92 | 2.80 | 3.89 | 2.31 | 4.03 | 2.96 | 2.44 | 2.70 | 3.14 | 3.48 | 5.82 | 8.28 |
| $FeO$ | 5.94 | 5.94 | 6.54 | 3.36 | 3.02 | 2.57 | 3.01 | 0.40 | 5.52 | 7.40 | 6.16 | 8.87 | 8.41 | 8.96 | 7.26 | 8.17 | 7.86 | 8.88 | 5.58 | 0.00 |
| $MnO$ | 0.13 | 0.17 | 0.13 | 0.11 | 0.11 | 0.10 | 0.13 | 0.17 | 0.13 | 0.19 | 0.12 | 0.16 | 0.17 | 0.16 | 0.12 | 0.18 | 0.18 | 0.15 | 0.14 | 0.24 |
| $MgO$ | 5.34 | 5.22 | 4.57 | 3.91 | 3.22 | 2.72 | 2.48 | 3.00 | 8.44 | 6.35 | 6.39 | 6.08 | 6.13 | 5.74 | 6.82 | 6.29 | 6.07 | 5.77 | 7.10 | 0.16 |
| $CaO$ | 8.72 | 8.97 | 8.35 | 8.64 | 7.98 | 7.25 | 8.58 | 6.13 | 11.54 | 10.80 | 10.76 | 10.79 | 9.88 | 9.60 | 11.11 | 10.29 | 9.88 | 9.94 | 10.21 | 0.17 |
| $Na_2O$ | 2.30 | 2.29 | 2.44 | 2.49 | 3.03 | 3.08 | 2.99 | 1.66 | 1.84 | 2.08 | 2.29 | 1.94 | 2.22 | 2.40 | 2.01 | 2.22 | 2.13 | 2.19 | 2.53 | 2.80 |
| $K_2O$ | 1.84 | 1.68 | 1.82 | 1.89 | 2.16 | 2.94 | 2.00 | 5.56 | 0.74 | 0.98 | 1.66 | 0.48 | 0.98 | 0.99 | 0.49 | 0.88 | 1.04 | 0.93 | 0.84 | 3.49 |
| $P_2O_5$ | 0.28 | 0.31 | 0.36 | 0.38 | 0.36 | 0.42 | 0.43 | 0.06 | 0.08 | 0.12 | 0.12 | 0.14 | 0.15 | 0.14 | 0.11 | 0.12 | 0.13 | 0.14 | 0.21 | 0.01 |
| $H_2O+$ | 0.85 | 0.67 | 1.06 | 1.02 | 0.94 | 1.50 | 1.13 | 1.39 | 0.70 | 0.20 | 1.33 | 3.05 | 0.48 | 0.89 | 1.02 | 0.30 | 1.30 | 0.31 | 1.05 | 0.99 |
| $CO_2$ | 0.17 | 0.68 | n.d. | n.d. | 1.13 | n.d. | n.d. | 4.76 | | 0.16 | 0.87 | | n.d. | n.d. | | | n.d. | n.d. | n.d. | |
| Total | 99.19 | 99.32 | 99.15 | 99.32 | 99.38 | 99.30 | 98.91 | 99.30 | 99.52 | 99.01 | 99.20 | 99.54 | 99.71 | 99.26 | 99.45 | 99.10 | 99.17 | 99.38 | 99.76 | 99.33 |
| **Trace elements (ppm)** | | | | | | | | | | | | | | | | | | | | |
| Ba | 602 | 659 | 702 | 718 | 752 | 820 | 794 | 295 | 168 | 249 | 291 | 183 | 311 | 287 | 230 | 265 | 204 | 240 | 330 | 358 |
| Ce | 69 | 71 | 78 | 71 | 70 | 72 | 70 | 18 | 22 | 30 | 13 | 22 | 31 | 22 | 23 | 14 | 20 | 24 | 29 | 526 |
| Co | 50 | 43 | 39 | 46 | 31 | 40 | 42 | 24 | 43 | 46 | 39 | 37 | 48 | 44 | 43 | 45 | 36 | 44 | 44 | 18 |
| Cr | 217 | 179 | 127 | 109 | 70 | 34 | 16 | 169 | 397 | 148 | 168 | 45 | 26 | 31 | 156 | 64 | 83 | 22 | 132 | <1 |
| Cu | 26 | 27 | 46 | 32 | 34 | 38 | 51 | 62 | 74 | 98 | 93 | 96 | 95 | 126 | 70 | 86 | 114 | 112 | 73 | 16 |
| Ga | 21 | 9 | 8 | 16 | 13 | 17 | 14 | 8 | 13 | 7 | 10 | 8 | 5 | 4 | 11 | 7 | 11 | 9 | 16 | 22 |
| Nb | 16 | 18 | 20 | 24 | 22 | 25 | 23 | 9 | 7 | 8 | 5 | 8 | 7 | 8 | 9 | 9 | 8 | 12 | 6 | 230 |
| Ni | 32 | 38 | 32 | 29 | 21 | 21 | 27 | 65 | 139 | 80 | 80 | 72 | 54 | 51 | 97 | 62 | 73 | 42 | 157 | 14 |
| Pb | 11 | 12 | 10 | 9 | 14 | 13 | 10 | 14 | 11 | 6 | 5 | 7 | 6 | 7 | 7 | 6 | 27 | 170 | 5 | 65 |
| Rb | 43 | 41 | 49 | 48 | 52 | 84 | 49 | 84 | 21 | 32 | 54 | 16 | 19 | 21 | 6 | 31 | 24 | 30 | 15 | 153 |
| Sr | 250 | 232 | 226 | 235 | 262 | 248 | 301 | 88 | 79 | 98 | 84 | 79 | 121 | 106 | 150 | 102 | 129 | 101 | 273 | 22 |
| Th | 4 | 4 | 8 | 6 | 6 | 5 | 6 | 4 | 1 | <1 | 2 | 3 | 4 | 5 | 2 | 3 | 4 | 2 | 3 | 34 |
| Y | 32 | 34 | 42 | 43 | 40 | 50 | 42 | 29 | 15 | 21 | 22 | 27 | 26 | 26 | 20 | 25 | 25 | 27 | 22 | 170 |
| Zn | 71 | 80 | 97 | 110 | 110 | 94 | 108 | 61 | 50 | 54 | 61 | 66 | 68 | 77 | 67 | 56 | 61 | 66 | 60 | 234 |
| Zr | 174 | 189 | 221 | 224 | 224 | 254 | 230 | 120 | 57 | 73 | 70 | 96 | 95 | 96 | 76 | 80 | 92 | 103 | 91 | 1445 |
| **Selected ratios** | | | | | | | | | | | | | | | | | | | | |
| K/Rb | 355 | 340 | 308 | 327 | 345 | 291 | 335 | 539 | 293 | 254 | 255 | 249 | 428 | 391 | 678 | 236 | 360 | 257 | 465 | 189 |
| $Ce/P_2O_5$ | 0.025 | 0.023 | 0.022 | 0.019 | 0.019 | 0.017 | 0.016 | 0.030 | 0.028 | 0.025 | 0.011 | 0.016 | 0.021 | 0.016 | 0.021 | 0.012 | 0.015 | 0.017 | 0.014 | 5.3 |
| $TiO_2/Zr$ | 80 | 86 | 86 | 86 | 81 | 80 | 87 | 53 | 95 | 99 | 97 | 94 | 103 | 101 | 78 | 96 | 96 | 97 | 110 | 3 |
| Zr/Nb | 10.9 | 10.5 | 11.1 | 9.3 | 10.2 | 10.2 | 10.0 | 13.3 | 8.1 | 9.1 | 14.0 | 12.0 | 13.6 | 12.0 | 8.4 | 8.9 | 11.5 | 8.6 | 15.2 | 6.3 |

4-2 is a tuff, 6 a dolerite dyke and 31 a rhyolite dyke. Other specimens are lavas.

Sample localities available from the authors.

Analyses by XRF, except FeO, $H_2O+$ and $CO_2$ - wet-chemical. n.d. = not detected.

and Cox (1980) have noted, the more evolved types may more appropriately be termed tholeiitic andesite on the basis of differentiation indices > 35 and relatively high Fe/Mg ratios.

With the exception of sample M4-2, there are clear chemical differences between the rocks of the two groups, the porphyritic group being higher in K, Ti, P, Ba, Ce, Nb, Y, and Zr and lower in Mg, Cu, and Ni than the aphyric group with no overlap of concentrations. M4-2 is anomalous; though petro-

graphically it belongs either to the porphyritic or to some transitional stage between the groups, its chemical affinities are with the aphyric volcanic rocks.

The chemical differences between the groups are of two types: those (*a*) dependent on and (*b*) independent of, stage of fractionation, of which MgO may be taken as an approximate measure. Examples are shown on MgO variation diagrams in fig. 2. Thus Ni and Y abundances appear to be the same in both sequences at equivalent MgO contents. Ce, Cr and Cu, on the other hand, show inter-suite differences independent of MgO content.

When all the data are considered and allowing for fractionation state, it can be seen that relative to the aphyric group, the basalts of the porphyritic group show: (i) Absolute enrichment in $K_2O$, $TiO_2$, $P_2O_5$, Ba, Ce, Cr, Sr, and Zr by factors of some 2 to 4. (ii) Possible enrichment of Nb and Rb by similar factors. (iii) Absolute depletion in Cu. This clear inter-suite difference has apparently not been commented on by previous Karroo workers.

There is no overlap in MgO contents of the lavas of the two groups. Cox (1972) has noted a tendency for lavas erupted during the earliest stages of the Karroo volcanic cycle in some areas, e.g. Nuanetsi

and Sabi, to be well-fractionated, low MgO-types. This may be the situation in the southern Malawi lavas. However, the chemical features summarized above stress what is clear from the sequence of phenocryst assemblages in each group—that the groups are not comagmatic but chemically and petrographically distinct. The non-overlap of MgO values is probably a result of inadequate sampling.

The differences between the porphyritic and aphyric groups are superficially similar to those which distinguish the northern and southern geochemical provinces of Cox *et al.* (1967), as can be seen by comparison of average K, Ti, P, Ba, and Zr analyses (Table III). Part of the similarity of the porphyritic group to the enriched types is related, however, to their highly fractionated nature, expressed in low MgO, Cr, and Ni contents and correspondingly elevated abundances of the incompatible trace elements.

In detail, the porphyritic group is most closely similar (fig. 3) to the Inter-bedded Basalts of Nuanetsi, which Cox (1972 and pers. comm., 1982) has suggested have southern province chemistry, or are at least transitional in type between enriched and normal chemistry.

The provincial status of the porphyritic group of Malawi basalts is thus in some doubt. The magmas
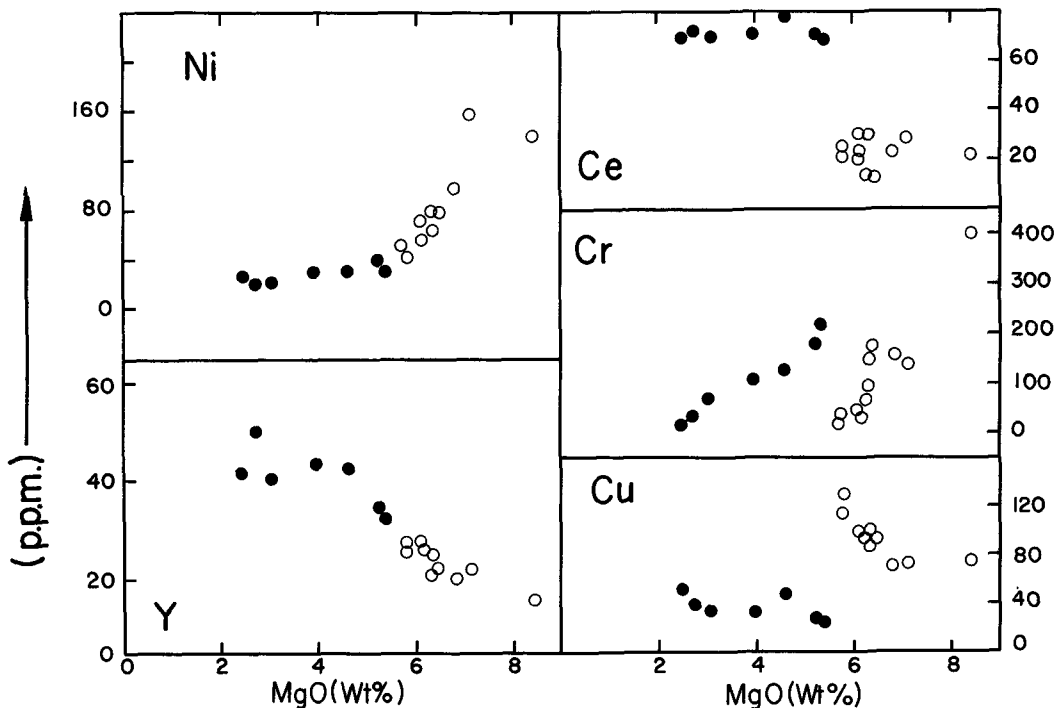


FIG. 2. Plot of selected trace elements (in ppm) against MgO (wt. %) for the Malawi Karroo basalts. Closed and open circles are rocks of the porphyritic and aphyric groups respectively. Specimen 4-2 (tuff) is not plotted.

TABLE III. *Average analyses of Karroo basaltic rocks (volatile-free basis)*

| | Enriched | | | | | Normal | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J |
| $SiO_2$ | 52.2 | 51.8 | 51.0 | 50.0 | 52.2 | 52.7 | 51.5 | 51.6 | 52.1 | 52.8 |
| $TiO_2$ | 1.86 | 3.20 | 3.42 | 2.94 | 2.67 | 1.16 | 0.95 | 1.65 | 0.90 | 0.85 |
| $Al_2O_3$ | 15.94 | 13.21 | 13.84 | 14.82 | 13.89 | 15.4 | 15.69 | 15.34 | 15.21 | 14.79 |
| $FeO_t$ | 11.99 | 12.89 | 11.21 | 13.15 | 11.87 | 10.59 | 9.87 | 11.68 | 10.39 | 10.83 |
| MnO | 0.13 | 0.18 | 0.15 | 0.15 | 0.16 | 0.22 | 0.16 | 0.16 | 0.21 | 0.16 |
| MgO | 4.04 | 5.48 | 5.47 | 4.65 | 5.60 | 6.6 | 7.01 | 5.56 | 7.79 | 6.60 |
| CaO | 8.61 | 9.37 | 8.94 | 9.55 | 8.12 | 9.96 | 10.69 | 10.29 | 10.35 | 10.66 |
| $Na_2O$ | 2.74 | 2.43 | 2.17 | 2.73 | 2.75 | 2.22 | 2.17 | 2.96 | 2.08 | 2.22 |
| $K_2O$ | 2.11 | 1.07 | 2.01 | 1.00 | 1.95 | 0.87 | 0.70 | 0.36 | 0.80 | 0.93 |
| $P_2O_5$ | 0.37 | 0.42 | 0.57 | 0.43 | 0.51 | 0.16 | 0.16 | 0.14 | 0.15 | 0.13 |
| ppm | | | | | | | | | | |
| Ba | 721 | 590 | 911 | 577 | 739 | 200 | 174 | 184 | 84 | 251 |
| Cr | 107 | — | 152 | — | 176 | 293 | 283 | 156 | 347 | 116 |
| Nb | 21 | 19 | 22 | 27 | 50 | — | 4.88 | 18–19 | — | 8 |
| Ni | 29 | 68 | 124 | — | 128 | 70 | 93.8 | 86 | 149 | 82 |
| Rb | 52 | 33 | 39 | 21 | — | 17 | 12 | < 50 | 119 | 24 |
| Sr | 251 | 577 | 936 | 641 | 656 | 168 | 192 | 264 | 126 | 120 |
| Zr | 217 | 352 | 364 | 311 | 197 | 88 | 94.1 | 70 | — | 84 |

$FeO_t$ = total Fe as FeO

A.  Basalt of porphyritic group, S. Malawi (7 analyses; this paper, Table II).
B.  Basalt, Nyamandhlovu (8; Cox *et al.*, 1967, Table 1, except Nb—new data).
C.  Basalt, Sabie River Formation, N. Lebombo (7; Cox and Bristow, in press).
D.  Basalt with MgO < 10% and excluding alkali-feldspar-bearing rocks Tuli (12; Vail *et al.*, 1969, Table 1).
E.  Basalt with MgO < 8%, Nuanetsi (9; Cox *et al.*, 1967, Table 3, cols. D1, D2).
F.  Karroo dolerite (44; Cox *et al.*, 1967, Table 3, col. G).
G.  Basalt, Lesotho Formation (49; unpublished data courtesy of Dr A. R. Duncan, University of Cape Town).
H.  Basalt, Swaziland (7; Cox *et al.*, 1967, Table 3, col. E).
I.  Karroo dolerite with MgO < 10%, S. Malawi (17; Woolley *et al.*, 1979, Table I).
J.  Basalt of aphyric group, S. Malawi (11; this paper, Table II, excluding specimen 4-2).

may have been derived from more magnesian liquids of enriched type and further study may reveal the presence of such rock types in the lava sequence. Alternatively, given the known complexities of high- and low-pressure evolution of the Karroo magmas (Jamieson, 1966; Cox and Jamieson, 1974; Cox, 1972, 1980), it is possible that the porphyritic lavas represent normal, southern province magmas enriched by protracted, low-pressure fractionation. Unfortunately, the fractionation histories of the Malawi rocks cannot yet be modelled realistically since there are too few data from each group to establish meaningful compositional *trends*. The similar Cr and Fe contents of the two Malawi groups preclude, however, any *simple* fractionation relationship between them.

The new data for the lavas are consistent with the conclusions of Woolley *et al.* (1979) that rocks of southern province character are present in the Karroo sequence of Malawi. The aphyric group lavas are broadly comparable to the dykes but significantly the dykes are systematically higher in Rb and Zn and lower in Ba than the lavas at equivalent MgO contents. Assuming that the analyzed samples are representative and that there are no problems caused by comparison of data from different laboratories, the analytical results indicate that dykes and lavas are not comagmatic.

These differences between lavas and dykes stress a point that was implicit in the overlapping of geochemical province data in the diagrams of Cox *et al.* (1967), viz. that superimposed on the broad pattern of geochemical types in the Karroo volcanic rocks, there is a second-order variability whereby individual suites within a group may show features different from each other and even
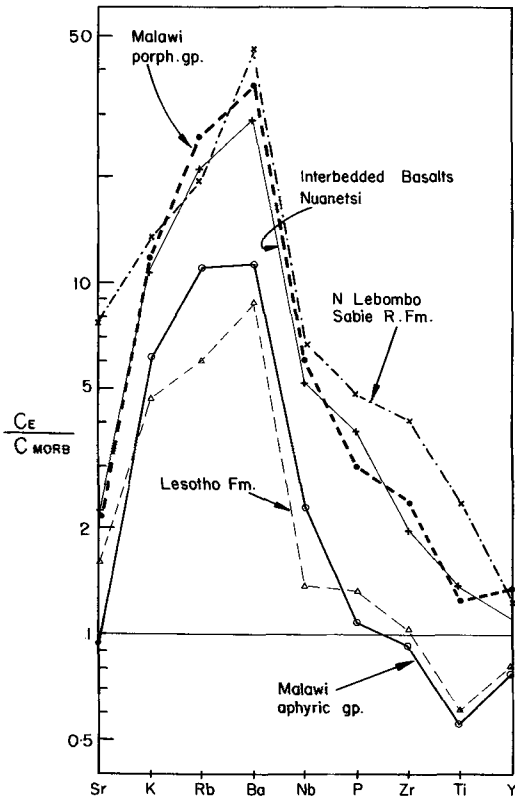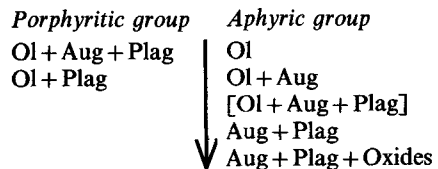
FIG. 3. Comparisons of selected elements in Malawi basalts and other Karroo sequences. Average concentrations ($C_E$) normalized to average mid-ocean ridge basalt ($C_{MORB}$) as given by Pearce (1982). Data for Inter-bedded Basalts, Nuanetsi, from K. G. Cox (pers. comm.); for other sequences, Table III (this paper).

Within the aphyric group there is a slight but clear tendency for the lavas to become increasingly differentiated with decreasing age (*vide* the stratigraphically controlled sequences M11 to M16 and M27 to M30, Table II). The position of the most magnesian specimen (M18) near the base of the aphyric group is consistent with such a trend. Cox and Hornung (1966) noted a similar relationship among the compositionally equivalent basalts in Lesotho. In a general model for continental flood basalt provinces, Cox (1980) suggested that parental picritic magmas intrude the base of the crust as a series of sills. The magmas fractionate in this sill complex and evolved magmas ascend to the surface as their density becomes sufficiently low. The increasingly evolved character of younger lavas may then be seen as a function of the time spent fractionating in the sills. The trace element data for the aphyric Malawi basalts and those of the central Karroo basin require that the eruptive products belong to a large number of liquid lines of descent. This in turn requires a large number of deep crustal sills comparable to the zones of multiple sill injection envisaged by Cox (1980, fig. 7).

*Relationships between rock chemistry and phenocryst assemblages.* Petrographic and chemical evidence may be used to distinguish the following sequence of phenocryst assemblages in the Malawi rocks with the arrow showing increasing differentiation:

| Porphyritic group | Aphyric group |
|---|---|
| Ol + Aug + Plag | Ol |
| Ol + Plag | Ol + Aug |
| | [Ol + Aug + Plag] |
| | Aug + Plag |
| | Aug + Plag + Oxides |

The assemblage Ol + Aug + Plag observed in lavas of the porphyritic group is common in enriched (northern province) suites (Cox *et al.*, 1967). The assemblage Ol + Plag is rare, having been noted only in three flows from the Tuli Sycline (Vail *et al.*, 1969). Cox *et al.* (1967) distinguished three stages in the evolution of the Rhodesian magmas: Ol + Aug + liquid, Ol + Aug + Plag + liquid and Aug + Plag + liquid. In the Malawi porphyritic group, however, it is augite rather than olivine which apparently disappears from the phenocryst assemblage, although the reaction relationship which removes it is not obvious petrographically. Higher pressure removal of clinopyroxene (Cox, 1980) is the most likely explanation for the failure of early crystallizing clinopyroxene in these magmas.

Differences to the regional picture also occur in the lavas of the aphyric group. The sequence of phenocryst assemblages is exactly that considered typical of northern province magmas by Cox *et al.*

characteristic of the other group. Erlank *et al.* (1980) noted that the mafic rocks in the central Karroo basin, while of normal affinity, have systematic compositional differences in such ratios as Zr/Nb and TiO$_2$/Zr. These differences are difficult to relate to any process of crystal fractionation or crustal contamination and Erlank *et al.* (1980) suggest that the mantle sources for those basalts were compositionally heterogeneous. The same features may be seen in the Malawi data. Selected ratios of incompatible trace and minor elements are given in Table II. The relative constancy of these ratios in the porphyritic group lavas is notable while the aphyric group rocks show a wide range of ratios which encompasses those in the porphyritic rocks. It would appear, therefore, that the lavas of the aphyric group at least, while closely related genetically, represent the products of separate fusion events of compositionally variable mantle sources.

(1967), especially if it may be assumed that the assemblage Ol + Aug + Plag has not yet been recorded only because of inadequate sampling.

The differing order of appearance of the phenocryst phases in the two provinces was ascribed by Cox *et al.* (1967) to their different chemistries. In southern province rocks, generally rather higher in CaO and $Al_2O_3$ (and thus normative anorthite), plagioclase crystallization preceded that of augite. In Malawi, the normal tholeiites are no more calcic, and perhaps actually less aluminous, than those of enriched type. The chemistry did not promote earlier separation of plagioclase than augite. The relationships between phenocryst assemblages and rock chemistry in the Malawi lavas, while apparently anomalous on a regional scale, are actually those established by Cox *et al.* (1967).

*Regional geochemical significance of the Malawi lavas.* Cox (1972) incorporated into his model of the Karroo volcanic cycle evidence from the Nuanetsi area that while stratigraphically lower tholeiites were of enriched, potassic type, younger lavas (such as the Inter-bedded Basalts) were distinctly less potassic, of more nearly normal tholeiitic chemistry. The new evidence from the Malawi lavas indicates that magmas similar to the Nuanetsi Interbedded Basalts predated the eruption of lavas of typically southern province chemistry. In both areas, there was a trend in time towards relative depletion in such elements as K, Ti, P, Ba, Sr, and Zr. Whether this trend resulted from depletion of the mantle sources by successive fusion events, or was a function of some more complex process such as mantle metasomatism, cannot yet be determined. The occurrence of a range of provincial characteristics in one area perhaps suggests that the differences are process-related rather than determined by any large-scale, lateral changes in source mantle composition.

An important aspect of the data from the Malawi lavas and dykes is that they require a modification to the concept of Karroo geochemical provinces as defined by Cox *et al.* (1967). The northern province must now be seen as areas where the most potassic, enriched rocks occur, even though they may be accompanied by more normal tholeiites, especially in the later stages of the volcanic cycle.

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