

GEOCHEMICAL AND PETROGRAPHIC PROVINCES IN THE KARROO BASALTS OF SOUTHERN AFRICA

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ABSTRACT

New analytical data are presented to show that the Karroo basalts are divisible into two distinct provinces. A northern province includes all the Rhodesian basalt localities and is characterised by values of K, Ti, P, Ba, Sr and Zr which are abnormally high for tholeiitic rocks. The southern province includes the basalts of Basutoland and Swaziland, and the Karroo dolerites of South Africa, all of which have a normal tholeiitic geochemistry.

Petrographically the provinces may be distinguished by a different order of crystallisation. The rocks of the southern province are relatively aluminous, and plagioclase appears as a phenocryst phase before pyroxene. In the less aluminous northern province, pyroxene appears earlier than plagioclase. Within the northern province, three main fractionation stages may be distinguished on the basis of phenocryst assemblages, and may be used to classify the basalts.

INTRODUCTION

During the investigation of the Karroo igneous rocks of the Nuanetsi district of Rhodesia (Cox, Johnson, Monkman, Stillman, Vail and Wood, 1965) it was observed that Karroo basalts from different areas of southern Africa showed rather marked chemical differences. On the information then available it appeared that the Karroo dolerites of South Africa (Walker and Poldervaart, 1949) and the Drakensberg (Basutoland) basalts resembled each other and were normal in their chemical features, while the basalts of the Victoria Falls and Nuanetsi areas of Rhodesia were notably rich in potassium and titanium. The basalts of Swaziland were noted as being less titanium rich than those of Nuanetsi, although lying on the same structural feature, the Lebombo monocline. The localities referred to are illustrated in Figure 1.

A detailed study of the Basutoland basalts was subsequently carried out (Cox and Hornung, 1966) and the basalts of Swaziland and the Rhodesian localities of Nyamandhlovu, Wankie, and Featherstone were sampled. The analytical results of these latter studies are given in this paper, together with new trace element data for the Nuanetsi basalts, for which we are indebted to Dr. Joan M. Rooke. As a result of the new data it is possible to comment more fully on the geochemistry of the Karroo basalts as a whole, and to divide them into two broad provinces, although it is not yet possible to define their exact extents, nor the nature of their mutual boundary.

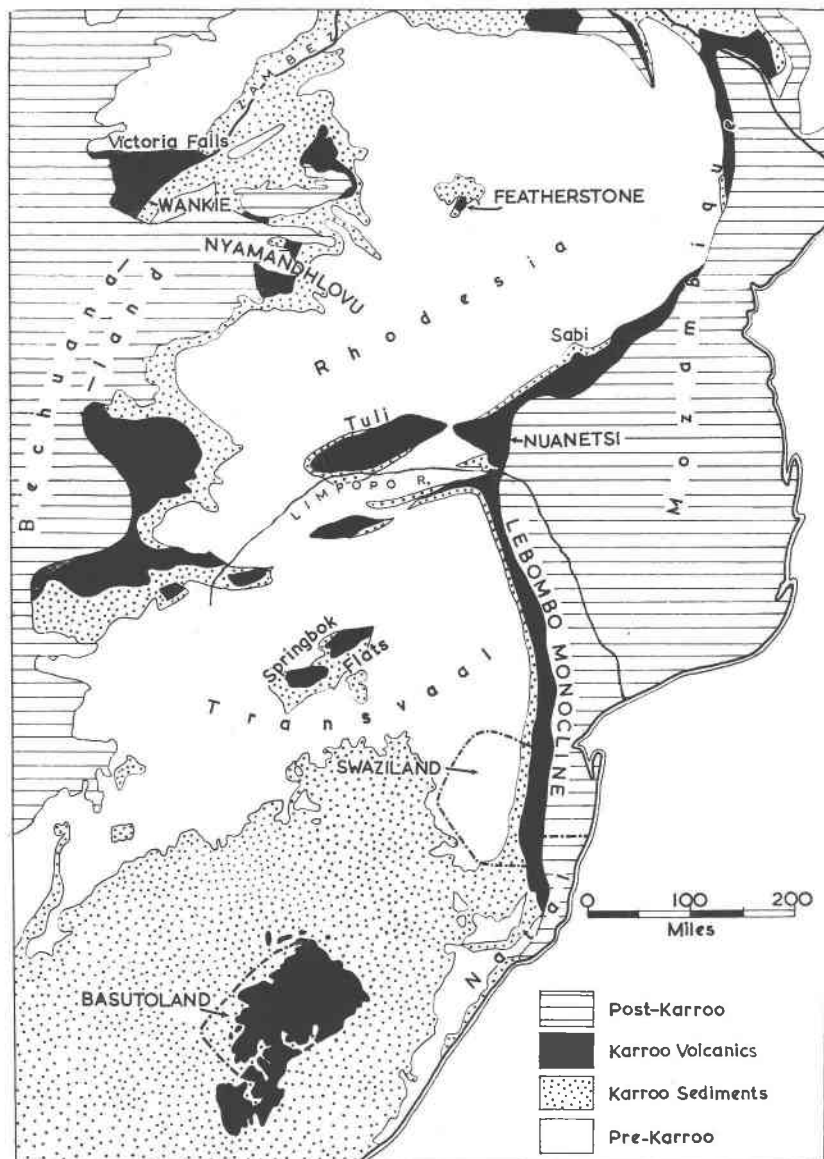


FIG. 1. Locality map for Karroo volcanics in southern Africa.

At the same time, petrographic observations enable us to relate the geochemical differences to mineralogical and textural features of the rocks. Within the northern province itself it is also possible to find an

explanation for the petrographic contrasts which Worst (1962) found between the basalts of western Rhodesia and south-eastern Rhodesia. These differences can be attributed to varying stages of fractionation of the magma, rather than to a fundamental chemical difference such as that which distinguishes the northern and southern provinces.

GEOLOGICAL SETTINGS OF THE BASALTS

For general accounts of the Karroo vulcanism the reader is referred to Du Toit (1954) and Haughton (1963). More specific accounts are given by Stockley (1947) for Basutoland, Urie and Hunter (1963) for Swaziland, and Swift (1961) for Rhodesia. For present purposes the following brief notes are appended.

The basalts of Swaziland lie near the southern end of the Lebombo monocline, a powerful late-Karroo flexure where the volcanics pass eastwards beneath the Cretaceous and later sediments which fringe the continent. The Nuanetsi basalts lie within a large volcano-tectonic syncline at the point where the north end of the Lebombo meets the zone of strong Karroo faulting and warping which runs along the Limpopo valley.

The Wankie basalts lie in the Zambezi valley, which like the Limpopo area, was a zone of Karroo faulting. Westwards, the basalts pass beneath the Kalahari sands. Further south, the rocks of Nyamandhlovu are also marginal to the Kalahari basin and represent the edge of a wide area of basalts largely concealed by the Kalahari sands within Bechuanaland.

The small outlier of basalts at Featherstone lies centrally upon the Rhodesian shield.

The thickness of the basalts remaining varies from a few hundred feet at Featherstone, to 3000 feet at Victoria Falls, and is over 5000 feet in the Maluti Mountains of Basutoland. This thickness is still small however compared with the Lebombo area where, for example, Urie and Hunter (1963) estimate the basalts to be 6–7000 feet in thickness. Cox *et al.* (1965) estimate 26,000–28,000 feet as the total thickness of volcanics (including rhyolites) at Nuanetsi.

Certain basalt areas have not been included in the present study, the more important being the Kaokoveld (South West Africa), the Springbok Flats (Transvaal, South Africa), eastern Bechuanaland, and Tuli (Rhodesia). Tuli is a westward extension of the Nuanetsi province and is currently being studied by J. R. Vail and others.

CHEMICAL ANALYSES

New analyses for 23 basalts from Nyamandhlovu, Wankie, Featherstone, and Swaziland are given in Table 1. Also included are the major element analyses of 12 rocks from Nuanetsi (Cox *et al.*, 1965) for which

TABLE 1. ANALYSES OF KARROO BASALTS FROM RHODESIA & SWAZILAND, TRACE ELEMENT VALUES GIVEN IN PPM

| Specimen Number | Nyamandhlovu | | | | | | | | Featherstone | | | | | | Wankie | |
|--------------------------------|--------------|--------|--------|--------|--------|--------|--------|--------|--------------|--------|--------|--------|--------|--------|--------|--------|
| | Bu. 1 | Bu. 2 | Bu. 3 | Bu. 4 | Bu. 5 | Bu. 6 | Bu. 7 | Bu. 8 | F. 1 | F. 2 | F. 3 | F. 4 | F. 6 | F. 8 | W. 3 | W. 5 |
| SiO ₂ | 51.7 | 50.9 | 51.2 | 50.8 | 51.3 | 51.6 | 51.3 | 51.4 | 53.8 | 52.9 | 52.7 | 52.8 | 50.6 | 52.1 | 50.5 | 52.0 |
| TiO ₂ | 3.42 | 2.94 | 3.18 | 3.22 | 3.13 | 3.16 | 3.12 | 3.18 | 3.00 | 2.88 | 2.61 | 2.86 | 2.76 | 2.64 | 2.72 | 3.68 |
| Al ₂ O ₃ | 13.67 | 12.65 | 12.98 | 12.93 | 13.00 | 13.03 | 13.18 | 13.30 | 10.99 | 10.55 | 12.30 | 13.30 | 12.71 | 9.25 | 12.98 | 12.54 |
| Fe ₂ O ₃ | 5.78 | 6.45 | 4.83 | 4.67 | 5.03 | 4.96 | 4.52 | 4.75 | 3.88 | 5.21 | 4.29 | 4.85 | 7.29 | 4.08 | 6.32 | 4.77 |
| FeO | 5.71 | 7.09 | 8.96 | 9.14 | 8.25 | 8.16 | 8.67 | 8.40 | 6.68 | 5.46 | 6.58 | 6.66 | 4.46 | 7.51 | 8.04 | 8.96 |
| MnO | 0.14 | 0.17 | 0.20 | 0.18 | 0.19 | 0.17 | 0.17 | 0.19 | 0.15 | 0.12 | 0.21 | 0.17 | 0.14 | 0.14 | 0.18 | 0.16 |
| MgO | 4.90 | 5.08 | 5.54 | 5.29 | 5.45 | 5.64 | 5.70 | 5.80 | 7.74 | 7.79 | 7.19 | 5.65 | 6.20 | 10.88 | 5.95 | 3.95 |
| CaO | 8.14 | 9.33 | 9.40 | 9.32 | 9.66 | 9.16 | 9.52 | 9.70 | 8.22 | 8.34 | 9.52 | 9.49 | 9.72 | 7.68 | 9.55 | 8.00 |
| Na ₂ O | 2.61 | 2.44 | 2.58 | 2.51 | 2.09 | 2.37 | 2.38 | 2.28 | 2.17 | 2.02 | 2.18 | 2.49 | 2.21 | 1.89 | 2.47 | 2.47 |
| K ₂ O | 1.82 | 0.78 | 0.95 | 0.93 | 0.79 | 1.20 | 1.14 | 0.86 | 2.13 | 1.94 | 1.10 | 1.69 | 1.14 | 1.68 | 0.89 | 1.30 |
| H ₂ O ⁺ | 1.82 | 1.81 | 0.77 | 0.65 | 0.78 | 0.94 | 0.61 | 0.71 | 1.57 | 2.72 | 1.68 | 0.49 | 2.41 | 1.96 | 0.79 | 1.42 |
| H ₂ O ⁻ | | | | | | | | | | | | | | | | |
| P ₂ O ₅ | 0.64 | 0.46 | 0.38 | 0.37 | 0.38 | 0.37 | 0.36 | 0.36 | 0.44 | 0.41 | 0.33 | 0.39 | 0.41 | 0.41 | 0.36 | 0.74 |
| Total | 100.35 | 101.00 | 100.97 | 100.01 | 100.05 | 100.76 | 100.67 | 100.93 | 100.77 | 100.34 | 100.69 | 100.84 | 100.05 | 100.22 | 100.75 | 100.19 |
| Ba | 940 | 470 | 530 | 645 | 530 | 530 | 530 | 545 | 1160 | 1125 | 850 | 800 | 1120 | 1070 | 350 | 830 |
| Be | | | | | | | | | | | | | | | | |
| Co | | | | | | | | | | | | | | | | |
| Cr | | | | | | | | | | | | | | | | |
| Ga | | | | | | | | | | | | | | | | |
| Li | | | | | | | | | | | | | | | | |
| Mo | | | | | | | | | | | | | | | | |
| Nb | 14 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | 10 | <10 | 13 |
| Ni | 60 | 60 | 60 | 65 | 70 | 70 | 75 | 80 | 150 | 170 | 140 | 95 | 110 | 305 | 70 | 50 |
| Pb | | | | | | | | | | | | | | | | |
| Rb | 34 | 36 | 35 | 40 | 28 | 28 | 29 | 31 | 61 | 51 | 42 | 44 | 30 | 59 | 29 | 63 |
| Sc | | | | | | | | | | | | | | | | |
| Sr | 900 | 420 | 544 | 508 | 560 | 540 | 558 | 582 | 912 | 888 | 592 | 662 | 680 | 812 | 368 | 812 |
| V | | | | | | | | | | | | | | | | |
| Zr | 595 | 305 | 320 | 320 | 315 | 320 | 320 | 320 | 505 | 480 | 350 | 400 | 395 | 435 | 245 | 570 |

TABLE 1.—Continued

| Specimen Number | Nuanetsi | | | | | | | | | | Swaziland | | | | | | | | | |
|--------------------------------|------------------|--------|--------|--------|--------|--------|-------|--------|--------|--------|-----------|--------|--------|--------|--------|-------|--------|--------|-------|--------|
| | C. | LM. | LM. | KC. | LM. | DW. | C. | DW. | LM. | LM. | KC. | LM. | S. 4 | S. 5 | S. 9 | S. 10 | S. 11 | S. 13 | S. 17 | |
| 922 | 341 ¹ | 126 | 619A | 389 | 868 | 21 | 434 | 436 | 428 | 37 | 432 | 432 | 52.5 | 53.8 | 52.1 | 47.2 | 49.4 | 48.3 | 48.3 | |
| SiO ₂ | 51.00 | 50.55 | 52.90 | 47.27 | 50.37 | 50.05 | 54.2 | 49.61 | 45.61 | 49.11 | 49.58 | 48.98 | 1.74 | 1.55 | 1.87 | 1.13 | 1.03 | 1.58 | 2.40 | |
| TiO ₂ | 1.90 | 1.62 | 1.70 | 2.69 | 2.22 | 2.54 | 2.79 | 3.54 | 4.81 | 2.99 | 2.87 | 3.34 | 13.75 | 14.33 | 15.02 | 15.35 | 16.49 | 15.78 | 13.76 | |
| Al ₂ O ₃ | 16.30 | 16.20 | 12.43 | 13.05 | 13.23 | 14.16 | 12.33 | 12.83 | 11.28 | 10.31 | 9.39 | 9.17 | 7.74 | 4.23 | 4.77 | 2.86 | 1.52 | 2.86 | 1.66 | 1.77 |
| Fe ₂ O ₃ | 4.00 | 1.65 | 5.18 | 3.58 | 4.36 | 3.03 | 3.84 | 1.35 | 2.13 | 3.51 | 1.83 | 2.47 | 3.75 | 7.24 | 9.31 | 8.61 | 9.79 | 7.89 | 9.87 | 11.84 |
| FeO | 7.62 | 8.13 | 10.08 | 8.20 | 7.97 | 9.53 | 7.69 | 8.50 | 10.11 | 9.80 | 7.90 | 8.49 | 6.53 | 0.16 | 0.15 | 0.15 | 0.16 | 0.16 | 0.16 | 0.19 |
| MnO | 0.14 | 0.10 | 0.24 | 0.14 | 0.17 | 0.15 | 0.13 | 0.18 | 0.14 | 0.14 | 0.15 | 0.13 | 0.13 | 5.90 | 4.70 | 4.70 | 6.30 | 5.70 | 4.90 | 5.70 |
| MgO | 3.39 | 3.80 | 3.95 | 4.85 | 5.72 | 6.19 | 6.74 | 6.9 | 7.67 | 10.97 | 12.84 | 14.82 | 15.52 | 9.57 | 8.33 | 7.32 | 12.60 | 11.53 | 11.25 | 9.51 |
| CaO | 7.25 | 3.89 | 7.33 | 8.69 | 7.40 | 9.29 | 9.18 | 8.65 | 9.66 | 7.90 | 7.18 | 7.36 | 6.44 | 2.97 | 2.76 | 4.51 | 2.20 | 2.65 | 2.77 | 2.27 |
| Na ₂ O | 3.20 | 3.53 | 2.76 | 2.36 | 3.49 | 2.04 | 2.45 | 1.96 | 2.37 | 2.21 | 2.31 | 2.07 | 1.40 | 0.50 | 0.86 | 0.16 | 0.08 | 0.23 | 0.10 | 0.50 |
| K ₂ O | 2.55 | 3.38 | 2.07 | 1.63 | 1.98 | 0.47 | 1.58 | 1.60 | 1.83 | 2.62 | 1.42 | 1.98 | 2.44 | 2.04 | 2.51 | 2.56 | 3.97 | 2.23 | 2.73 | 3.80 |
| H ₃ O ⁺ | 1.71 | 3.49 | 1.90 | 1.35 | 2.76 | 1.64 | 1.74 | 1.58 | 0.80 | 1.13 | 3.59 | 0.52 | 2.36 | 0.13 | 0.13 | 0.13 | 0.14 | 0.09 | 0.18 | 0.17 |
| H ₂ O ⁻ | 0.26 | 0.62 | 0.36 | 0.18 | 0.78 | 0.75 | 0.27 | 0.01 | 0.42 | 0.52 | 0.62 | 0.18 | 0.91 | 100.73 | 100.20 | 99.99 | 100.44 | 100.26 | 99.28 | 100.21 |
| P ₂ O ₅ | 0.58 | 1.07 | 0.28 | 0.39 | 0.59 | 0.29 | 0.36 | 0.32 | 0.52 | 0.70 | 0.83 | 0.52 | 0.54 | 100.73 | 100.20 | 99.99 | 100.44 | 100.26 | 99.28 | 100.21 |
| Total | 99.90 | 100.18 | 100.33 | 100.01 | 100.18 | 100.13 | 99.92 | 100.82 | 100.12 | 100.23 | 100.15 | 100.18 | 100.08 | 145 | 320 | 390 | 80 | 85 | 100 | 165 |
| Ba | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 |
| Be | 20 | 20 | 25 | 30 | 25 | 30 | 35 | 30 | 35 | 55 | 40 | 60 | 50 | 30 | 30 | 30 | 35 | 35 | 35 | 35 |
| Cr | 55 | 20 | 50 | 60 | 120 | 260 | 320 | 250 | 450 | 850 | 1100 | 1100 | 1100 | 120 | 95 | 170 | 240 | 250 | 120 | 100 |
| Ga | 26 | 17 | 16 | 23 | 20 | 19 | 17 | 19 | 22 | 14 | 19 | 16 | 16 | 17 | 18 | 20 | 13 | 15 | 15 | 16 |
| Li | 80 | 20 | 70 | <10 | 35 | <10 | 15 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | 20 | <10 | <10 | 20 | 15 |
| Mo | 6 | 13 | 3 | 3 | 6 | 5 | 3 | 6 | 8 | <3 | 4 | 4 | 3 | 4 | 3 | 4 | <3 | <3 | <3 | <3 |
| Nb | 65 | 85 | 25 | 40 | 55 | 40 | 50 | 50 | 30 | 50 | 45 | 45 | 30 | 25 | 30 | 15 | 10 | 15 | <10 | <10 |
| Ni | 80 | 85 | 50 | 90 | 110 | 190 | 180 | 120 | 250 | 550 | 600 | 950 | 950 | 85 | 90 | 130 | 85 | 80 | 65 | 65 |
| Pb | <10 | 18 | <10 | 10 | <10 | 13 | <10 | <10 | <10 | 15 | <10 | 16 | 18 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| Rb | 70 | 50 | 50 | <50 | <50 | 55 | <50 | <50 | <50 | 110 | <50 | 80 | 80 | <50 | <50 | <50 | <50 | <50 | <50 | <50 |
| Sc | 40 | 30 | 50 | 25 | 30 | 30 | 40 | 45 | 40 | 30 | 35 | 30 | 25 | 35 | 25 | 20 | 80 | 65 | 50 | 55 |
| Sr | 1000 | 330 | 190 | 850 | 750 | 380 | 700 | 800 | 900 | 1400 | 1100 | 1100 | 1200 | 270 | 250 | 430 | 160 | 250 | 270 | 220 |
| V | 240 | 75 | 300 | 300 | 290 | 300 | 350 | 280 | 240 | 260 | 250 | 260 | 240 | 200 | 200 | 300 | 300 | 350 | 300 | 300 |
| Y | 45 | 65 | 30 | 30 | 45 | 35 | 30 | 40 | 45 | 25 | 25 | 25 | 20 | 35 | 30 | 30 | 15 | 10 | 20 | 15 |
| Zr | 310 | 130 | 130 | 220 | 230 | 130 | 200 | 200 | 220 | 270 | 280 | 270 | 320 | 90 | 90 | 100 | 45 | 35 | 60 | 70 |

¹ Plus 2.15% CO₂.

new trace element data are given. A single Nuanetsi analysis, (DW.21), appears for the first time.

CIPW norms are given in Table 2 and specimen localities and brief petrographic descriptions are given in a later section.

The Swaziland basalts were analysed in the Department of Earth Sciences, The University of Leeds, by G. Hornung (major elements by Siemens XRF) and Dr. J. M. Rooke (minor elements by optical spectrograph), by methods already employed for the Basutoland basalts (Cox and Hornung *op. cit.*). The minor elements of Nuanetsi rocks were also determined by Dr. Rooke as part of the same programme. The remaining Rhodesian basalts (Nyamandhlovu, Wankie and Featherstone) were analysed by R. Macdonald in the Grant Institute of Geology, The University of Edinburgh, using Philips XRF equipment (PW-1310/50 generator with PW1320 control cabinet) and the techniques outlined below. For major elements rock powder was diluted with lanthanum oxide and lithium tetraborate, fused, crushed and briquetted using boric acid as a binder. For minor elements loose rock powder was used against a mylar film. Na and K were determined by flame photometer, P by spectrophotometer, and Fe²⁺ by titration with dichromate. H₂O was determined gravimetrically.

The problem arises in the present work of comparing data obtained by a variety of analytical methods. To ensure comparability of major element analyses a number of samples were analysed by the different methods employed. As a result of this we can be certain that the differences between provinces which we shall comment upon, are well outside the range of experimental error. For minor elements there is less certainty, although a reasonable agreement between optical spectrograph and XRF determination of Ba and Zr was obtained in a previous test (Cox and Hornung, *op. cit.*). In the present study we have found an excellent agreement between Zr results obtained by Dr. Rooke for the Nuanetsi basalts by optical spectrograph, and Zr results for other Nuanetsi rocks obtained by XRF by G. B. Jamieson (pers. commun.). The optical spectrograph data for Basutoland basalts are in good agreement with the data given by Nockolds and Allen (1956) for the Karroo dolerites (see Table 3).

Some doubts must still exist however, concerning the comparability of trace element data and we have therefore been careful to comment only on large differences which are clearly not due to experimental error (*e.g.* the difference between Ba in the two provinces), or, in cases where concentrations are low or differences small we have restricted comparison to the optical spectrograph data obtained by Dr. Rooke. In this way we can be sure that the inter-province distinctions which we shall make are genuine.

PETROGRAPHIC DESCRIPTIONS AND KEY TO TABLE 1

Nyamandhlovu

Bu. 1—On main road from Bulawayo to Victoria Falls in bed of Bembezi R., 78 miles from Bulawayo.

Phenocrysts—Plagioclase (up to 10 mm.) 15 percent. Augite (0.25–0.50 mm.) 1 percent.

Groundmass—Intersertal augite, plagioclase, ore, glass (21 percent) aggregate. Some alteration of glass to yellow micaceous mineraloid. Apatite a prominent accessory as acicular crystals (some with hollow centres) within the glass.

Bu. 2—Road as above, near Insuza R., 49 mi from Bulawayo. A rather coarse-grained rock in which there is little distinction between phenocrysts and ground mass. This is the only Nyamandhlovu rock containing olivine (2 percent, completely pseudo-

morphed by yellow mineraloid). Brown, partly altered glass makes up 22 percent of the rock.

Bu. 3—Road as above, 2 mi north of Umguza R., 39 mi from Bulawayo.

Phenocrysts—Plagioclase (up to 1 mm.) 4.5 percent. Augite (0.25–0.50 mm.) 1.5 percent.

Groundmass—Intergranular aggregate of augite, plagioclase and ore, the latter in thin ophitic plates. A little glass..

Bu. 4—Same as Bu. 3.

Phenocrysts—Plagioclase (1–3 mm.) 5.5 percent. Augite (0.25–0.50 mm.) 1.5 percent.

Groundmass—Holocrystalline intergranular, augite, plagioclase, ore aggregate.

Bu. 5—Road as above, 2 mi S. of Umguza R., 33 mi from Bulawayo.

Phenocrysts—Plagioclase (0.5 mm.) 4 percent. Augite (0.25–0.50 mm.) 1 percent.

Groundmass—As Bu. 3 but holocrystalline.

Bu. 6—Road as above 29 mi from Bulawayo.

Phenocrysts—Plagioclase (0.5–1 mm.) Augite (0.25–0.50 mm.). The phenocrysts are not well differentiated from the groundmass because of their small size.

Groundmass—as in Bu. 4.

Bu. 7—Road as above 28 mi. from Bulawayo.

Phenocrysts—Plagioclase (1 mm.) 4 percent. Augite (1–2.5 mm.) 1.5 percent.

Groundmass—Holocrystalline intergranular aggregate of augite, pigeonite (subordinate to augite), plagioclase and ore.

Bu. 8—Road as above, 27 mi from Bulawayo.

Phenocryst—Plagioclase (3 mm.) 11 percent. Augite (0.25–0.50 mm.) 1 percent.

Groundmass—as in Bu. 4.

General. At the time of extrusion the phenocryst assemblage was probably augite + plagioclase in all cases, though the evidence of the glassy rock, Bu.2, suggests that olivine may have been resorbed shortly before solidification. The plagioclase phenocrysts show moderate zoning, both normal and oscillatory. Compositions of crystal centres lie in the range An_{65} – An_{70} , using the extinction angle data given for high temperature plagioclases by Tobi (1963). In most of the rocks the ore mineral occurs as equidimensional sub-ophitic grains 0.1–0.3 mm. in diameter and was probably formed after extrusion. A solitary example of a euhedral spinel enclosed within a plagioclase phenocryst suggests that an ore mineral may have been a phenocryst phase at an earlier, intratelluric, stage. A few internally melted plagioclase crystals are found, also suggesting some complexity in the intratelluric history. Bu.5 contains a rectangular clot of augite phenocrysts which could be a pseudomorph after a high-pressure orthopyroxene as described by Jamieson (1966).

Phenocryst textures are in general glomeroporphyritic and the groundmasses are fine-grained with plagioclase laths ranging from 0.1 to 0.5 mm. and pyroxenes from 0.03 to 0.1 mm. The two glassy rocks contain larger crystals. Pigeonite has been identified in only one sample but is probably generally present. The glassy rocks are superficially similar to the Basutoland lavas but, amongst other things, they are distinguished by the presence of visible apatite in the glass. This is a reflection of the high P content of the northern province rocks.

With the possible exceptions of Bu.1 and Bu.8, the low content of phenocrysts and their small size indicates that the bulk compositions of these rocks are little removed from liquid compositions. The compositional uniformity of the group is striking.

Featherstone

F.1—The kopje, Featherstone. A rather coarse-grained rock consisting of subhedral and euhedral crystals of augite and hypersthene (0.5–1 mm.) with euhedral crystals of basic plagioclase, and combs of opaque ore. The mesostasis (ca 15 percent) consists of brown glass, in part altered to yellowish micaceous aggregates. There may have been 1–2 percent of olivine originally present but this is difficult to distinguish from altered glass. The glass is densely charged with skeletal plagioclase crystals and acicular apatites.

F.2—As above.

Phenocrysts—sparse altered olivines (0.5–1 mm.). Some of the augite (up to 0.5 mm.) could also be considered as a phenocryst phase.

Groundmass—Augite crystals (0.25 mm.) and plates of ragged, comb-like, ore are set in a matrix of small skeletal plagioclase laths and brown glass. There is some alteration of the glass to yellow-green micaceous products.

F.3—As above.

Phenocrysts—Olivine (1 mm.) 3.5 percent.

Groundmass—Euhedral plagioclase laths (up to 1 mm.) with some skeletal features, small grains of augite (mainly ca 0.1 mm.) with a glassy mesostasis containing parallel growths of ore.

F.4—As above. An unusual rock compared with the others from this locality.

Phenocrysts—Abundant small phenocrysts of augite (0.15 mm.), olivine (0.15 mm.) 5 percent, plagioclase tablets (0.5 mm.).

Groundmass—Very fine grained but not obviously glassy. The ore is disseminated as fine granules. The rock is texturally distinct in not showing the skeletal growths of plagioclase and ore minerals, and in being free of glass.

F.6—As above.

Phenocrysts—Abundant small phenocrysts of olivine, 5 percent, (completely pseudomorphed by orange micaceous alteration product) augite, and plagioclase. All the phenocryst species form crystals up to 0.5 mm. in diameter. The mesostasis (50 percent) is a very dark, cloudy glass in which small skeletal crystals of ore, augite and plagioclase are visible.

F.8—By roadside 1.5 mi south of the kopje at Featherstone, on the road to Enkel-doorn.

Phenocrysts—Fresh olivines (ca Fa_{25}), some skeletal in habit, make up 11 percent of the rock. They reach 1 mm. in length. Euhedral augites are abundant (up to .5 mm.).

Groundmass—Dark glass full of sheaves of plagioclase microlites and plates of ore.

General. The extreme similarity between the Featherstone rocks and those from the Sabi area of south-eastern Rhodesia has been noted by Worst (1962). According to the classificatory scheme which we shall put forward for the Rhodesian basalts in a later section of this paper, the Featherstone rocks are grouped as follows: F.1, the hypersthene-bearing rock, is an unusual type which is not included in the scheme. Note that it is the most siliceous of the analysed rocks. F.2, F.3, and F.8 are 2-phenocryst olivine basalts, the latter not far removed from the 2-phenocryst limburgites. F.4 and F.6 are 3-phenocryst olivine basalts.

Wankie

W.3—Matetsi Siding, on railway between Wankie and Victoria Falls.

Phenocrysts—Plagioclase (3 mm.) about 5 percent. Augite (up to 0.5 mm.) less than 1 percent.

Groundmass—Holocrystalline intergranular with augite, pigeonite, plagioclase and ore.
Apatite needles moderately prominent.

W.5—18 mi S. of Matetsi Siding on road to Robins Camp.

Phenocrysts—Very sparse plagioclases (up to 0.5 mm.). Very occasional orthopyroxene phenocrysts (1 mm.) marginally replaced by augite granules.

Groundmass—40–50 percent glass with prominent “tubular” apatite crystals. Augite granules 0.03–0.15 mm., plagioclase laths 0.15–0.3 mm.

General. A number of Wankie specimens were collected but many were not sufficiently fresh for analysis. Thin section examination of these and specimens from Victoria Falls, however, shows that pigeonite is quite common, and often has a distinctive appearance with a more tabular habit than the augites, and systems of curving cracks.

The orthopyroxene phenocrysts in W.5 are similar to those described from the Nuanetsi lavas by Cox *et al.* (1965) and Jamieson (1966). Since these are probably derived from crystallisation at considerable depth and are clearly not in equilibrium with the liquids at atmospheric pressure, it is of interest to note their occurrence in the most glass-rich rock collected from the western part of Rhodesia during this study. The implication is that they are preserved only in thoroughly quenched rocks.

Nuanetsi

The analyses are taken from Cox *et al.* (1965). Brief notes are appended here to show the rock type of each specimen in accordance with the scheme of classification used later in this paper.

C.922 pyroxene-plagioclase-phyric basalt.

LM.341 an altered feldspar-phyric basalt. The low CaO, high K₂O, CO₂ content, and normative corundum are all abnormal.

LM.126 a non-porphyritic basalt.

KC.58 a non-porphyritic basalt.

LM.619A a non-porphyritic basalt which is probably identical with the groundmass of associated 3-phenocryst olivine basalts.

DW.389 basalt with sparse, partially resorbed, phenocrysts of biotite. An unusual type.

C.868 3-phenocryst olivine basalt.

DW.21 *New analysis* by G. Hornung of non-porphyritic basalt from the Hippo Mine, Mutandawhe Complex, Nuanetsi province. A spectrographic analysis of this rock was given by Cox *et al.* (1965).

LM.434 Erroneously reported as a limburgite by Cox *et al.* (1965, p. 145), this rock is a typical 2-phenocryst olivine basalt since it contains groundmass plagioclase.

LM.436 olivine-monzonite from the Chilembeni intrusion. This analysis is included with the basalts because of its trace-element and minor element similarity.

LM.428, KC.37, and LM.432 are all 2-phenocryst limburgites.

Note on spectrographic data. The trace element contents of these rocks were re-determined by Dr. J. M. Rooke at the time the analyses of the other rocks covered in this paper were carried out. The analyses quoted here for Nuanetsi rocks are intended to replace the analyses previously published in Cox *et al.* (1965).

Swaziland

S.4—10 mi E. of Maloma on road to Nsoko.

Phenocrysts—Extremely sparse tabular crystals of basic plagioclase (up to 0.5 mm.)

Groundmass—Very fine grained with plagioclase laths up to 0.15 mm., slightly serici-

tised. Smaller turbid crystals of clinopyroxene visible. The ore is disseminated as fine granules. A small amount of epidote and chlorite is present.

S.5— $\frac{1}{2}$ mi E. of S.4. Non-porphyrific. Feldspar laths are sericitised and reach 0.3 mm. Original pyroxene granules (0.1 mm.) replaced by tremolite-actinolite. There is some chlorite interstitially and a certain amount of epidote is present. The ore is in equidimensional crystals having the typical skeletal appearance of ilmenite.

S.9—Maloma-Nsoko road, $1\frac{3}{4}$ mi W of Lubuli township.

Phenocrysts—Large (8 mm.) plagioclases (andesine) replaced partly by veins of chlorite, plus small amounts of altered olivine.

Groundmass—Coarse sub-ophitic texture with plagioclase laths (oligoclase-andesine) reaching 0.5 mm. Clinopyroxene partly replaced by tremolite. Moderately abundant interstitial chlorite.

S.10— $\frac{1}{2}$ mi E. of S.9

Phenocrysts—Equidimensional basic plagioclases (2–3 mm.) partly replaced by chlorite veins, ca 10 percent. Small amounts of chloritised small olivines (ca 1 percent).

Groundmass—Plagioclase somewhat chloritised, clinopyroxene fresh. The ore is as in S.5.

S.11—Lubuli township, Maloma-Nsoko road. Rock almost identical with S.10. The olivine is somewhat less abundant.

S.13—Cecil Mack pass, exactly on Swaziland-Natal boundary.

Phenocrysts—Altered olivine and plagioclase similar to the two specimens above.

Groundmass—like the above. The texture is intergranular, occasionally subophitic.

S.17—Quarry 200 yds. N. of new bridge, Big Bend.

Phenocrysts—Large basic plagioclases (10 mm., partly replaced by epidote and carbonate), extremely sparsely distributed.

Groundmass—Ophitic texture, the augites are relatively large and sparsely distributed. ophitically enclosing euhedral plagioclase laths.

General. It is probable that the high degree of alteration of the Swaziland basalts is caused by mild thermal metamorphism as a result of the great concentration of large dolerite dykes which cuts the succession. A total of 11 basalts, including the analysed specimens, was examined. Phenocryst assemblages were distributed as follows:—olivine+plagioclase (4); nonporphyritic (3), plagioclase only (2), plagioclase+augite+ore (1), olivine+(?) augite (1).

BASUTOLAND

An average analysis of the Basutoland basalts is given in Table 3, quoted from Cox and Hornung (*op. cit.*). The rocks included in this average are either sparsely microporphyrific olivine-plagioclase-phyric basalts or their nonporphyritic equivalents.

GEOCHEMICAL COMPARISON OF THE PROVINCES

The analytical data are made more readily digestible by the series of averages given in Table 3. The division into northern and southern provinces is to some extent arbitrary since there are considerable fluctuations within the provinces themselves. Nevertheless as the analyses are grouped it will be seen that values for Ti, K, P, Ba, Sr, and Zr are all

TABLE 2. CIPW NORMS OF NEW ANALYSES OF KARROO BASALTS

| | Nyamandhlovu | | | | | | | | Featherstone | | | | | | Wankie | | Nuanetsi | Swaziland | | | | | | |
|-----|--------------|------|------|------|------|------|------|------|--------------|------|------|------|------|------|--------|------|----------|-----------|------|------|------|------|------|------|
| | Bu1 | Bu2 | Bu3 | Bu4 | Bu5 | Bu6 | Bu7 | Bu8 | F1 | F2 | F3 | F4 | F6† | F8 | W3 | W5 | | DW21 | S4 | S5 | S9 | S10 | S11 | S13 |
| Q | 10.0 | 10.1 | 7.0 | 7.0 | 10.1 | 8.3 | 7.1 | 8.2 | 8.3 | 10.6 | 8.8 | 7.7 | 10.2 | 5.6 | 6.6 | 11.5 | 8.3 | 6.3 | 7.6 | 1.2 | — | 0.6 | — | 1.4 |
| Or | 11.1 | 4.4 | 5.6 | 5.6 | 5.0 | 7.2 | 6.7 | 5.0 | 12.8 | 11.7 | 6.7 | 10.0 | 6.7 | 10.0 | 5.0 | 8.9 | 9.5 | 2.8 | 5.0 | 1.1 | 0.6 | 1.1 | 0.6 | 3.3 |
| Ab | 22.5 | 21.0 | 21.5 | 21.5 | 17.8 | 19.9 | 19.9 | 19.4 | 18.3 | 17.3 | 18.3 | 21.0 | 18.9 | 16.2 | 21.0 | 21.0 | 16.8 | 25.7 | 24.1 | 39.3 | 19.4 | 23.1 | 24.1 | 19.9 |
| An | 20.3 | 21.4 | 21.1 | 21.4 | 23.6 | 21.4 | 22.0 | 23.4 | 14.2 | 14.5 | 20.9 | 20.0 | 22.2 | 12.0 | 21.7 | 19.2 | 21.7 | 23.1 | 24.7 | 20.6 | 32.8 | 33.1 | 31.4 | 26.7 |
| {Wo | 6.7 | 9.4 | 9.4 | 9.3 | 9.2 | 8.9 | 9.4 | 9.2 | 10.1 | 10.4 | 10.4 | 10.1 | 10.1 | 10.0 | 10.7 | 7.0 | 8.2 | 10.1 | 7.0 | 6.6 | 13.0 | 10.2 | 10.7 | 8.9 |
| | En | 5.7 | 6.3 | 5.7 | 5.5 | 5.8 | 5.8 | 5.9 | 7.4 | 8.6 | 7.5 | 7.2 | 8.7 | 7.3 | 7.2 | 4.0 | 4.9 | 6.3 | 3.2 | 3.4 | 6.5 | 5.6 | 4.9 | 4.1 |
| {Fs | 0.1 | 2.4 | 3.2 | 3.3 | 2.8 | 2.5 | 3.0 | 2.6 | 1.7 | 0.5 | 2.0 | 2.0 | — | 1.7 | 2.6 | 2.6 | 2.9 | 3.2 | 3.7 | 3.0 | 7.5 | 4.2 | 5.7 | 4.8 |
| | Hy | 6.6 | 6.4 | 8.0 | 7.7 | 7.8 | 8.2 | 8.3 | 8.5 | 11.9 | 11.2 | 10.5 | 6.8 | 7.0 | 7.6 | 5.9 | 12.3 | 8.5 | 8.7 | 8.6 | 4.5 | 8.8 | 7.1 | 10.6 |
| {Fs | 0.3 | 2.4 | 4.4 | 4.8 | 3.6 | 3.4 | 4.4 | 4.0 | 2.8 | 0.8 | 2.8 | 1.7 | — | 4.6 | 2.8 | 4.1 | 7.3 | 4.1 | 10.0 | 7.9 | 3.8 | 6.7 | 8.3 | 12.4 |
| | {Fo | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| {Fa | | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 3.6 | — | 0.4 | — |
| Mt | 8.6 | 9.5 | 7.0 | 6.7 | 7.4 | 7.2 | 6.5 | 7.0 | 5.6 | 7.7 | 6.3 | 7.0 | 7.2 | 6.0 | 9.3 | 7.0 | 2.1 | 6.3 | 2.6 | 4.2 | 2.3 | 4.2 | 2.6 | 2.8 |
| | Il | 6.5 | 5.6 | 6.1 | 6.2 | 5.9 | 6.1 | 5.9 | 5.8 | 5.6 | 5.0 | 5.5 | 5.3 | 5.2 | 5.2 | 7.1 | 5.3 | 3.3 | 3.0 | 3.6 | 2.3 | 2.0 | 3.2 | 4.7 |
| Ap | 1.7 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 | 0.3 | 1.7 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |

^a +2.6% He

TABLE 3. AVERAGE ANALYSES OF KARROO BASALTS (ANHYDROUS BASIS)

| | Northern Province | | | | | | Southern Province | | |
|--------------------------------|-------------------|-------|-------|----------------|----------------|----------------|-------------------|-------|------|
| | A | B | C | D ₁ | D ₂ | D ₃ | E | F | G |
| SiO ₂ | 51.50 | 53.19 | 51.59 | 53.16 | 51.38 | 49.45 | 51.61 | 51.8 | 52.7 |
| TiO ₂ | 3.18 | 2.83 | 3.22 | 2.04 | 3.18 | 3.58 | 1.65 | 1.13 | 1.16 |
| Al ₂ O ₃ | 13.14 | 11.68 | 12.83 | 14.93 | 13.05 | 9.36 | 15.34 | 14.8 | 15.4 |
| Fe ₂ O ₃ | 5.14 | 5.00 | 5.58 | 3.71 | 3.00 | 2.96 | 2.45 | 3.92 | 1.38 |
| FeO | 8.19 | 6.31 | 8.55 | 8.76 | 8.95 | 8.37 | 9.47 | 7.26 | 9.35 |
| MnO | 0.18 | 0.16 | 0.17 | 0.16 | 0.16 | 0.14 | 0.16 | 0.17 | 0.22 |
| MgO | 5.45 | 7.68 | 4.98 | 4.12 | 6.78 | 13.86 | 5.56 | 7.1 | 6.6 |
| CaO | 9.32 | 8.95 | 8.83 | 6.99 | 9.03 | 7.39 | 10.29 | 10.57 | 9.96 |
| Na ₂ O | 2.42 | 2.19 | 2.48 | 3.05 | 2.51 | 2.05 | 2.96 | 2.40 | 2.22 |
| K ₂ O | 1.06 | 1.63 | 1.21 | 2.48 | 1.52 | 2.17 | 0.36 | 0.74 | 0.87 |
| P ₂ O ₅ | 0.42 | 0.39 | 0.55 | 0.60 | 0.43 | 0.67 | 0.14 | 0.13 | 0.16 |

Trace Elements in ppm

| | | | | | | | | | |
|----|-----|------|-----|-------|-------|------|-------|-------|-----|
| Ba | 590 | 1021 | 590 | 875 | 630 | 925 | 184 | 256 | 200 |
| Co | — | — | — | 24 | 29 | 51 | 33 | 34 | 38 |
| Cr | — | — | — | 46 | 280 | 875 | 156 | 317 | 293 |
| Ga | — | — | — | 21 | 19 | 17 | 16 | 16 | 24 |
| Li | — | — | — | 43-45 | 10-16 | <10 | 8-14 | <10 | 9 |
| Nb | — | — | — | 54 | 47 | 43 | 18-19 | 11-16 | — |
| Ni | 68 | 162 | 60 | 76 | 170 | 763 | 86 | 73 | 70 |
| Rb | 33 | 48 | 46 | 43-55 | — | — | <50 | <50 | 17 |
| Sc | — | — | — | 36 | 37 | 30 | 47 | 34 | 38 |
| Sr | 577 | 758 | 590 | 593 | 706 | 1200 | 264 | 190 | 168 |
| V | — | — | — | 229 | 292 | 253 | 279 | 300 | 225 |
| Y | — | — | — | 43 | 39 | 24 | 22 | 23 | 22 |
| Zr | 352 | 428 | 408 | 198 | 196 | 285 | 70 | 85 | 88 |

KEY

Number of analyses averaged in parentheses

A —Average Nyamandhlovu basalt (8)

B —Average Featherstone basalt (6)

C —Average Wankie basalt (2)

D₁—Average Nuanetsi basalt with MgO <5% (4)D₂—Average Nuanetsi basalt with MgO 5-8% (5)D₃—Average Nuanetsi basalt with MgO >8% (4)

E —Average Swaziland basalt (7)

F —Average Basutoland basalt (after Cox & Horning (*op. cit.*) Table 1) (21)G —Average Karroo dolerite after Cox & Horning (*op. cit.*, Table 1) from data of Walker & Poldervaart (1949) and Nockolds & Allen (1956). (44)

Where some of the trace element values fall below detection limits a range of values within which the average must lie is given.

consistently high in the northern province. The data for strontium confirm the results of Turekian and Kulp (1956), who obtained an average value of 491, p.p.m. Sr from 9 Karroo basalts mainly from the Wankie district (northern province) which contrasted with an average of 175 p.p.m. from 4 rocks termed basalt from Swaziland (southern province).

Although the data are incomplete for Nb and Y, these two elements are also probably enriched in the northern province.

Other elements such as Al, Ca and Ni are strongly affected by the

fractionation stage of the rock, and differences are best shown by variation diagrams. Figures 2 to 6 show values of CaO, Al_2O_3 , K_2O , Ni and Y plotted against MgO as an approximate gauge of the fractionation stage. Since Jamieson (1966) has demonstrated some of the extreme complexity of the fractionation of Karroo basalt magma, we feel

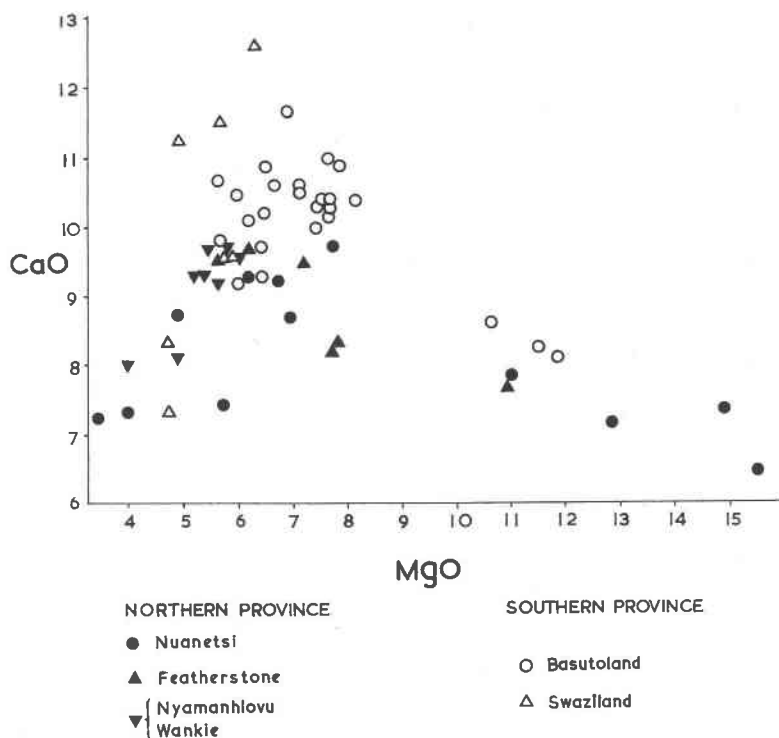


FIG. 2. Variation in CaO.

that it would be unjustified to use a more sophisticated fractionation index at present.

Figure 2 shows the variation of CaO in the two provinces and although feldspar accumulation may have resulted in a few rocks having abnormal values this is not sufficient to obscure the generally more calcic nature of the southern province. The southern province is similarly enriched in Al_2O_3 (see Fig. 3).

Figure 4 showing the variation of K_2O is given as one example of the group of elements (K, Ti, P, Ba, Sr, and Zr) in which there is little overlap between values for the two provinces. We have not thought it necessary

to show the others in variation diagrams because the differences are sufficiently striking in the tables of analyses.

Figure 5 shows the variation in Ni, and here the Swaziland rocks appear to match those of the northern province, rather than those of the southern province as they do in all other elements.

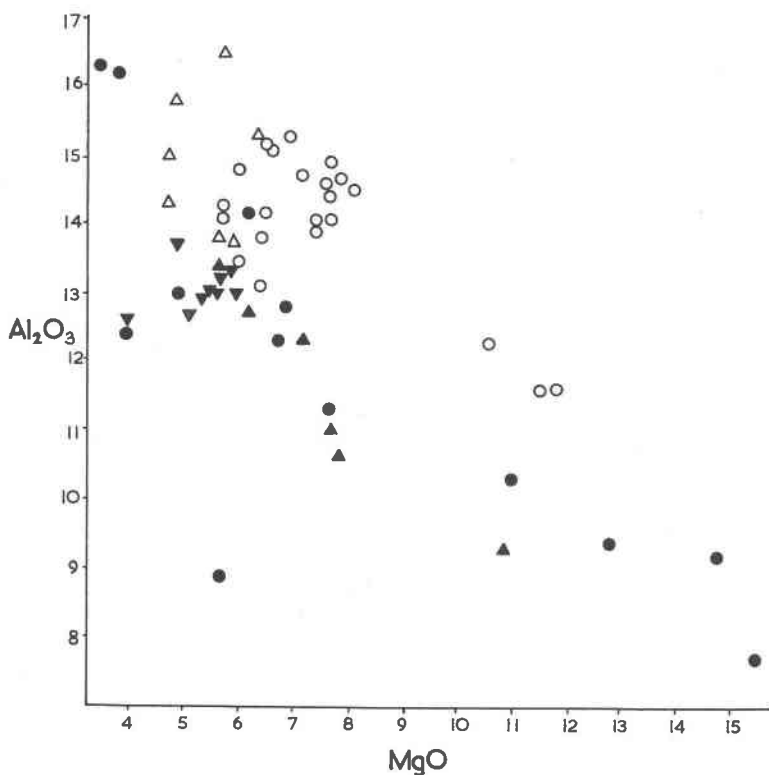
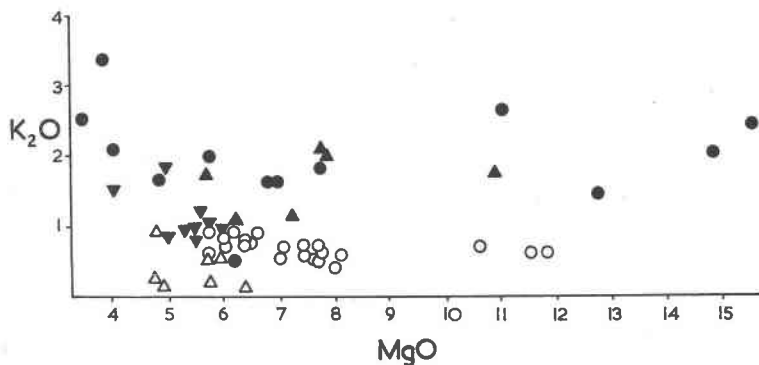


FIG. 3. Variation in Al_2O_3 . Symbols as in Fig. 2.

Figure 6 is based on data from Nuanetsi, Swaziland and Basutoland only, but suggests that the northern province is somewhat enriched in Y. A similar pattern can be discerned in the behaviour of Nb, though some doubt must be attached to the absolute accuracy of the Nb figures in view of the much smaller concentrations obtained by XRF analysis for the Nyamandhlovu, Wankie, and Featherstone rocks compared with the Nuanetsi rocks.

Of the remaining elements for which adequate data are available we cannot discover significant differences between the provinces for Fe, Mn, Na, Co, Cr, Ga, Li, Sc, and V.

FIG. 4. Variation in K_2O . Symbols as in Fig. 2.

To summarise, relative to the southern province the northern province shows:

1. Absolute enrichment in K, Ti, P, Ba, Sr, and Zr, by factors of approximately 2-4.
2. Probable enrichment by a similar amount in Nb and Y.
3. A ratio of Ni/Mg which is approximately twice that of the Karroo dolerites and Basutoland basalts, but the same as that of the Swaziland basalts.
4. Slightly reduced ratios of CaO/MgO and Al_2O_3/MgO .

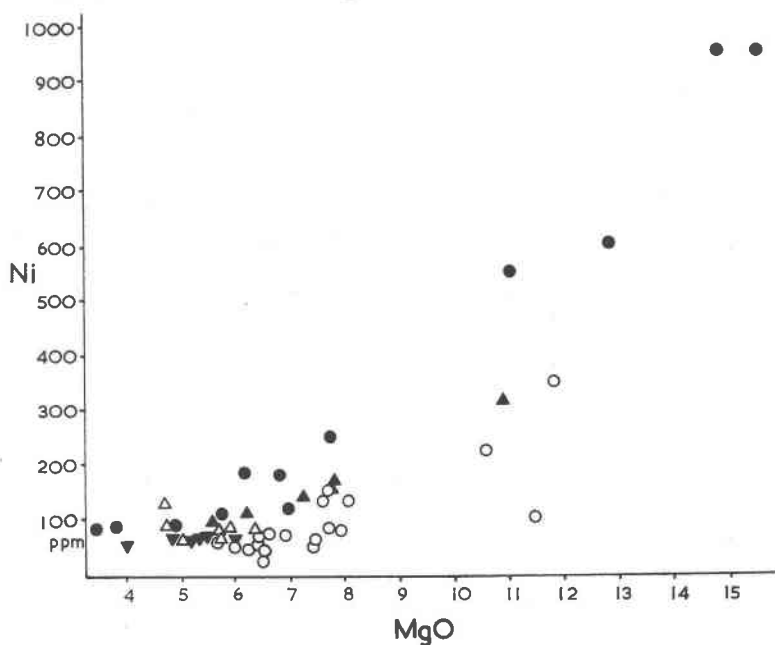


FIG. 5. Variation in Ni. Symbols as in Fig. 2.

PETROGRAPHIC COMPARISONS

Variation within the Northern Province. Worst (1962) and Swift (1961) have drawn attention to the considerable contrast in petrographic type between the Rhodesian basalts of the Nyamandhlovu-Wankie-Victoria Falls area on one hand, and the basalts of south-eastern Rhodesia (Tuli-Nuanetsi-Sabi) and Featherstone on the other. They note that the south-eastern area includes large amounts of olivine-bearing rocks while the rocks of the north-western and western areas are olivine free. To account for this contrast they suggest on the evidence of the lack of feeders within central Rhodesia, that the basalts were erupted in two great troughs only, the one in the vicinity of the Limpopo and the other along the Zambezi.

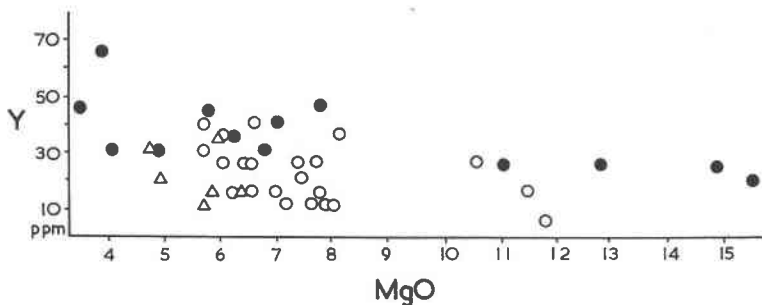


FIG. 6. Variation in Y. Symbols as in Fig. 2.

Basalts such as those of Nyamandhlovu and Featherstone, it is suggested, have flowed long distances (some 150 miles is involved) from the source areas, to reach their present positions. The present writers admit this as a possibility but regard it as more likely that local feeders are in fact sparsely present within the central area.

The petrographic differences between the two basalt areas delimited by Worst are apparently not the result of any fundamental chemical difference, but rather of a variation in the stage of evolution of the basaltic magmas in the different areas.

Studies of the evolution of the basalts of the Nuanetsi-Tuli area of south-eastern Rhodesia, based on Cox *et al.* (1965), Jamieson (1966), and Vail and Hornung (pers. commun.) show that the order of appearance of the principal solid phases during the fractionation of the magma is *olivine* followed by *clinopyroxene* (augite), followed by *plagioclase*. The petrographic evidence consists of the existence of the following rock-types:

1. What we shall term *1-phenocryst limburgites*, that is, rocks containing phenocrysts of olivine set in a glassy groundmass in which augite appears only as dendrites, and in which plagioclase is not visible.

2. *2-phenocryst limburgites*, rocks similar to the above but containing microphenocrysts of augite.

3. *2-phenocryst olivine basalts*, rocks with phenocrysts of olivine accompanied by microphenocrysts of augite and visible plagioclase microlites within the glassy groundmass.

4. *3-phenocryst olivine basalts*, rocks containing phenocrysts of olivine, augite, and plagioclase, set in a fine-grained semi-glassy or holocrystalline groundmass.

5. *augite-plagioclase-phyric basalts*, rocks similar to the above but devoid of olivine. The groundmasses are usually very fine-grained but mainly crystalline.

Types 1 and 4 above are rare, while types 2 and 3 are the commonest rock types of the lower part of the succession (the Olivine-rich Group of Cox *et al. op. cit.*), and type 5 is common in the upper part of the succession (Upper Basalts of Cox *et al.*). An order of crystallisation, olivine-augite-plagioclase is implied by these phenocryst assemblages.

The rocks analysed by Jamieson (1966) are predominantly limburgites and 2-phenocryst olivine basalts, and he has shown that they lie within the primary phase volume of olivine in the simple basalt system olivine-clinopyroxene-plagioclase-quartz for 1 atmosphere which is based upon experimental work in the pseudo-quaternary Fo-Di-An-Qz and upon the data from experimentally melted tholeiites. He has further shown that the rocks have compositions which can not in the main be due to the accumulation of olivine or other ferromagnesian minerals in more normal cotectic basalts (*i.e.* basalts saturated with respect to 3 of the principal solid phases) at near-atmospheric pressure, and they are thus regarded as primitive relative to other basalts of the area. The non-accumulative origin of the phenocrysts together with the fact that both olivine and augite are present as phenocrysts in rocks which lie within the primary phase volume of olivine, implies that there has been no major change of bulk composition of the erupted magmas after the appearance of augite as a phenocryst phase. In other words, although olivine may have been separating from the liquid and responsible for fractionation before the eruption of the lavas, clinopyroxene began to crystallize at such a late stage that it was not responsible for further fractionation. Phenocrysts of this type must presumably always be rather small, and will often, as they do in many of the rocks under discussion, show signs of skeletal crystallization. They form during the relatively rapid cooling which accompanies or immediately precedes the eruption of the magma, and may be distinguished for convenience by the term *nonfractionating phenocrysts*. They may be defined as crystals which are significantly larger than groundmass crystals but have not separated from the liquid in which they were originally formed. The converse type, phenocrysts which represent phases responsible for fractionation, may be termed *fractionating-phenocrysts*, and are probably the commonest type in normal porphyritic rocks.

Thus we cannot at present make a useful distinction between the

evolutionary status of the 1- and 2-phenocryst limburgites and 2-phenocryst olivine basalts, since the second phenocryst, augite, is probably a nonfractionating phase in most cases. The distinction between the three types is therefore more one of cooling history rather than of fractionation history.

The 3-phenocryst olivine basalts and the augite-plagioclase-phyric basalts, however, probably represent a more straight-forward case where the three major solid phases are present as fractionating phenocrysts. Although these rocks have not so far been studied in the light of the experimental data, their textures give little evidence of rapid quenching, and their chemical compositions suggest strongly that they are more evolved types than the rocks previously mentioned. The chemical evidence also suggests that the augite-plagioclase-phyric basalts are more evolved than the 3-phenocryst olivine basalts, with the implication that olivine is lost by reaction in the passage from one type to the other.

We can thus distinguish at present three important stages in the evolution of the Nuanetsi magma:-

Stage 1. Rocks defined by the equilibrium olivine+liquid in the simple basalt system, and including the 1- and 2-phenocryst limburgites and the 2-phenocryst olivine basalts.

Stage 2. Rocks defined by the equilibrium olivine+augite+plagioclase+liquid, represented by the 3-phenocryst olivine basalts.

Stage 3. Rocks defined by the equilibrium augite+plagioclase+liquid, represented by the augite-plagioclase phyric basalts.

Since the order of crystallization demonstrates that augite and plagioclase do not appear simultaneously, and since Jamieson (*op. cit.* has demonstrated that the stage 1 rocks are not merely low-pressure cotectic basalts enriched in cumulus olivine, it follows that between stages 1 and 2 as defined above, the magma should pass through a stage in which both olivine and augite are fractionating phenocrysts. Corresponding rocks are almost certainly present in the area (*e.g.* see Cox *et al*, *op. cit.* Fig. 37(a)) but have not yet been investigated in detail.

The phase relations for the simple basalt system predict that under conditions of equilibrium crystallisation the principal phases would appear in the order olivine-clinopyroxene-orthopyroxene-plagioclase (Jamieson, 1966). This may be extended to natural conditions of fractionation to predict that orthopyroxene rather than plagioclase would appear as the third phenocryst. From our observations above, however, this is generally not so. Phenocryst assemblages including orthopyroxene formed at or near atmospheric pressure (*i.e.* excluding the orthopyroxene phenocrysts discussed by Jamieson and believed to be derived from an

earlier crystallization period at higher pressures) have been noted only extremely rarely in the Nuanetsi-Tuli rocks.

It seems likely that the presence of the enstatite molecule in solution within the augites appearing as the second phenocryst phase may be sufficient to account for this discrepancy. These crystals are currently under study and may prove to resemble the metastable subcalcic augites investigated by Yoder, Tilley and Schairer (1963). In the equilibrium diagram figured by Jamieson (1966) any solution of enstatite in the clinopyroxene will have the effect of fractionating this phase, and will tend to give liquid compositions a component of movement away from the orthopyroxene composition point. The residual liquids rather than moving directly towards the $OL+CPX+OPX+L$ boundary will thus tend to deviate towards the $OL+CPX+PL+L$ curve, and the appearance of plagioclase as the third phenocryst phase will be favoured.

It is now possible to comment on the areal variation of the northern province (Rhodesian) basalts as a whole, since the similarities of geochemistry between the Nuanetsi rocks and the rocks of the other Rhodesian localities justifies an extension of the evolutionary scheme to the whole province. The different areas may be summarised in terms of evolutionary stages as follows:-

1. Tuli-Nuanetsi-Sabi. All stages are present. The lower part of the succession is typified by stage 1, the upper part by stage 3.
2. Featherstone. Most of the rocks of this small outlier belong to stage 1.
3. Nyamandhlovu-Wankie-Victoria Falls. It is probable that the majority of the rocks belong to stage 3. There is thus a considerable similarity with the upper part of the succession in the Nuanetsi-Tuli-Sabi area.

The possible reasons for the variation between the different areas are beyond the scope of the present work, but it seems most likely that different rates of magmatic ascent are likely to have been an important factor.

Variation within the Southern Province. The basalts of Swaziland and Basutoland, as we have shown, resemble each other closely in their geochemical characters. There are, however, quite considerable field and petrographic differences between the rocks of the two areas.

The Basutoland lavas, as has been recorded by practically all who have studied them, are monotonously uniform. In the area of northern Basutoland studied by two of the present authors (Cox and Hornung *op. cit.*), for example, almost every flow consists of sparsely microporphyritic olivine-plagioclase-phyric basalt. Only at or towards the base of the sequence are a few flows found which are olivine-rich and hence of different appearance.

In Swaziland one is faced immediately with a much greater variability, evident in the field as well as in thin sections. The most obvious contrast with Basutoland is the presence of porphyritic rocks, some of them very coarsely so. Added to this, the presence of a substantial dyke-swarm through the basalt area appears to have caused a quite variable degree of metamorphism within the basalts, resulting in appreciable differences in colour and hardness.

Study of thin-sections suggests, despite the degree of alteration of many of the rocks, that the phenocryst assemblage *olivine*+*plagioclase* is characteristic of the Swaziland basalts. Urie and Hunter (1963) have previously commented on the occurrence of plagioclase phenocrysts, but the accompanying olivine had not been noted. This is due to the complete alteration of all the olivine phenocrysts, and to their low concentration, both factors which make them difficult to distinguish from the ground-mass in the altered rocks which make up so large a part of the Swaziland succession. There is, however, an obvious similarity in phenocryst assemblages between the Swaziland and Basutoland rocks. A further similarity exists in the occurrence in both areas, of basalts with an ophitic groundmass texture. The possible significance of these similarities is discussed in the next section.

The differences between the rocks in the two areas, disregarding the alteration of the Swaziland rocks, can probably be attributed mainly to the eruptive mechanism. The horizontal lava plateau of Basutoland was probably formed during a period of tectonic stability so that there was a steady and continuous flow of magma towards the surface. Conditions were probably such that near-perfect fractionation (implying a relatively low rate of magma ascent) operated almost throughout, and gave rise to a uniform lava type almost devoid of phenocrysts. Variations in the sequence have thus been detected only by chemical analyses. In Swaziland, in contrast, it is virtually certain that the lavas were erupted *during* the formation of the Lebombo Monocline. Du Toit (1929) first put forward this idea of the evolution of the monocline, and Cox *et al* (1965) showed that the related Nuanetsi Syncline developed during the extrusion of the volcanics. In this type of situation it is possible that the rate of magmatic ascent may undergo considerable fluctuations. The interplay of relative rates of crystal settling, magma ascent, and cooling, would result in a variety of phenocryst concentrations and sizes in the eruptive products.

Differences between the Northern and Southern Provinces. The most common order of appearance of phenocryst phases during the fractionation of the magma in the northern province has been shown to be *olivine-augite-plagioclase*. Within the southern province there has been less chance of

establishing a complete phenocryst sequence firstly because of the uniformity of the Basutoland rocks, and secondly because the Swaziland rocks have not been studied in detail. The point that is well established, however, is that the phenocryst assemblage *olivine* + *plagioclase* is very common amongst the southern province rocks. Thus whatever the detailed sequence may be, there can be no doubt that plagioclase crystallizes earlier than augite in the southern province, while plagioclase begins to crystallize later than augite in the northern province. The order of crystallization established for the Karroo Dolerites (belonging to the southern province as defined here) by Walker and Poldervaart (1949) adds confirmation to this hypothesis, and is *spinel-olivine-plagioclase-pyroxene*.

The difference in order of crystallization in the two provinces can readily be attributed to the variations in CaO and Al₂O₃ which we have observed. The magma of the southern province was generally richer in normative anorthite than that of the northern province. Reference to the 'simple basalt system' (e.g. see Cox and Hornung *op. cit.*) shows that fractionating liquids lying within the primary phase volume of forsterite will produce plagioclase as the second phase, if they are relatively rich in normative anorthite, and diopside if they are relatively poor in anorthite.

There is evidence too that the order of crystallization affects groundmass textures and may account for the common occurrence of the subophitic texture in the southern province basalts. In the olivine-plagioclase phyric rocks which are so common in this province, it is evident that the liquid was saturated with respect to plagioclase but undersaturated with respect to pyroxene, at the time of eruption and the commencement of the groundmass stage of crystallization. Thus plagioclase may have begun to form before pyroxene during this stage, with a resultant subophitic relationship between the two minerals. In broadly comparable northern province rocks (*i.e.* 2- and 3-phenocryst olivine basalts, and augite-plagioclase-phyric basalts) the subophitic relationship has not been observed in the groundmasses, and we must attribute this to the fact that the liquids at the time of extrusion were either saturated with respect to both augite and plagioclase or were saturated with respect to augite only.

Amongst the other chemical differences noted between the provinces, only the variation in phosphorus is reflected in an obvious petrographic difference. Basalts containing substantial amounts of glass are relatively common throughout the Karroo area, and those of the northern province commonly contain abundant apatite needles within the glass. Southern province rocks show no such evidence of richness in phosphorus.

Finally, some further comment is required on the analysed Swaziland rocks because of their considerable degree of alteration. If the correlation

with the Basutoland lavas rested on chemical analyses alone, it would be difficult to place much confidence in it, but since there are important similarities in mineralogy and texture, similarities of a type which are dependent on bulk chemical composition, it seems unlikely that the chemical evidence is misleading. The alteration appears to have been of a largely isochemical nature and was probably caused by a mild thermal metamorphism due to the intensity of the dyke swarm cutting the Swaziland basalts (*e.g.* see Du Toit 1929, Urie and Hunter, 1963). A similar alteration in the upper basalts of Nuanetsi was attributed by Cox *et al* (1965) to deuteric processes, but if a broad view is taken, metamorphism by minor intrusions may be a general cause of alteration of Karroo basalts. During the present study the rocks suffering least from this type of alteration (principally the amphibolisation of the groundmass pyroxene) have been obtained from Nyamandhlovu and Basutoland, both areas almost devoid of post-basalt dykes (*e.g.* see Stockley 1947, Macgregor 1937, Amm 1940).

DISCUSSION

From the data available there can be no hesitation in describing the rocks of the southern province as having a typical tholeiitic geochemistry. This is no doubt due partly to the fact that the studies by Walker and Poldervaart (1949) and Nockolds and Allen (1956) of the Karroo dolerites which belong to this province, have contributed towards our idea of a typical tholeiite. But it is also due to the great similarity in major elements between these rocks and other flood basalt suites such as the Decan Traps (Washington 1922, Fermor 1934, West 1958) and the Columbia River basalts, particularly the Picture Gorge type (Waters, 1961). The southern province rocks also show minor element concentrations which are similar to those found in other tholeiitic suites such as those studied by Nockolds and Allen (1956).

While the term tholeiite is still adequate to describe the rocks of the northern province, since they are oversaturated and carry conspicuous amounts of pigeonite, or, more rarely, orthopyroxene, the geochemistry is distinctly unusual even though particular geochemical features can be matched in other tholeiitic suites. The K/Na ratio is high by comparison with any normal basalts, and is a particularly rare feature of oversaturated suites (although, for an exception to this, some of the analyses of tholeiitic sills from Ontario given by Blackadar (1956) also show high K/Na ratios). The content of Ti, Sr, and Zr shown by the northern province rocks also appear to be high by tholeiitic standards, though again high values for titanium, for example, can be matched by some of the Columbia River basalts (*cf.* Waters 1961), and the Sr content is not

exceptionally high compared with the average value of 465 p.p.m. given for basaltic rocks by Turekian and Kulp (*op. cit.*), except in the more basic rocks from Nuanetsi. The Ba content of the northern province rocks is high even by comparison with the alkalic suites given by Nockolds and Allen (1954).

Monkman (1961) first drew attention to the points of similarity between the Nuanetsi rocks and the potassic lavas of Uganda (Holmes and Harwood 1932, Higazy 1954). The present study has confirmed this impression and also demonstrated that rocks of this type are widespread throughout the Rhodesian area of Karroo volcanics.

The main purpose of the present paper has been to record the differences between the two provinces within the extensive Karroo basalt area of southern Africa, and to note the unusual geochemical features of the northern province. The petrogenetic implications, whether the differences are due to processes of magmatic evolution or to variation in the source material, are under study and will be discussed in a future paper.

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