Contr. Mineral. and Petrol. 35, 277—292 (1972)

Potassium-Argon Ages and Strontium Isotope Ratio Measurements from Volcanic Rocks in Northeastern Nigeria

Norman Kennedy Grant
Department of Geology, Oberlin College, Oberlin, Ohio 44074, U.S.A.

David C. Rex
Department of Earth Sciences, The University of Leeds, Leeds, England

Samuel J. Freeth
Department of Geology, University College of Swansea, Swansea, Wales

Received April 17, 1972

Abstract. The Cenozoic volcanic activity in northeastern Nigeria began with the intrusion into the Benue trough of a trachyte-phonolite suite of plugs 22–11 m.y. ago. Later activity, which was more widespread and dominantly basaltic in character, began some 7 m.y. ago and has continued until very recent times. It resulted in basaltic plugs and lava plateaux within the Benue trough, and cinder cones and lavas on the Jos Plateau.

The initial $^{87}Sr/^{86}Sr$ ratios of nine of the fifteen analyzed basic and alkalic rocks lie in the range 0.7025–0.7032, and the highest ratio measured is 0.7129.

The main group of trachytes and phonolites are considered to be fractional melts derived from the upper mantle, modified in small part by potassium feldspar crystal fractionation. Two Sr-rich phonolite plugs may have a separate origin from the main group of trachytes and phonolites.

The Cenozoic volcanic activity in northeastern Nigeria is probably related to the nearby Cameroun volcanic line. The concentration of plugs within the Benue trough may reflect internal adjustments along old lines of weakness within the African lithosphere plate, in response to synchronous changes affecting the plate's external dimensions and internal structure, such as the growth of the Red Sea and the Gulf of Aden, and the volcanism of the east African rift valley.

Introduction

The Cenozoic volcanic activity in northeastern Nigeria is part of a widespread igneous episode related to basement uplifts in the Ahaggar and Tibesti massifs of the Sahara (Black and Girod, 1970), and finding its most striking expression in the Cameroun volcanic line, which extends from the Adamawa highlands of Cameroun into the South Atlantic by way of the volcanic islands of Fernando Po, Principe, Sao Tome and Annobon (Fig. 1).

The structural trend of the volcanic line follows the Benue trough to the northwest. The trough runs from the Niger delta to the Chad basin, and is filled with folded Cretaceous sediments and scarce volcanic rocks with a maximum total thickness of 5500 m (Fig. 1; Carter *et al.*, 1963; Cratchley and Jones, 1965). Interpreted by Cratchley and Jones (1965) as a lower Cretaceous rift valley which later closed and folded the infilling sediments, the trough is characterized by a

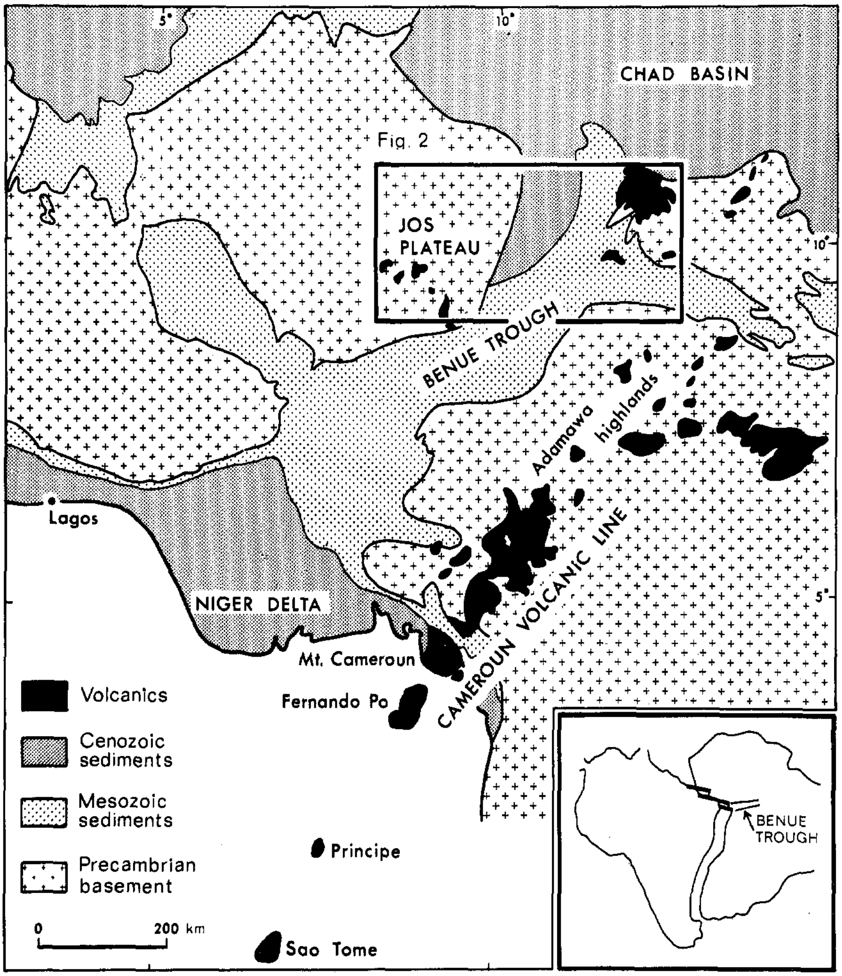

Fig. 1. The Benue trough extends from the Niger delta to the Chad basin, and is paralled by the younger Cameroun volcanic line. Inset: the Benue trough as one arm of a Cretaceous triple junction (Burke *et al.*, 1971; Grant, 1971). Modified from ASGA-UNESCO 1:5 million Geological Map of Africa (1963)

central zone of relatively high and positive Bouguer gravity values flanked on either side by elongated negative anomalies (Cratchley and Jones, 1965). The central zone also coincides with a 560 km-long belt of Pb-Zn sulphide mineralization, which was emplaced towards the end of a period of basic to intermediate intrusive igneous activity of late Albian to Senonian age (Farrington, 1952; Cratchley and Jones, 1965; Snelling, 1965).

Although the connection between the Benue trough and the Cameroun volcanic line is obscure, it is perhaps worth noting that the trough is related to the separation of Africa from South America (King, 1950; Kennedy, 1965; Stonely, 1966; Wright, 1968a; McConnell, 1969). If the trough is seen in the context of the lower Cretaceous positions of Africa and South America its relation to the Gulf of Guinea and the South Atlantic suggests the presence of a Cretaceous triple lithosphere plate junction (Fig. 1, inset; Burke *et al.*, 1971; Grant, 1971).

Short-lived lower Cretaceous lithosphere plate separation under the Benue trough is consistent with the medial gravity animalies, while a present-day analogue of the origin of the central belt of Pb-Zn mineralization may be provided by the geothermal heavy-metal bearing brines of the Red Sea and the Salton Sea area of California, which are localized above lines of current lithosphere separation (Grant, 1971).

The present work is concerned with the numerous alkali olivine basalt, olivine basanite and trachyte-phonolite plugs, and the Biu lava plateau of the Benue valley, and the cinder cones and basalt lavas of the Jos Plateau (Falconer, 1911; Mackay *et al.*, 1949; Carter *et al.*, 1963).

The study is based on K-Ar ages (DCR), $^{87}Sr/^{86}Sr$ ratios (NKG), and new chemical data (SJF) which supplements previously published analyses (Carter *et al.*, 1963). A detailed account of the geochemistry will be presented later (Freeth, in preparation).

K-Ar Data

a) Analytical Techniques

The K-Ar determinations were made on whole rock samples, the same powders being used for Rb-Sr where applicable. The potassium was determined by flame photometry using an E.E.L. machine, sample solutions being bracketed by standards. Each determination is an average of three separate dissolutions. The potassium content of DB 48 (4.67% K) was determined six times in triplicate, with a relative standard error of 1% at the 95% confidence limit.

The argon was extracted by fusion in vacuo, pure ^{38}Ar added as a "spike". The isotopic ratios were measured on an A.E.I.–G.E.C. MS10 mass spectrometer operated under static conditions and fitted with digital output (Rex and Dodson, 1970).

The errors are quoted for the 95% confidence levels, and are calculated from the duplicate analyses.

b) Results

The K-Ar ages (Table 1; Figs. 2 and 3a) show that the trachytes and phonolites are older than the basaltic rocks. Five of the six dated trachyte and phonolite plugs give ages in the range 11.2–14.4 m.y., and one, dated with duplicate samples (trachyte DB51–52), has given identical K-Ar ages of 12.0 ± 0.3 my. The sixth, a phonolite plug west of Bambam, is also dated by duplicate samples (DB12–13) which suggest that the initial alkaline igneous activity began at least 22 m.y. ago, in early Miocene times.

Evidence for younger alkalic igneous activity in Nigeria is inconclusive. In one instance, Wright (1969) has described a composite basalt-trachyte plug of unknown age near Bokkos on the Jos Plateau, where the intrusion of the trachyte followed that of the basalt, a reversal of the broad age relations shown by the K-Ar ages. In another, Wright and McCurry (1970) have suggested that at least two of the phonolite bodies are not plugs but extrusive tholoids with intrusive spines, and have concluded they belong to a relatively late stage of the Benue valley igneous activity. That conclusion is incorrect since one of the examples

Table 1. Ages and potassium-argon analytical data

Sample No.	Rock type	Area[a]	% K	^{40}Ar rad. scc/g ± 10^{-6}	% ^{40}Ar radiogenic	Age m.y.
Benue valley						
DD 2	Trachyte	Wase	4.56	2.630	62.7	14.4 ± 0.4
DB 12	Phonolite	Bambam	3.36	3.068	49.0	22.8 ± 0.6
DB 13	Phonolite	Bambam	3.45	2.974 2.945	56.4 57.2	21.4 ± 0.5
DB 17	Trachyte	Filiya	4.13	1.919	50.6	11.6 ± 0.3
DB 48	Phonolite	Biliri	4.67	2.093 2.064	30.7 30.9	11.2 ± 0.2
DB 51	Trachyte	Biliri	4.44	2.143	68.9	12.0 ± 0.3
DB 52	Trachyte	Biliri	4.22	2.045	52.1	12.0 ± 0.3
DB 60	Phonolite	Biliri	3.42	1.588 1.583	33.1 39.9	11.6 ± 0.2
DJ 1	Basalt[b]	Bembel	0.79	0.159 0.152	16.8 11.6	4.9 ± 0.2
DJ 2	Basalt[b]	Ngurore	0.57	0.117 0.108 0.120	27.6 22.1 16.6	5.0 ± 0.2
DB 1	Alkali olivine basalt	Dadin Kowa	1.34	4.670 4.708	75.0 74.8	86.0 ± 2.0
DB 10	Nepheline melabasalt	Biliri	1.38	0.206	22.4	3.7 ± 0.1
DB 43	Olivine basanite	Biliri	1.86	0.541	26.6	7.4 ± 0.2
DB 58	Alkali olivine basalt	Biliri	1.16	0.171	13.3	3.7 ± 0.2
DB 64	Olivine basalt	Biliri	1.82	0.177	14.9	2.5 ± 0.1
Biu plateau						
DF 1	Basalt[b]	Biu	1.23	0.069	23.9	1.4 ± 0.1
DF 8	Basalt[b]	Biu	1.20	0.223	38.5	4.7 ± 0.1
DB 29	Olivine basanite	Biu	1.19	0.019	2.3	< 0.8
DB 34	Alkali olivine basalt	Biu	1.08	0.217	22.9	5.0 ± 0.2
15 BI[c]	Basalt[b]	Biu	1.40	0.152 0.172	15.7 23.9	2.9 ± 0.1
Jos plateau						
DE 1	Basalt[b]	Kass hill	1.31	0.077	27.4	1.5 ± 0.1
DE 2	Basalt[b]	Vom	1.82	0.064	16.4	0.9 ± 0.2
DE 10	Basalt[b]	Bassa	1.40	0.117	25.9	2.1 ± 0.1

Analyst: D. C. Rex.

Decay constants: $\lambda_\beta = 4.72 \times 10^{-10}$ yr^{-1}, $\lambda_\varepsilon = 0.584 \times 10^{-10}$ yr^{-1}, ^{40}K/K = 0.0119 atomic %.

[a] Full locality given in Appendix 1.

[b] Rock name based on thin section examination. All other samples have been chemically analysed (S. J. Freeth, unpublished), and named on the basis of CIPW norms.

[c] Analyst: A. E. Evans; result communicated by J. M. Ade-Hall.

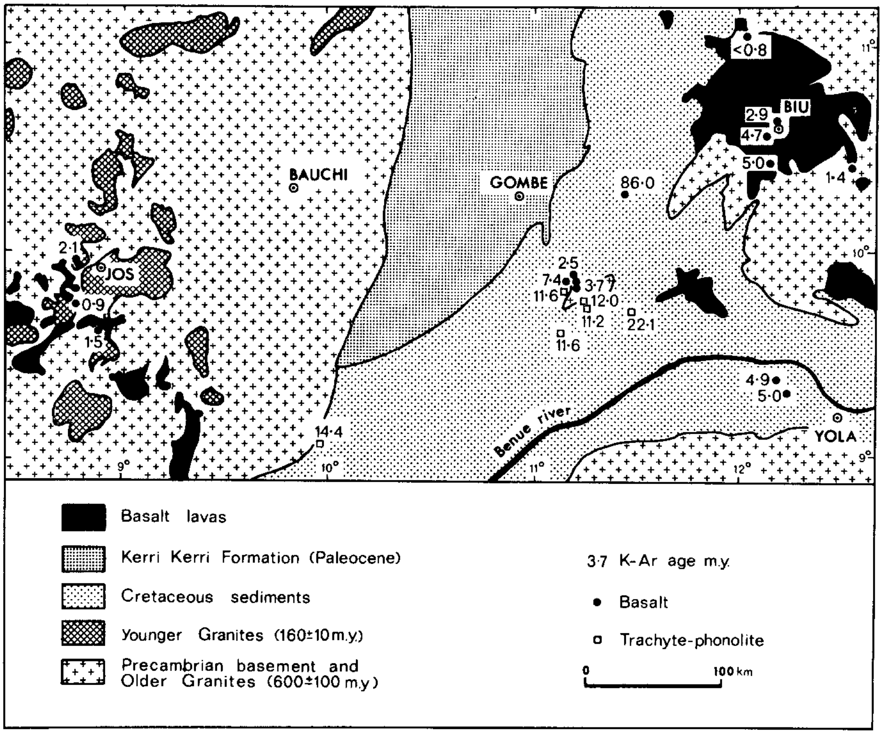

Fig. 2. The geographical distribution of the K-Ar ages reported here. Note that the anomalous age of 86 m.y. from a basalt plug east of Gombe is attributed to excess ^{40}Ar. Modified from 1:2 million Geological Map of Nigeria (1964)

cited by them has given K-Ar ages of 22.8 ± 0.6 and 21.4 ± 0.5 m.y. (DB12–13, Table 1), the oldest ages found in the present study, and in consequence the original form of the body must be much more strongly modified by erosion than Wright and McCurry (1970) supposed. The other example is undated, but lies about 2 km from a phonolite plug with a K-Ar age of 11.6 ± 0.2 m.y. (DB60, Table 1).

With one exception the ages of the basaltic rocks range from 7.4 to < 0.8 m.y. (Table 1; Fig. 3a), and it seems likely that the basalt plugs of the Benue valley, the Biu and probably Longuda basalt plateaux, and the basalts of the Jos Plateau belong to a period of widespread basaltic activity extending back to at least 7 m.y. B.P. The K-Ar ages from the Jos Plateau date only the youngest volcanic activity of the Plateau. Two of the dated samples come from the "more recent newer basalts" of Mackay *et al.*, (1949), which they divided into two sub-groups: DE2 (0.9 ± 0.2 m.y.) comes from the younger sub-group, DE1 (1.5 ± 0.1 m.y.) from the older. The third sample DE10 (2.1 ± 0.1 m.y.) comes from a basalt flow southwest of Bassa which was included by Mackay *et al.* (1949) in the "earlier newer basalts", and later designated "Older Basalt" by the Nigerian Geological Survey (1:100000 Sheet 168).

One basalt sample, from a possible lava flow near Dadin Kowa to the east of Gombe (DB 1, Table 1; Fig. 2), has given an anomalously high age of 86 ± 2 m.y. This is considered to be the result of excess ^{40}Ar, a feature which will be discussed later.

The volcanic sequence reported here can be compared to that in the Adamawa highlands sector of the Cameroun volcanic line (Fig. 1), where andesites, peralkaline trachytes, phonolites and rhyolites constitute a notable part of the volcanic assemblage. The second of three volcanic phases recognized by Gèze (1943) consists of Miocene (de Swardt, 1956) trachyte and phonolite flows and associated plugs and domes, and is followed by younger basalt lavas and cinder cones. The oldest phase, heavily laterized basalt and andesite flows of possible lower Cenozoic age, is unrepresented in the present work, but might parallel the lateralized basalts of the Jos Plateau (Mackay *et al.*, 1949). Other early igneous activity along this sector of the Cameroun volcanic line is represented by the twenty or so intrusive riebekite-bearing syenite and granite masses which occur intermittently along the line from Cameroun to Chad. Although these masses resemble the sub-volcanic Jurassic Younger Granites of the Jos Plateau of Nigeria, and like them are also tin-bearing, they are much younger. Biotites have given Rb-Sr ages of 56 ± 8 m.y. for one mass, and between 33 and 38 m.y. for two others (Lasserre, 1967), and this suggests that their emplacement may have extended into the lowermost Oligocene.

Further southwest the character of the volcanic line changes. Cameroun Mountain and the offshore island of Fernando Po belong to the third phase of the activity of Gèze (Piper, 1970), and are built entirely of alkali olivine basalts no older than middle Miocene and possibly younger than early Pliocene (Hedberg, 1968). The more distant offshore islands (Fig. 1) of Annobon, Sao Tome and Principe are older, with histories probably going back to the Oligocene-Miocene (Hedberg, 1968), and are formed largely of alkali olivine basalt, intruded by phonolite, tephrite and trachyte, and followed in places by renewed basaltic activity (Piper, 1970). Two phonolites from Sao Tome have given K-Ar ages between 3 and 5 m.y. (Fig. 3a; Hedberg, 1968), and are thus entirely distinct from the phonolites reported here.

Rb-Sr Data

a) Analytical Techniques

An MS5 mass spectrometer was used to measure ^{87}Sr/^{86}Sr ratios and determine Rb and Sr concentrations by isotope dilution. The mass spectrometer was equipped with digital output and magnet current peak switching. The ^{87}Sr/^{86}Sr ratios were determined on unspiked Sr runs by measuring three sets of eleven scans of ^{85}Rb, ^{86}Sr, ^{87}Sr and ^{88}Sr peaks *and* the baseline at 84.5, 85.5, 86.5, 87.5 and 88.5 mass units. The ^{87}Sr/^{86}Sr measurements were normalized to ^{88}Sr/^{86}Sr $= 8.375$, and data reduction was performed with computer programmes developed by Drs. M. H. Dodson and M. Coleman. All ^{87}Sr/^{86}Sr ratio measurements were repeated with duplicate sample dissolutions.

The mean of seven runs of the Eimer and Amend Sr standard is 0.70776 with a standard deviation of 0.00021. The standard deviation calculated for the fifteen pairs of duplicate analyses is 0.00037, a value which is only marginally higher statistically, and may reflect sample inhomogeneity. The ^{87}Sr/^{86}Sr ratio measurements have been adjusted to an Eimer and Amend ^{87}Sr/^{86}Sr ratio of 0.7080.

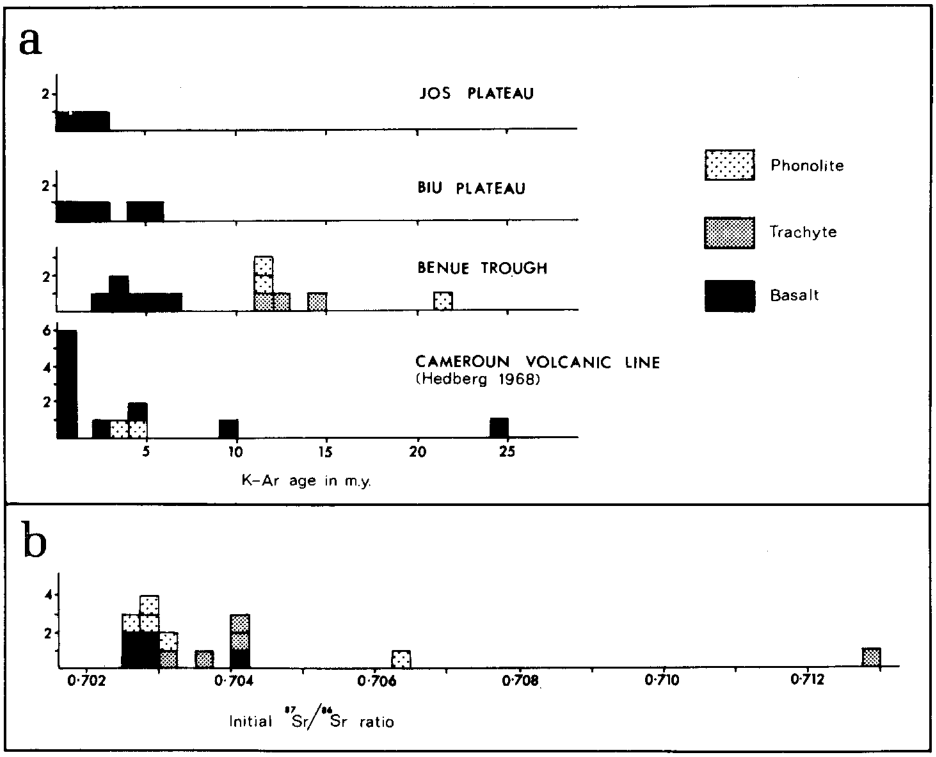

Fig. 3a and b. Summary of the isotopic data. a Comparison of the K-Ar ages with those from the southern part of the Cameroun volcanic line (Hedberg, 1968), where the dated phonolites come from the island of Sao Tome. b Histogram of initial $^{87}Sr/^{86}Sr$ ratios

b) Results

The initial $^{87}Sr/^{86}Sr$ ratios for the trachytes and phonolites lie (with one exception) between 0.7026–0.7063 (Table 2; Fig. 3b). The one exception, the trachyte from Filiya (DB17), has an initial ratio of 0.7129. The normal age of this sample (11.6 m.y.) shows that excess ^{40}Ar is not present.

Examination of differences in initial ratios given by duplicate samples from the same plug (DB12–13, DB51–52) suggest that some of the trachyte and phonolite magmas were not in isotopic equilibrium at the time of their intrusion. In the case of DB12–13, where the K-Ar ages for the same samples differ by an amount that is just outside the experimental error (Table 1), the disequilibrium may reflect the possibility that this plug is a multiple body (*cf.* Wright and McCurry, 1970).

Three of the four analyzed basaltic rocks have initial $^{87}Sr/^{86}Sr$ ratios in the range 0.7025–0.7029. The fourth (DB1), from a lava flow, or possibly a plug, near Dadin Kowa east of Gombe, has an initial ratio of 0.7041 (Table 2; Fig. 3b). This value, which was calculated relative to the anomalously high K-Ar age of 86 m.y. (Table 1), provides evidence for the presence of both excess ^{87}Sr and ^{40}Ar in the Dadin Kowa basalt.

Table 2. Rb and Sr data

Sample No.	Rock type	Rb (ppm)	Sr (ppm)	Rb/Sr	^{87}Sr/^{86}Sr	Mean ^{87}Sr/^{86}Sr	Initial[a] ^{87}Sr/^{86}Sr
DD 2	Trachyte	227	35.6	6.38	0.7075 0.7082	0.7079	0.7040
DB 12	Phonolite	154	348	0.443	0.7032 0.7028	0.7030	0.7026
DB 13	Phonolite	149	253	0.589	0.7033 0.7041	0.7037	0.7032
DB 17	Trachyte	152	147	1.034	0.7130 0.7138	0.7134	0.7129
DB 21	Trachyte	127	271	0.469	0.7045 0.7040	0.7042	0.7040
DB 48	Phonolite	180	12.2	14.75	0.7132 0.7135	0.7133	0.7063
DB 51	Trachyte	138	354	0.390	0.7034 0.7033	0.7033	0.7031
DB 52	Trachyte	136	492	0.276	0.7037 0.7038	0.7038	0.7036
DB 60	Phonolite	86.0	1865	0.0461	0.7029 0.7027	0.7028	0.7028
DB 61	Phonolite	90.0	1810	0.0497	0.7030 0.7027	0.7028	0.7028
DB 1	Alkali olivine basalt	37.3	830	0.0449	0.7041 0.7045	0.7043	0.7041
DB 10	Nepheline melabasalt	44.4	1430	0.0310	0.7027 0.7029	0.7028	0.7028
DB 43	Olivine basanite	43.6	919	0.0474	0.7025 0.7026	0.7026	0.7025
DB 58	Alkali olivine basalt	56.7	829	0.0684	0.7029 0.7029	0.7029	0.7029
DB 64	Olivine basalt	46.0	1020	0.0451	0.7031 0.7023	0.7027	0.7027

[a] Initial ratios on undated samples are calculated relative to 12 m.y. for trachytes and phonolites, and 3 m.y. for basalts. The initial ratio for basalt DB 1 is calculated relative to the anomalously high K-Ar age of 86 m.y., and therefore is a minimum value.

Fisher (1971) has demonstrated that the level of excess ^{40}Ar is several magnitudes greater than that recorded elsewhere, and has reported concordant K-Ar ages of about 95 m.y. for the Dadin Kowa basalt and large oligoclase-andesine crystals mantled with calcic plagioclase contained in it (Wright, 1968b). Fisher (1971) also reported U-He and fission track ages of 750 and < 30 m.y. respectively for a plagioclase megacryst, and concluded that excess ^{4}He is also present. Our work shows that the Dadin Kowa basalt in anomalous in one further way: it contains substantially greater amounts of Ba (3150 ppm) than all other analyzed basalts (490–1280 ppm).

If this evidence for excess ^{87}Sr, ^{40}Ar and ^{4}He is accepted, the nominal concordance of the basalt and plagioclase megacryst K-Ar ages is difficult to understand, partly because Fisher's (1971) isotopic analyses do not make clear whether they refer to the sodic core or the calcic mantle of the megacrysts. If the megacrysts are interpreted as phenocrysts crystallized under deep crustal or upper mantle conditions (Wright, 1968b), and the excess ^{40}Ar and ^{4}He is present in both megacryst core and mantle, the excess of rare gases in the Dadin Kowa basalt must have been established prior to the crystallization of the megacryst core, and hence prior to the equilibrium change in the plagioclase crystallization. In this case the rare gases are likely to be of upper mantle origin.

If the rare gases are restricted to the calcic margin of the megacrysts, it is likely that they were introduced into the basalt after the plagioclase equilibrium change, that is late in the history of the basalt and possibly from sialic sources when the basalt rose through the crust. In both of these cases the nominal K-Ar age concordance between basalt and megacryst requires, either the partitioning of ^{40}Ar between plagioclase and basalt in such a way that age concordance resulted, and the closure of the basalt-megacryst system to argon migration after crystallization of the megacrysts, or that the argon partitioning and any subsequent migration were balanced in such a way as to result in age concordance. Both alternatives seem fraught with difficulties, and would imply that the age concordance is largely fortuitous.

A crustal origin for the excess ^{87}Sr, ^{40}Ar and ^{4}He receives some support from the presence of quartz xenocrysts in the Dadin Kowa basalt, and this raises the question of whether the plagioclase megacrysts might also be interpreted as xenocrysts, as suggested for similar zoned megacrysts in basalts from the Southern Rocky Mountains (Doe *et al.*, 1969), and Rodriguez Island in the Indian Ocean (Upton *et al.*, 1967). Although a certain intellectual economy may result from ascribing the unusual isotopic and geochemical constitution and the plagioclase megacrysts of the Dadin Kowa basalt to sialic contamination, it is also very possible that the present analytical data is incapable of resolving what may be an exceedingly complex history for the basalt.

Discussion

a) Petrogenesis

The Nigerian alkali basalts, trachytes and phonolites are a small part of a widespread Cenozoic-Recent suite of similar rocks in West Africa, which Black and Girod (1970) have shown to be restricted to the parts of the shield affected by the Pan-African thermo-tectonic reactivation. Black and Girod have further drawn attention to the contrast between this alkali basalt suite and a post-Visean to pre-Jurassic tholeiite to granophyre suite, which is restricted to the West African Craton. The Craton has remained stable for the last 1600 m.y., and if the *inverse* correlation demonstrated between heat flow and age of continental crust (Hamza and Verma, 1969) is applied to it and the mobile Pan-African domain, then the tholeiites have originated in a low heat flow environment within which deep-seated rocks such as kimberlites appear to be preferentially distributed (Dawson, 1970), while the alkaline suite is associated with a high heat flow continental environment. These relations between heat flow and continental tholeiitic and alkali basalt suites are the opposite to those found for

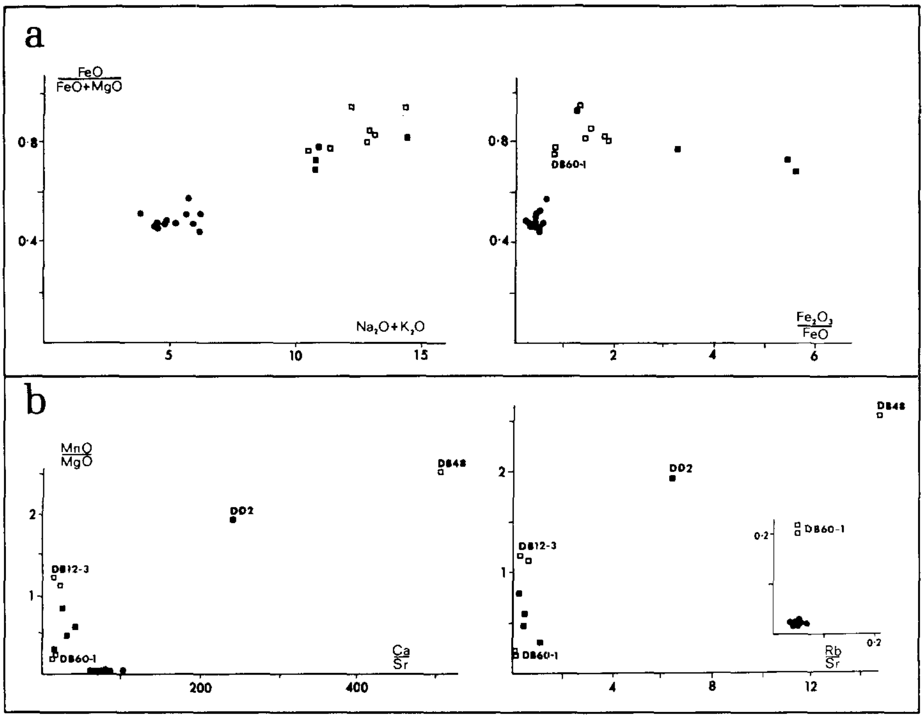

Fig. 4a and b. Geochemical data. a $\frac{\text{FeO}}{\text{FeO} + \text{MgO}}$ *versus* $K_2O + Na_2O$ and Fe_2O_3/FeO. b MnO/MgO *versus* Ca/Sr and Rb/Sr. Solid circles—basalts: solid squares—trachytes: open squares—phonolites

tholeiites and alkali basalts on oceanic regions (*cf.* McBirney and Gass, 1967), and it would seem that oceanic models for basalt genesis may not be directly applicable to continents.

Black and Girod (1970) have demonstrated, with some 140 analyses of this West African alkali basalt suite, the presence of a distinct compositional gap between the basic members (basanites, basanitoids, ankaratrites) and the alkali and peralkaline members (trachytes, phonolites, comendites, pantellerites).

This compositional gap can also be recognized in the Benue valley and Jos Plateau basic and alkalic rocks (Fig. 4a).

The explanation for the gap, in the case of the Nigerian rocks, is of course very clear, because the age relations make it unlikely that the trachytes and phonolites lie on a line of liquid descent from the basaltic rocks. The alkalic rocks, by implication, must be primary melts, and their low initial $^{87}Sr/^{86}Sr$ ratios (Fig. 3b) indicate that they are examples of the upper mantle-derived trachytes and phonolites whose existence has been cogently argued for by Wright (1970). Further reasons for concluding the trachytes and phonolites are primary fractional melts concern the dispersed nature of the plugs, which precludes a common underlying parental magma chamber (Wright, 1970), and the wide range of initial

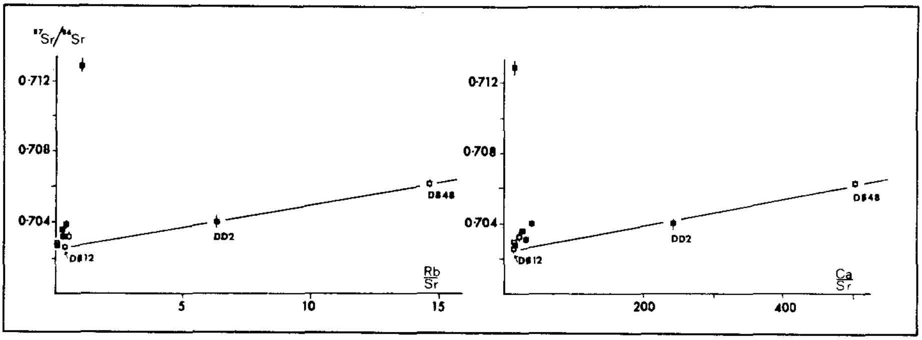

Fig. 5. Initial $^{87}Sr/^{86}Sr$ *versus* Rb/Sr and Ca/Sr. The vertical bars show the limits of the duplicate $^{87}Sr/^{86}Sr$ analyses. Solid squares—trachytes: open squares—phonolites

$^{87}Sr/^{86}Sr$ ratios and the possibility of isotopic disequilibrium within single plugs (DB12–13 and DB51–52, Table 2). Such disequilibrium would be consistent with these rocks being more or less independently derived fractional melts, preserving local isotopic variations within the upper mantle. Varying degrees of contamination with crustal ^{87}Sr is perhaps a less likely explanation for this disequilibrium, unless it is limited to some isotopic exchange involving Sr only, a process which is difficult to envisage. For instance, trachyte DB17 with the very high initial $^{87}Sr/^{86}Sr$ ratio of 0.7129, is not geochemically anomalous, and its K-Ar age, which is concordant with other alkalic rocks around 12 m.y., indicates that excess ^{40}Ar is absent. This would seem to rule out bulk assimilation of crustal rocks as an explanation for the high initial ratio. Examination of the isotopic data for DB12–13 and DB51–52 tends to confirm the conclusion that rocks with a higher than usual initial ratio do not always contain excess ^{40}Ar, for in the first case the slightly *older* sample (DB12) has the *lower* initial ratio, and in the second the K-Ar ages are perfectly concordant (Tables 2 and 3).

Two observations can be made about the geochemistry of the alkalic rocks. The first is that two phonolite plugs (DB60 and DB61) near Biliri are characterized by much greater Sr abundances ($>$ 1800 ppm) than all other rocks, including the basalts (832–1430 ppm). Compared with the other phonolites, DB60–61 have a more basic composition, and it seems likely that they have originated or equilibrated under different conditions from the other alkalic rocks.

The second observation is that three plugs form a series showing mutual correlation of between MnO/MgO, Ca/Sr and Rb/Sr ratios (Fig. 4b). The series, represented by phonolites DB12–13 from a plug west of Bambam, trachyte DD2 from Wase, and phonolite DB48 from Biliri, shows notable depletion in certain elements such as Sr (DB12–13, 253–348 ppm; DD2, 35.6 ppm; DB48, 12.2 ppm), and also MgO and Ba. Further, there is a correlation between the initial $^{87}Sr/^{86}Sr$ and Rb/Sr ratios of DB12 (at the low initial $^{87}Sr/^{86}Sr$ end of the trachyte-phonolite array), DD2 and DB48 (Fig. 5), with the slope of the regression line corresponding to an "age" of 6 m.y. ($^{87}Rb\ \lambda = 1.47 \times 10^{-11} yr^{-1}$). The initial ratios of these samples also correlate with Ca/Sr (Fig. 5), and MnO/MgO.

Because of the considerable distances between the plugs represented by DB 12, DD 2 and DB 48, and because the correlations involve element and isotopic ratios, rather than element abundances, it is considered they are better accounted for by crystal fractionation and not by the mixing of two distinct magmas. Alkali feldspar fractionation may explain the Sr depletion, and also the fact that the most depleted (DB 48) has also the lowest Ba and highest Zr abundances of all rocks, as both anorthoclase and sanidine deplete residual liquids in Sr and Ba (Berlin and Henderson, 1969). The MnO/MgO evolution may involve the crystallization of aegerine which is present in all three samples.

What is argued here is not that DB 12, DD 2 and DB 48 are comagmatic, but that DD 2 and DB 48 have separately evolved from liquids with similar Rb/Sr, Ca/Sr, MnO/MgO and initial $^{87}Sr/^{86}Sr$ ratios to DB 12, by differing amounts of the *same* fractionation process. The possible parental character of DB 12 is of some interest in view of the fact that it and the duplicate sample DB 13 come from the oldest plug found in this work, giving K-Ar ages of 22.8 ± 0.6 and 21.4 ± 0.5 m.y. respectively. The shortest possible time span required to evolve the initial $^{87}Sr/^{86}Sr$ ratios of DD 2 (0.7040) and DB 48 (0.7063) from that of DB 12 (0.7026) is 6 m.y., on the assumption that complete fractionation occurred almost instantaneously relative to the time magnitude under consideration. Given this constraint the DD 2 and DB 48 magmas would be available for eruption some 16 m.y. ago. The K-Ar ages of DD 2 (14.4 ± 0.4 m.y.) and DB 48 (11.2 ± 0.2 m.y.), however, suggest that this constraint is unrealistic, and that fractionation operated over a perceptable period of time (longest for DB 48, the most highly fractionated plug), during which the Rb/Sr, Ca/Sr, MnO/MgO and $^{87}Sr/^{86}Sr$ ratios evolved to their final values.

This interpretation, therefore, recognizes three independent phases to the Cenozoic-Recent igneous activity of the Benue valley and Jos Plateau area. The earliest consists of alkaline melts which were partly intruded about 22 m.y. ago (phonolite DB 12–13), and partly modified by potassium feldspar crystal fractionation and intruded at 14.4 (trachyte DD 2) and 11.2 m.y. (phonolite DB 48). The second phase is marked by the intrusion of trachytes (DB 17, DB 51–52) and the Sr-rich phonolites (DB 60, DB 61) close to 12 m.y. ago. The third by the extrusion of widespread alkali olivine basalts and olivine basanites from 7 m.y. down to very recent times. The upper mantle sources for all of these rocks is characterized by $^{87}Sr/^{86}Sr$ ratios between 0.7025 and 0.7032, although values up to 0.7040 are possible, and others up to 0.7129 cannot be ruled out.

b) Cameroun Volcanic Line

The strongly linear character of the Cameroun volcanic line is best developed in southern Cameroun, and in the offshore islands which continue as the Guinea seamount chain in the direction of the island of St. Helena. To the northeast the linear character is harder to recognize. The contemporaneous volcanism of the Tibesti is often cited as a continuation of the line, but igneous rocks of this age are of widespread occurrence, and may be more related to local basement uplifts (Black and Girod, 1970).

The line cannot be accounted for in terms of a lithosphere plate moving over a sub-lithosphere magma source, because its igneous activity has not developed in episodic and sequential fashion along the line.

The suggestion that the line is a new ridge-rift feature marking incipient lithosphere separation (Burke *et al.*, 1971) is harder to assess. It is difficult to understand, for instance, why such a feature should form on the southeastern flank of the Benue trough, rather than follow the pre-existing line of weakness of the trough itself. It may be noted, however, that the low initial $^{87}Sr/^{86}Sr$ ratios of the Benue trough rocks are comparable with those in oceanic tholeiites from spreading ridges (Peterman and Hedge, 1971). Although none of the Nigerian rocks are tholeiites, the presence of phonolite and basalt lavas under the Cretaceous salt of the Cuanza basin of Angola (Brognon and Verrier, 1966), shows that alkalic igneous rocks can occur during the very early stages of continental separation, and then be buried under the continental margin sediments.

Attention might also be directed to the subvolcanic Younger Granites of Nigeria and the Air, which extend northwards the general north-south trend of the western continental margin of equatorial Africa (*see* Black and Girod, 1970, Fig. 3), and which Black and Girod (1970) relate to mantle and heat flow events leading to the separation of Africa and South America. If this supposition is correct, could it be asked if the similar Cenozoic granites along the Cameroun volcanic line might fore-shadow incipient continental separation along the line?

Although the volcanic activity in northeastern Nigeria is probably related to the Cameroun volcanic line, the concentration of intrusive plugs in the Benue trough suggests that the trough has localized a notable amount of this igneous activity. It is perhaps, therefore, of interest to consider the tectonic and igneous events elsewhere in the African lithosphere plate, which appear to be synchronous with the Miocene and younger volcanism which was locally centered on the trough. We note the Miocene changes in the height of the Mid-Atlantic ridge and the South Atlantic spreading rates (Maxwell *et al.*, 1970), the early Miocene appearance of the Red Sea graben and the start to the generation of oceanic crust in the Gulf of Aden (Laughton, 1966; Girdler, 1969), and the early Miocene to Recent history of the East African rift system (King, 1970). Insofar as the rigid African lithosphere plate may have served to provide a mechanical linkage between these diverse phenomena, it may be possible to consider the Benue trough igneous activity as reflecting internal adjustments along old lines of weakness within the plate, in response to changes affecting the plate's external dimensions and internal structure.

Acknowledgements. Thanks are due to Dr. M. H. Dodson and Professor J. L. Powell who commented on the manuscript.

Appendix I

Localities of analysed samples

Sample no.	Locality
Benue Valley	
DD 2	Plug. Wase rock (9°04′30″N, 9°57′40″E).
DB 12	Plug 4.4 miles west of Bambam, on the northern side of the Gombe-Biu road (9°42′12″N, 11°28′24″E).
DB 13	Same locality as DB 12.
DB 17	Plug 1.9 miles east of Filiya on the northern side of the Filiya-Dadiya track (9°35′42″N, 11°08′13″E).
DB 48	Large plug 0.6 miles south of Chongwom (9°46′40″N, 11°14′55″E).
DB 51	Plug 1.5 miles south-west of Chongwom, the sample was taken from the outer part of the plug (9°46′45″N, 11°14′05″E).
DB 52	Same locality as DB 51, sample taken from inner part of the plug.
DB 60	Southern end of large plug 1.4 miles N 250°E of Labore Peak (9°48′00″N, 11°10′00″E).
DJ 1	Plug near mile post 24 on the Numan-Yola road, 5.5 miles northwest of Ngurore (9°22′N, 12°11′E).
DJ 2	Plug. Ngurore North (9°18.5′N, 12°14′E).
DB 1	Lava flow near Dadin Kowa, 21 miles east of Gombe on the Gombe-Biu road (10°16.5′N, 11°28.5′E).
DB 10	Plug. Biliri Hill 2 miles south of Biliri village (9°50′10″N, 11°13′05″E).
DB 43	Hill 1.8 miles N 130°E of Biliri (9°50′45″N, 11°14′35″E).
DB 58	Plug. 0.8 miles west of Biliri Hill (9°50′22″N, 11°12′24″E).
DB 64	Volcanic cone 0.6 miles north-west of Kalmai, on the Biliri-Filiya road (9°52′30″N, 11°11′45″E).

Biu Plateau

For the Biu Plateau all localities are given relative to the old road which ran south from Damaturu, through Biu and on to Little Gombi. The new road, construction date 1971/72, follows much the same line as the old road except for the Biu-Shani section which follows a much shorter route. All distances given in miles are based on car odometer readings along the old road.

Sample no.	Locality
DF 1	Lava flow, bed of the Hawal River on the Biu-Garkida road (10°23′32″N, 12°32′26″E).
DF 8	Top lava flow on the northern side of Tilla lake caldera (10°33′00″N, 12°07′55″E).
DB 29	Lava flow at the northern edge of the Biu Plateau, 35.6 miles north of Biu Rest House on the old Biu-Damaturu road (11°04′N, 12°03′E).
DB 34	Lava flow near Kuvai, 17.2 miles south of Biu Rest House on the road to Shani and 1.8 miles north of the southern edge of the Biu Plateau (10°25′30″N, 12°09′30″E).
15 BI	Lava flow underlying Biu town, sampled east of the Yola road immediately south of Rest House (10°35′40″N, 12°11′30″E).
Jos Plateau	
DE 1	Volcanic cone, Kass Hill (9°36′N, 8°53.5′E).
DE 2	Volcanic cone behind Vom Rest House (9°44′N, 8°47′E).
DE 10	Lava flow 2.4 km east of Bassa on the Buka Bokwai-Bassa road (9°56′05″N, 8°45′45″E).

References

Berlin, R., Henderson, C. M. B.: The distribution of Sr and Ba between alkali feldspar, plagioclase and groundmass phases of porphyritic trachytes and phonolites. Geochim. Cosmochim. Acta **33**, 247–255 (1969).

Black, R., Girod, M.: Late Palaeozoic to Recent igneous activity in West Africa and its relationship to basement structure. In: African magmatism and tectonics, Clifford, T.N. and Gass, I. G., eds., p. 185–210. Edinburgh: Oliver & Boyd 1970.

Brognon, G. P., Verrier, G. R.: Oil and geology in Cuanza basin of Angola. Bull. Am. Ass. Petrol. Geologists **50**, 108–150 (1966).

Burke, K., Dessauvagie, T. F. J., Whiteman, A. J.: Opening of the Gulf of Guinea and geological history of the Benue depression and the Niger delta. Nature Physical Science **233**, 51–55 (1971).

Carter, J. D., Barber, W., Tait, E. A.: The geology of parts of Adamawa, Bauchi and Bornu Provinces in northeastern Nigeria. Bull. Geol. Surv. Nigeria, No. 30 (1963).

Cratchley, C. R., Jones, G. P.: An interpretation of the geology and gravity anomalies of the Benue valley, Nigeria. Overseas Geol. Surv., Geophys. Paper No. 1 (1965).

Dawson, J. B.: The structural setting of African kimberlite magmatism. In: African magmatism and tectonics, Clifford, T. N. and Gass, I. G., eds., p. 321–335. Edinburgh: Oliver & Boyd 1970.

de Swardt, A. M. J.: The 1954 eruption of Cameroun Mountain. Records Geol. Surv. Nigeria, No. 1, 35–40 (1956).

Doe, B. R., Lipman, P. W., Hedge, C. E., Kurasawa, H.: Primitive and contaminated basalts from the southern Rocky Mountains, U.S.A. Contr. Mineral. and Petrol. **21**, 142–156 (1969).

Falconer, J. D.: The geology and geography of northern Nigeria. London: Macmillan & Co. Ltd. 1911.

Farrington, J. L.: A preliminary description of the Nigerian lead-zinc field. Econ. Geol. **47**, 583–608 (1952).

Fisher, D. E.: Excess rare gases in a subaerial basalt from Nigeria. Nature Physical Science **232**, 60–61 (1971).

Gèze, B.: Géographie physique et géologie du Cameroun occidental. Mem. Mus. Natn. Hist. Nat. Paris, No. **17**, 1–272 (1943).

Girdler, R. W.: The Red Sea—a geophysical background. In: Hot brines and recent heavy metal deposits in the Red Sea, Degens, E.T. and Ross, D.A., eds., p. 38–58. Berlin-Heidelberg-New York: Springer 1969.

Grant, N. K.: The South Atlantic, Benue trough and Gulf of Guinea Cretaceous triple junction. Bull. Geol. Soc. Am. **82**, 2295–2298 (1971).

Hamza, V. M., Verma, R. K.: The relationship of heat flow with age of basement rocks. Bull. Volcanol. **33**, 123–152 (1969).

Hedberg, J. D.: A geological analysis of the Cameroun trend. Ph. D. Thesis, Princetown University, 1968.

Kennedy, W. O.: The influence of basement structure on the evolution of the coastal (Mesozoic and Tertiary) basins of Africa. In: Salt basins around Africa, Institute of Petroleum, London, p. 7–16. Amsterdam: Elsevier Publ. Co. 1965.

King, B. C.: Vulcanicity and rift tectonics in East Africa. In: African magmatism and tectonics, Clifford, T. N. and Gass, I. G., eds., p. 263–283. Edinburgh: Oliver & Boyd 1970.

King, L.: Speculations upon the outline and mode of disruption of Gondwanaland. Geol. Mag. **87**, 353–359 (1950).

Lasserre, M.: Données géochronologiques nouvelles aquises au ler Janvier 1967 par la methode au strontium appliquée au formations cristallines et crystallophylliennes du Cameroun. Ann. Fac. Sci., Univ. Clermont, No. 36, Géol. Min., fasc. **16**, 109–144 (1967).

Laughton, A. S.: The Gulf of Aden, in relation to the Red Sea and the Afar depression of Ethiopia. Geol. Surv. Canada Paper 66–14, 78–97 (1966).

Mackay, R. A., Greenwood, R., Rockingham, J. E.: The geology the plateau tinfields—resurvey 1945–1948. Bull. Geol. Surv. Nigeria, No. **19** (1949).

Maxwell, A. E., Herzen, R. P. von, Hsu, K. J., Andrews, J. E., Saito, T., Percival, S. F., Jr., Milow, E. D., Boyce, R. E.: Deep sea drilling in the South Atlantic. Science **168**, 1047–1059 (1970).

McBirney, A. R., Gass, I. G.: Relations of oceanic volcanic rocks to midoceanic rises and heat flow. Earth Planet. Sci. Lett. **2**, 265–276 (1967).

McConnell, R. B.: Fundamental fault zones in the Guinea and West African shields in relation to presumed axes of Atlantic spreading. Bull. Geol. Soc. Am. **80**, 1775–1782 (1969).

McKenzie, D. P., Morgan, W. J.: Evolution of triple junctions. Nature **224**, 125–133 (1969).

Peterman, Z. E., Hedge, C. E.: Related strontium isotopic and chemical variations in oceanic basalts. Bull. Geol. Soc. Am. **82**, 493–500 (1971).

Piper, J. D. A.: Palaeomagnetic study of the Guinea volcanic chain, West Africa. 14th Ann. Rept. Res. Inst. Afr. Geol., Univ. Leeds 49–52 (1970).

Rex, D. C., Dodson, M. H.: Improved resolution and precision of argon analysis using an MS10 mass spectrometer. Eclogae Geol. Helv. **63**, 275–280 (1970).

Snelling, N. J.: Age determination unit. Ann. Rept. Institute Geological Sciences for 1964, **35** (1965).

Stonely, R.: The Niger delta region in the light of the theory of continental drift. Geol. Mag. **103**, 385–397 (1966).

Upton, B. G. J., Wadsworth, W. J., Newman, T. C.: The petrology of Rodriguez Island, Indian Ocean. Bull. Geol. Soc. Am. **78**, 1495–1506 (1967).

Wright, J. B.: South Atlantic continental drift and the Benue trough. Tectonophysics **6**, 301–310 (1968a).

Wright, J. B.: Oligoclase-andesine phenocrysts and related inclusions in basalts from part of the Nigerian Cenozoic province. Mineral. Mag. **36**, 1024–1031 (1968b).

Wright, J. B.: Olivine nodules and related inclusions in trachyte from the Jos Plateau, Nigeria. Mineral. Mag. **37**, 370–374 (1969).

Wright, J. B.: The phonolite-trachyte spectrum. Lithos **4**, 1–5 (1970).

Wright, J. B., McCurry, P.: Composite phonolite tholoids in the Cenozoic volcanic province of Nigeria. Geol. Mag. **107**, 357–360 (1970).

Wright, J. B.: K/Ar data and the origin of feldspar megacrysts in alkali basalt. Nature Physical Science **236**, 89 (1972).

Note Added in Proof. Wright (1972) has incorrectly attributed to our study the conclusion that the plagioclase megacrysts and the excess ^{40}Ar in the Dadin Kowa basalt are of crustal origin, and has attempted to argue that Fisher's (1971) data showing the K-Ar age concordance of 95 m.y. between the megacrysts and the host basalt favours a cognate rather than a xenocrystic origin for the megacrysts. His argument is inconclusive for the following reasons.

The concordance, which reflects similar ^{40}K/^{40}Ar ratios in both megacryst and host basalt, is significant *only* in relation to a specific mechanism relating ^{40}K to ^{40}Ar abundances. Because Fisher's (1971) work shows that the bulk of the ^{40}Ar in the Dadin Kowa basalt is excess argon, it follows that the apparent K-Ar age of this rock is geologically unreal (Wright, 1972). Therefore, by common consent, the mechanism of radioactive decay cannot be used to interpret the similar ^{40}K/^{40}Ar ratios in the megacrysts and host basalt. Until some specific mechanism is proposed to account for the partitioning of excess ^{40}Ar between megacrysts and host basalt in proportion to their K contents, it follows that no significance can be attached at present to the similar ^{40}K/^{40}Ar ratios in both the basalt and the megacrysts.

This conclusion must hold irrespective of whether the megacrysts are cognate phases or xenocrysts. Wright (1972) argued that the megacrysts are cognate phases, since there is no known mechanism which would partition excess ^{40}Ar derived from megacrysts of crustal origin between the megacrysts and host basalt in proportion to their K contents, and ignored the fact that the same difficulty applies to the similar partitioning of upper mantled derived excess ^{40}Ar between cognate megacrysts and basalt. Therefore, for as long as the bulk of the ^{40}Ar in the Dadin Kowa basalt is regarded as excess argon, Fisher's (1971) intriguing data remains without significance until it can be related to a mechanism partitioning ^{40}Ar between the megacrysts and the host basalt.

Dr. N. K. Grant Department of Geology, Oberlin College, Oberlin, Ohio 44074, U.S.A.