*Chemical Geology*, 31 (1981) 271—283
Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

# RARE-EARTH ELEMENT GEOCHEMISTRY OF THE MERUOCA AND MUCAMBO PLUTONS, CEARÁ, NORTHEAST BRAZIL

ALCIDES N. SIAL[1], MARIO C.H. FIGUEIREDO[2,*] and LEON E. LONG

[1] *Department of Geology, Federal University of Pernambuco, Recife, PE (Brazil)*
[2] *Department of Geology, University of Western Ontario, London, Ont. N6A 5B7 (Canada)*
[3] *Department of Geological Sciences, University of Texas, Austin, TX 78712 (U.S.A.)*

(Received July 21, 1980; accepted for publication October 20, 1980)

## ABSTRACT

Sial, A.N., Figueiredo, M.C.H. and Long, L.E., 1981. Rare-earth element geochemistry of the Meruoca and Mucambo plutons, Ceará, northeast Brazil. Chem. Geol., 31: 271—283.

The Cambrian Meruoca and Mucambo plutons in Ceará, northeastern Brazil, are high-level crosscutting anorogenic intrusions with well-developed aureoles. The Meruoca pluton is predominantly alkalic to peralkalic granite, fayalite-bearing in part. Mucambo is comprised of porphyritic granite, quartz monzonite, quartz syenite and granite. A Rb—Sr whole-rock isochron age for Mucambo is close to 550 m.y.; the Meruoca pluton may be of similar age, but its Rb—Sr system has been disturbed by a prolonged, late hydrothermal event.

Rare earth element (REE) abundances were determined on 5 whole-rock samples from each intrusion. All the REE fractionation patterns are similar, exhibiting smooth-trending enrichments of light REE and a prominent negative Eu anomaly. Concentrations of total REE are very much higher than for most granites, the enrichment of the lightest rare earths being as much as 1500 times that in chondrites. The field and laboratory data suggest that the Meruoca and Mucambo magmas originated by partial fusion of heterogeneous continental crust whose REE were already enriched and fractionated. Plagioclase was fractionated out of the melt prior to its final emplacement. Other granites in northeastern Brazil have similar REE patterns.

## INTRODUCTION

The origin of granitic magmas has been a controversial subject for many years. Recently the problem has been clarified by experimental studies of phase chemistry and of partitioning of trace elements during fractional crystallization or partial fusion. Granitic magma has been postulated to form: (a) by partial fusion of oceanic crust or upper mantle in a subduction zone inclined beneath a continental margin (Dickinson, 1968, 1970; Hamilton, 1969); (b) by partial melting of oceanic sediments dragged down into a subduction zone (Gilluly, 1971; Huang and Wyllie, 1973); (c) by partial fusion of crustal

---

[*] *On leave from*: Institute of Geosciences, Federal University of Bahia, Salvador, BA, Brazil.

rocks (Eskola, 1932; Brown and Fyfe, 1970; Brown, 1973; Stern et al., 1975); and (d) by fractional crystallization of basic magma (Bowen, 1928). During recent years, a popular approach to the problem has been through interpretation of the abundances of the rare earth elements (REE) (e.g., Taylor et al., 1968; Aleksiyev, 1970; Nagasawa and Schnetzler, 1971; Barker et al., 1976; Condie and Hunter, 1976; Glikson, 1976; de Albuquerque, 1977, 1978; Frey et al., 1978; Hanson, 1978). This study makes similar use of the REE data to interpret the origin of the Cambrian Meruoca and Mucambo granitic plutons, in Ceará, northeastern Brazil.

## GEOLOGIC SETTING, PETROGRAPHY

Many "granites" are present in the northeastern corner of Brazil, but for only a few of them do field relationships point indisputably to an igneous origin. Among these are the post-kinematic Meruoca and Mucambo plutons, 240 km west of Fortaleza (Fig. 1). Both plutons are truncated on the east by the prominent Cafe—Ipueiras fault system that continues northeastward to the Atlantic coast. The fault and its associated sedimentary—volcanic trough are probably the Brazilian counterpart to a similar system in eastern Ghana, in Africa.

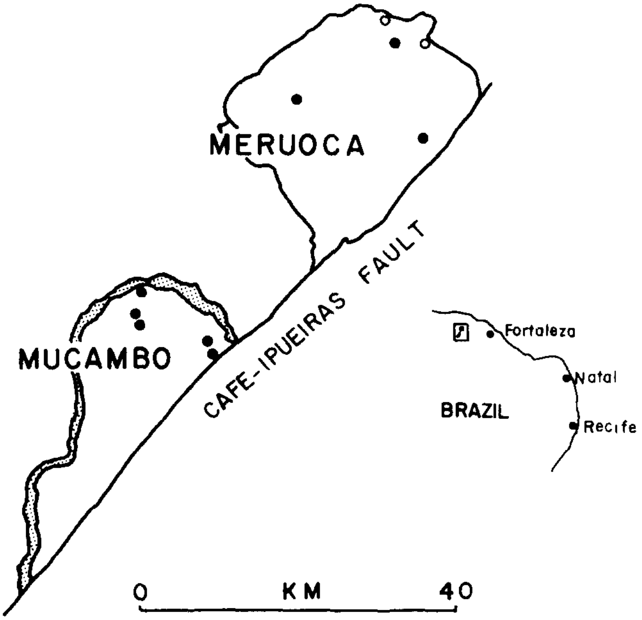

Fig. 1. Index location map and map of Meruoca and Mucambo plutons. *Stipple pattern*: thermal aureole adjacent to Mucambo. *Open circles* : sample locations of Meruoca fayalite-bearing granite samples (R-*240* and R-*229*); *filled circles* : locations of fayalite-free samples from Meruoca and Mucambo.

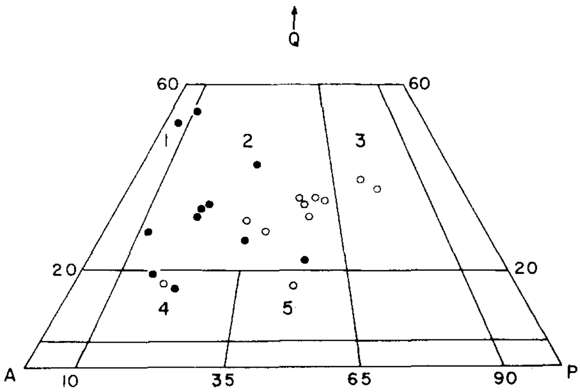

Fig. 2. Modal proportions of quartz (Q)—alkali feldspar (A)—plagioclase (P) of silica-oversaturated rocks from the Meruoca pluton (*filled circles*) and Mucambo pluton (*open circles*). Included are samples listed in Tables I and II, and unpublished data (A.N. Sial and L.E. Long, 1979). Fields designated by I.U.G.S. classification (Streckeisen et al., 1973) are: *1* = alkali-feldspar granite; *2* = granite; *3* = granodiorite; *4* = quartz syenite; and *5* = quartz monzonite.

Meruoca, the northernmost of the two intrusions, stands as a high massif barely exhumed by erosion and with patches of granite-roof facies still preserved. It is comprised of alkalic to peralkalic, coarse- to fine-grained granitic rocks occupying an area of ~ 400 km$^2$. Most of the pluton is a gray, to pink, to brick-red, fayalite-free unit; a gray, green, or brown fayalite-bearing unit is restricted to its northern part. According to the I.U.G.S. classification (Streckeisen et al., 1973) both of these rock units are predominantly granites, quartz syenites, and alkali-feldspar granites (Fig. 2). The fayalite-free rocks, whose grain size varies from pegmatitic to very fine, contain abundant graphic and granophyric intergrowths and drusy miarolitic cavities. These textures are much less common in the fayalite-bearing rocks which are slightly porphyritic with average grain size of feldspar phenocrysts around 2 cm. The contact between the two rock units is gradational and indeed, where they are weathered they cannot be distinguished in hand-specimen. Large areas characterized by turbid brick-red feldspar indicate that the Meruoca pluton was a high-level intrusion that experienced pervasive, late hydrothermal alteration.

The southern, Mucambo pluton, exposed over an area of ~ 180 km$^2$, is comprised of porphyritic granodiorite to quartz monzonite, to quartz syenite and hornblende—biotite granite. Feldspar phenocrysts as long as 2 cm are common, and exceptionally they are as long as 10 cm. Textures are similar to those at Meruoca except that at Mucambo the occurrence of granophyric intergrowths and of miarolitic cavities is much less common. This, and the general absence of brick-red feldspar, suggest that at Mucambo the $H_2O$ was tied to hydrous minerals (amphibole and biotite) since the early stages of crystallization.

In both plutons, crystallization of the magma began with zircon, apatite and fayalite, magnetite and ilmenite where the latter minerals are present. Then followed plagioclase, alkali feldspar, quartz, ferrohastingsite and biotite (annite), and where present, the accessory minerals sphene, tourmaline, fluorite and allanite.

Autoliths of variable size and composition are abundant in the Mucambo pluton. Mineralogically they are similar to the enclosing igneous rocks except that some of them are much more mafic (quartz diorite) with plagioclase, green to brown hornblende, red to brown biotite, Fe-oxide minerals, and apatite, with or without quartz. Their rounded shapes and the presence of accumulations of fine-grained mafic minerals along their boundaries are evidence that the autoliths have reacted with the magma.

The metasedimentary rock (Ubajara Group) that is host to both plutons is only weakly metamorphosed and was deposited probably ~ $10^9$ years ago. It lies nonconformably upon deeper basement consisting of gneisses and migmatites. Emplaced into the host rock are numerous ENE-trending diorite to rhyolite dikes which in turn are crosscut by the Meruoca granite. Disc-shaped xenoliths, abundant especially in the Mucambo pluton, include fragments from the deeper basement, baked limestone and dark sandstone of the Ubajara Group, and felsic igneous rocks.

Where not bounded by faults, both plutons cut the host rock discordantly and have well-developed contact aureoles whose mineralogy indicates shallow emplacement. Adjacent to the Mucambo pluton the aureole is of albite—epidote, hornblende, or pyroxene hornfels facies. In the northwest corner of the Meruoca pluton are found xenoliths of hornfels composed of plagioclase, quartz, biotite, hornblende, apatite and Fe-oxide minerals, and skarn-containing diopside, quartz, epidote, and plagioclase in a granoblastic texture.

## Rb—Sr GEOCHRONOLOGY

Whole-rock Rb—Sr isochrons were determined separately for the Meruoca and Mucambo plutons (A.N. Sial and L.E. Long, unpublished data, 1979). An isochron based upon six data points for the Mucambo pluton indicates an age of 548 ± 24 m.y. ($2\sigma$ error), with initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = 0.7107 \pm 0.0011$ ($2\sigma$). For Meruoca the indicated age is 507 ± 36 m.y. ($2\sigma$) and initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = 0.7071 \pm 0.0015$ ($2\sigma$), based upon fourteen data points. But, as already mentioned, the Meruoca pluton has experienced a prolonged, low-temperature interaction with meteoric water as indicated by the presence of brick-red feldspar and a remarkable bull's-eye pattern centered upon the pluton, wherein $\delta^{18}O$ of feldspar becomes systematically higher toward the interior (A.N. Sial and L.E. Long, unpublished data, 1979). This profound change has disturbed the Rb—Sr system, as evidenced by a scatter of data on the isochron diagram far in excess of scatter due to analytical error. We suggest that both plutons were emplaced ~ 550 m.y. ago but that at Meruoca the superimposed low-temperature event caused partial loss of Sr, rotating the isochron clockwis

TABLE I

Whole-rock rare earth data

| | Meruoca | | | | |
|---|---|---|---|---|---|
| | R-*240* | R-*229* | R-*14* | R-*210* | R-*70* |
| La (ppm) | 330 | 248 | 274 | 198 | 153 |
| Ce | 693 | 519 | 557 | 402 | 305 |
| Nd | 324 | 248 | 249 | 181 | 129 |
| Sm | 59.9 | 48.6 | 50.5 | 36.0 | 29.2 |
| Eu | 6.16 | 5.68 | 4.37 | 4.53 | 1.63 |
| Gd | 50.4 | 42.8 | 42.5 | 31.8 | 28.9 |
| Dy | 40.7 | 34.7 | 29.3 | 28.0 | 30.8 |
| Er | 18.5 | 17.9 | 12.3 | 14.4 | 18.7 |
| Yb | 13.5 | 13.6 | 9.25 | 13.1 | 17.9 |
| [a]Others | 97.8 | 76.7 | 76.7 | 59.2 | 49.9 |
| Σ REE | 1,634 | 1,255 | 1,305 | 968 | 764 |
| [b]$La_N/Sm_N$ | 3.4 | 3.1 | 3.4 | 3.3 | 3.2 |
| [b]$Ce_N/Yb_N$ | 13.1 | 9.8 | 14.4 | 7.8 | 4.4 |
| $Eu/Eu^*$ | 0.35 | 0.39 | 0.29 | 0.41 | 0.17 |

| | Mucambo | | | | |
|---|---|---|---|---|---|
| | MC-*70* | MC-*9* | MC-*134* | MC-*54* | MC-*45* |
| La (ppm) | 493 | 263 | 186 | 166 | 196 |
| Ce | 950 | 484 | 404 | 362 | 388 |
| Nd | 431 | 207 | 191 | 172 | 159 |
| Sm | 84.8 | 38.0 | 37.6 | 35.0 | 29.8 |
| Eu | 4.03 | 4.74 | 5.62 | 4.78 | 2.08 |
| Gd | 78.1 | 33.4 | 32.9 | 31.7 | 24.5 |
| Dy | 67.1 | 26.9 | 27.4 | 27.2 | 17.9 |
| Er | 33.1 | 13.3 | 14.1 | 15.6 | 8.82 |
| Yb | 25.3 | 10.6 | 10.8 | 13.9 | 8.77 |
| [a]Others | 136.6 | 65.1 | 59.6 | 55.8 | 51.1 |
| Σ REE | 2,303 | 1,146 | 969 | 884 | 886 |
| [b]$La_N/Sm_N$ | 3.5 | 4.2 | 3.0 | 2.9 | 4.0 |
| [b]$Ce_N/Yb_N$ | 9.6 | 11.7 | 9.6 | 6.7 | 11.3 |
| $Eu/Eu^*$ | 0.16 | 0.41 | 0.50 | 0.44 | 0.24 |

[a] = Pr + Tb + Ho + Tm + Lu, whose abundances were estimated.
[b] = chondrite-normalized La/Sm and Ce/Yb ratios.

*Sample locations:*
*Meruoca:* R-*240* = fayalite granite, 11 km W of Massape, on road to Padre Linhares; R-*229* = fayalite granite, ~ 6 km W of Massape; R-*14* = biotite granite, ~8 km NW of Sobral, on road to Meruoca; R-*210* = hornblende—biotite granite, 4 km W of Meruoca, on road to São Gonçalo and Riacho da Raiz; and R-*70* = biotite—hornblende granite, 10 km SW of Meruoca on road to Sobral and Alcantaras.

*Mucambo:* MC-*70* = hornblende—biotite granodiorite, summit of Serra do Carnutim; MC-*9* = hornblende quartz monzonite, 13 km NE of Mucambo; MC-*134* = biotite—hornblende granodiorite, 2.3 km W of junction on road from Mucambo to Ararius; MC-*54* = biotite—hornblende granite, Serra do Carnutim, road between Recreio and Lajeiro; and MC-*45* = biotite granite, 14 km N of Mucambo on road between Ibauna and Recreio.

TABLE II

Chemical compositions of whole rocks

| | Meruoca | | | | | Mucambo | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | R-*240* | R-*229* | R-*14* | R-*210* | R-*70* | MC-*70* | MC-*9* | MC-*134* | MC-*54* | MC-*45* |
| *Chemical analysis:* | | | | | | | | | | |
| $SiO_2$ | 69.60 | 70.50 | 76.87 | 71.72 | 75.33 | 65.60 | 70.00 | 69.07 | 68.20 | 71.67 |
| $TiO_2$ | 0.58 | 0.45 | 0.25 | n.d. | 0.11 | 1.18 | 1.86 | 0.42 | 0.67 | 0.47 |
| $Al_2O_3$ | 13.82 | 13.00 | 11.28 | 14.90 | 11.08 | 11.77 | 11.50 | 13.42 | 13.81 | 13.18 |
| $Fe_2O_3$ | 1.50 | 1.25 | 1.37 | 0.34 | 1.33 | 2.83 | 2.40 | 2.00 | 1.52 | 1.23 |
| FeO | 2.43 | 2.50 | 1.19 | 1.85 | 0.60 | 6.25 | 1.40 | 2.87 | 3.66 | 2.66 |
| MnO | 0.06 | 0.10 | 0.04 | 0.05 | 0.02 | 0.10 | 0.10 | 0.08 | 0.06 | 0.04 |
| MgO | 0.01 | 0.06 | 0.11 | 0.07 | 0.08 | 1.16 | 1.00 | 0.53 | 0.58 | 0.35 |
| CaO | 1.54 | 1.15 | 0.43 | 1.54 | 0.63 | 2.73 | 4.50 | 2.38 | 2.31 | 1.54 |
| $Na_2O$ | 3.60 | 4.00 | 2.66 | 4.44 | 2.79 | 2.83 | 5.00 | 3.30 | 3.10 | 2.83 |
| $K_2O$ | 5.50 | 5.50 | 5.16 | 5.24 | 4.76 | 3.91 | 1.00 | 4.34 | 5.02 | 5.14 |
| $P_2O_5$ | n.d. | n.d. | 0.05 | n.d. | 0.05 | n.d. | n.d. | n.d. | n.d. | n.d. |
| $CO_2$ | 0.00 | 0.00 | n.d. | 0.00 | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| $H_2O^+$ | 0.90 | 0.40 | 1.10 | 0.25 | 0.60 | 0.11 | 0.10 | 0.16 | 0.08 | 0.05 |
| $H_2O^-$ | 0.31 | 0.30 | 0.36 | 0.40 | 0.40 | 0.98 | 0.80 | 1.32 | 0.87 | 0.31 |
| | 99.85 | 99.21 | 100.87 | 100.80 | 97.78 | 99.45 | 99.66 | 99.90 | 99.88 | 99.47 |
| *C.I.P.W. norm:* | | | | | | | | | | |
| $q^2$ | 23.72 | 23.22 | 40.30 | 21.49 | 39.07 | 24.46 | 29.48 | 26.57 | 23.64 | 30.27 |
| *c* | 0.00 | 0.00 | 0.59 | 0.00 | 0.27 | 0.00 | 0.00 | 0.00 | 0.00 | 0.16 |
| *or* | 32.50 | 32.50 | 30.49 | 30.96 | 28.12 | 23.10 | 5.91 | 25.64 | 29.66 | 30.37 |
| *ab* | 30.46 | 33.85 | 22.51 | 37.57 | 23.61 | 23.95 | 42.31 | 27.92 | 26.23 | 23.95 |
| *an* | 5.31 | 1.28 | 2.01 | 5.25 | 2.91 | 7.87 | 5.98 | 8.99 | 8.94 | 7.64 |
| *di* | 2.07 | 3.92 | 0.00 | 2.11 | 0.00 | 4.87 | 5.37 | 2.44 | 2.20 | 0.00 |
| *hy* | 1.30 | 1.08 | 0.99 | 2.27 | 1.16 | 7.78 | 0.00 | 3.15 | 4.78 | 4.04 |
| *mt* | 2.17 | 1.81 | 1.99 | 0.49 | 1.68 | 4.10 | 0.00 | 2.90 | 2.20 | 1.78 |
| *il* | 1.10 | 0.85 | 0.47 | 0.00 | 0.21 | 2.24 | 3.17 | 0.80 | 1.27 | 0.89 |
| others | 0.00 | 0.00 | 0.12 | 0.00 | 0.29 | 0.00 | 6.53 | 0.00 | 0.00 | 0.00 |
| K (%) | 4.57 | 4.57 | 4.28 | 4.35 | 3.95 | 3.25 | 0.83 | 3.60 | 4.17 | 4.27 |
| Rb (ppm) | 137 | 145 | 161 | — | 228 | 219 | — | 139 | 211 | — |
| Sr (ppm) | 71 | 40 | 2 | — | 2 | 109 | — | 211 | 155 | — |
| Ba (ppm) | — | — | 953 | — | 566 | — | — | — | — | — |
| K/Rb | 332 | 316 | 268 | — | 173 | 148 | — | 258 | 198 | — |
| Rb/Sr | 1.94 | 3.58 | 80.5 | — | 114 | 2.02 | — | 0.66 | 1.36 | — |
| K/Ba | — | — | 45 | — | 70 | — | — | — | — | — |
| Sr/Ba | — | — | 0.002 | — | 0.003 | — | — | — | — | — |

For sample locations see note to Table I.

and lowering the apparent age. Limited data suggest that, in contrast, REE patterns are quite immune to change by disturbing processes short of actual remelting of the rock. This is one further reason why a study of REE in these two plutons appeared attractive.

## ANALYTICAL METHODS

The REE contents of five samples from each pluton (Table I) were analyzed by a modified version (Fryer, 1977) of the thin-film X-ray fluorescence procedure of Eby (1972) at the Department of Geology, Memorial University of Newfoundland by one of the authors (M.C.H.F.). REE were separated as a group by ion-exchange chromatography, and transferred onto Reeve Angel® SA-*2* ion-exchange papers previously cut to fit the sample holders. Prior to separation, 50 μg of Tm was added as an internal yield standard. All samples were analyzed on a Philips® PW *1450* X-ray fluorescence spectrometer with a silver tube. The analytical error is estimated to be less than ± 10% for all the elements tabulated. Results for Pr, Tb, Ho and Lu are not reported because of relatively large analytical errors, and Tm is not reported because of its use in correcting for chemical yield.

The chondritic values used for normalization are Leedey chondrite data (Masuda et al., 1973), divided by 1.20 (Sun and Hanson, 1976; Taylor and Gorton, 1977) to make these data comparable to average chondrite data.

Major-element concentrations (Table II) were determined for the same samples at the Chemical Laboratory of SUDENE at Recife, Brazil, and at the Department of Geochemistry of the University of Bahia, Brazil. At Recife, most major elements were analyzed by atomic absorption spectrophotometry, Na and K by flame photometry, and FeO and volatiles by traditional methods. In Bahia, all major elements were analyzed by atomic absorption spectrophotometry except for P and Ti which were analyzed by X-ray fluorescence. Trace elements such as Rb, Sr, Ba and Nb were analyzed by X-ray fluorescence, and a few Rb and Sr analyses were by isotope dilution at the University of Texas at Austin.

## RARE EARTHS

To a first approximation, the REE patterns (Table I, Figs. 3 and 4) are rather similar to one another. Both plutons are enriched in REE relative to chondritic abundances, and depleted in heavy REE (Gd—Yb) relative to light REE (La—Sm). All samples show a pronounced negative Eu anomaly which is indicated by the ratio Eu/Eu*, where Eu* refers to the normalized Eu abundance anticipated by smooth interpolation between the adjacent elements Sm

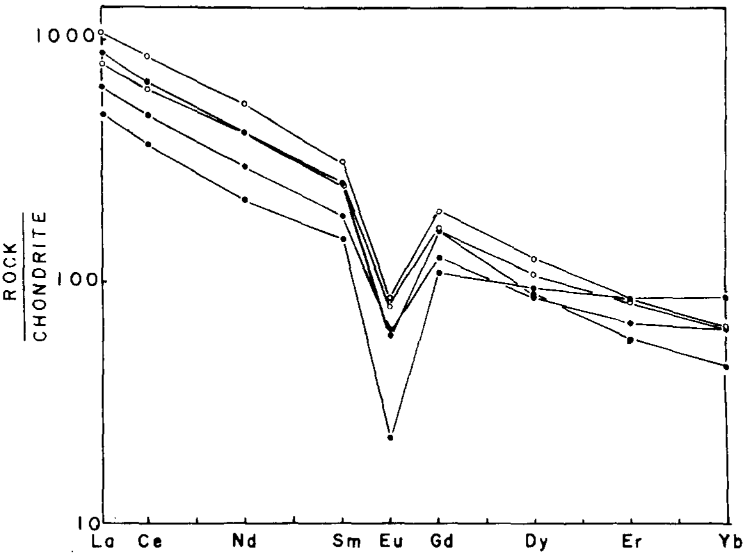

Fig. 3. Rare-earth element abundances in whole rocks from Meruoca, normalized to average chondritic abundances. *Open circles*: fayalite-bearing granite; *filled circles*: fayalite-free granite.

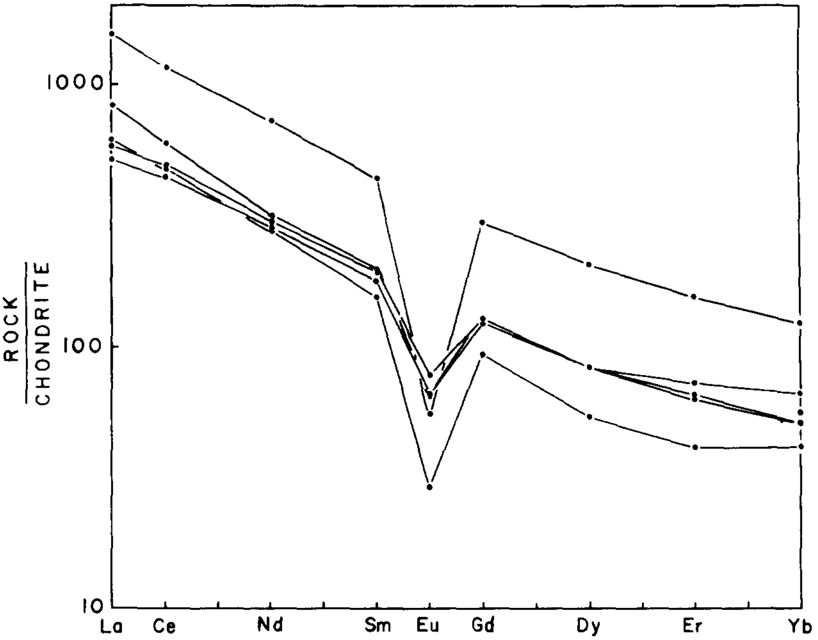

Fig. 4. Rare-earth element abundances in whole rocks from Mucambo, normalized to average chondritic abundances.

and Gd. Values of Eu/Eu* range between 0.17 and 0.41 in Meruoca, and between 0.16 and 0.50 in Mucambo.

Light-REE patterns in the five analyzed samples from Meruoca are remarkably parallel. The ratio $La_N/Sm_N$ varies only between 3.1 and 3.4, these values being indicative of light-REE fractionation. Heavy-REE patterns are less uniform, and for samples R-*70* and R-*210* they are nearly flat. The ratio $Ce_N/Yb_N$, which is a measure of the overall degree of REE fractionation, varies between 4.4 and 14.4. The fractionation is moderate (R-*229*, R-*210*, R-*70*) to strong (R-*240*, R-*14*).

$La_N/Sm_N$ ratios in the five Mucambo samples vary between 2.9 and 4.2, also indicating fractionated light REE but to somewhat different degrees. Heavy-REE patterns are almost parallel with $Ce_N/Yb_N$ ratios varying between 6.7 and 11.7.

Both plutons have abnormally high total REE abundances compared to those in granitic rocks in general (Ewart et al., 1968; Barker et al., 1976; Condie and Hunter, 1976; Glikson, 1976; de Albuquerque, 1977, 1978; Frey et al., 1978). In each pluton, the rocks containing a higher abundance of mafic minerals also contain a higher abundance of REE. These high total REE abundances, which range between 760 and 2300 ppm, the REE fractionation trends, and the negative Eu anomaly can be used to set limits on models of the origin of the rocks. Fractional melting or crystallization in the source region will influence REE abundances in the resultant magma. Although partition coefficients between minerals and melts of various chemical compositions are not yet well enough understood to justify quantitative modeling (Frey et al., 1978), we can discuss the data in the light of known general features of REE fractionation.

## DISCUSSION

The REE pattern in an igneous rock depends upon the characteristics of its source and upon subsequent differentiation, if any. During differentiation, the REE abundances may be so drastically changed as to obscure any information about the source. Differentiation and reaction melting [as the term is used by Barker et al. (1975)] have left the strongest imprint upon REE patterns at Meruoca and Mucambo. It is well known that garnet and hornblende (with only a moderately pronounced effect) preferentially scavenge heavy REE, and that plagioclase selectively incorporates Eu, especially where low oxygen fugacity has created a large $Eu^{2+}/Eu^{3+}$ ratio. Differentiation in which garnet or hornblende are removed will leave the residual magma relatively depleted in heavy REE but with a positive Eu anomaly (Hanson, 1978). Removal of plagioclase contributes to a negative Eu anomaly and generally depletes Sr in the melt, but it is questionable that this process could have reversed a positive Eu anomaly to the extent observed. Thus it is more likely that the Meruoca and Mucambo rocks were derived from an already REE-fractionated source that, during further magmatic differentiation, experienced removal of plagioclase but not of large amounts of garnet or hornblende.

The accessory minerals allanite and zircon may also play an important role. Allanite has a strong affinity for light REE, and zircon for the heavy REE. The presence of allanite at Meruoca is also consistent with the very high abundances of light REE in these rocks (La concentrations 500—1000 times that of chondrites). Note too that the curves for the fayalite-free granites (Fig. 3) are flattened in the heavy-REE region. This pattern may be ascribed to the contribution by zircon. The good parallelism of these curves suggests that allanite and zircon crystallized from an already-fractionated magma. If these minerals were xenocrysts (not in equilibrium with the magma), their sporadic distribution from sample to sample would have destroyed the regularity of the pattern.

## A PETROGENETIC MODEL OF THE MERUOCA GRANITE

The petrography of the Meruoca granite has been briefly summarized above. With local exceptions, the chemistry of the fayalite-free and fayalite-bearing granites of this pluton is quite consistent as follows (Table II and A.N. Sial and L.E. Long, unpublished data, 1979). The rocks are silicic and alkalic, with $Na_2O$ at ~ 3.5% and $K_2O$ ~ 5.2%. The rocks have low CaO and very low MgO, equivalent to exceptionally low values of *M* on the *AFM* plot. Eighty percent of the samples are peraluminous. On the (normative) *qz—ab—or* diagram, the data plot on the feldspathic side of the ternary minimum, indicatir that the melt was $H_2O$-undersaturated throughout most of its history of crystallization. High variability of $Fe_2O_3/FeO$ from sample to sample is a probable outcome of late-stage interaction with oxygenated meteoric water. The granite is enriched in the LIL elements K, Ba, Zr, Nb and Y, and as we have noted, strongly enriched in REE. High fluorine concentrations suggest that $F^-$ proxied for $OH^-$ as a fluxing agent in the magma.

A useful classification of granitoids was introduced by Chappell and White (1974) and subsequently elaborated. It uses a variety of criteria to infer the properties of the source of the granitic magma. In this regard, the Meruoca pluton provides an almost classic example of an A-type (for anorogenic) association of characters (Loiselle and Wones, 1979). Important among these diagnostic features are the regional setting adjacent to a rift zone (the Cafe—Ipueiras fault system), the chemical pattern described above, and the presence of fayalite.

The Meruoca granite may be compared to another A-type plutonic suite, the Pikes Peak batholith, Colorado (Barker et al., 1975, 1976). Both the Pikes Peak batholith and the Meruoca pluton are anorogenic, having been emplaced at a high level into thick Precambrian continental crust. Their mineralogy and chemistry (including that of the rare earths) are strikingly similar. There are important differences between the two bodies, as the Pikes Peak batholith is an order of magnitude larger and contains a greater variety of rock types including anorthosite and gabbro which are absent at Meruoca. (However, an aeromagnetic anomaly near the center of the Meruoca pluton may signify the presence of more mafic subsurface rocks.)

The model of Barker et al. (1975) proposes that a large mass of mantle-derived basaltic magma (the heat source) invaded and strongly reacted with granulitic lower crust. Early crystallization of plagioclase, and magnesian olivine and pyroxene caused depletion in Mg and Ca, with some enrichment in Na and silica in the differentiated liquid. These authors argued that further reaction of this liquid with continental crust at intermediate levels, where rocks are richer in $K_2O$ and silica, was necessary to produce the voluminous biotite and biotite—hornblende granites of the Pikes Peak batholith.

In their model, the basaltic liquid that initiated the process of reaction—differentiation, makes only a minor contribution to the final high-level magma, the major part being derived from heterogeneous continental crust. If the situation at Meruoca were similar, then the striking uniformity of the REE patterns imposes an additional requirement. The area of the Meruoca pluton is ~ 400 $km^2$ and, assuming a depth of at least 2 km, a volume of 800 $km^3$ is assumed. If we allow for only partial melting of a continental crustal source, the volume of that region could have been much larger. There must have existed an intermediate staging point at depth where the initially inhomogeneous magma was able to collect, become well mixed, and then differentiate and perhaps crystallize. The postulated intermediate-stage material, in which the light REE were already enriched, became the immediate source of the Meruoca magma which had very high total REE abundances, and patterns of strongly-enriched light REE.

The Mucambo pluton is less well-studied, although we have already seen that its REE patterns resemble those of Meruoca. Earlier stages of crystallization at Mucambo are represented by autoliths containing plagioclase, hornblende and biotite. Detailed study of these autoliths would provide useful information about the pathway of REE fractionation. The possible contaminating influence of abundant xenoliths at Mucambo is not known precisely, but it is probably small in view of the similarity of the REE trends. We lack oxygen-isotope data for this pluton, which would also be useful to define the nature of the source rocks.

## ACKNOWLEDGEMENTS

We are grateful for chemical analyses performed by Karl Hoops, by Ana Maria C.M. de Medeiros at the Chemical Laboratory of SUDENE at Recife, and by Pedro Linhares at the Geosciences Institute, Federal University of Bahia. Brian J. Fryer kindly provided laboratory facilities for REE analysis. A.N.S. thanks the Brazilian National Council for Technological and Scientific Development (CNPq) for financial support during this research. Daniel Barker and Douglas Smith made helpful criticisms and suggestions. The Geology Foundation, University of Texas at Austin, helped to defray the cost of publication.

## REFERENCES

Aleksiyev, E.I., 1970. Genetic significance of the rare-earth elements in the younger granites of northern Nigeria and the Cameroons. Geokhimiya, 2: 192—198.

Barker, F., Wones, D.R., Sharp, W.N. and Desborough, G.A., 1975. The Pikes Peak batholith, Colorado Front Range, and a model for the origin of the gabbro—anorthosite—syenite—potassic granite suite. Precambrian Res., 2: 97—160.

Barker, F., Hedge, C.E., Millard, Jr., H.T. and O'Neil, J.R., 1976. Pikes Peak batholith: geochemistry of some minor elements and isotopes, and implications for magma genesis. In: R.C. Epis and R.J. Weimer (Editors), Studies in Colorado Field Geology, Prof. Contrib. Colorado Sch. Mines, 8: 44—56.

Bowen, N.L., 1928. The Evolution of the Igneous Rocks. Dover, New York, N.Y., 332 pp.

Brown, G.C., 1973. Evolution of granite magma at destructive plate margins. Nature (London), 241: 26—28.

Brown, G.C. and Fyfe, W.S., 1970. The production of granitic melts during ultrametamorphism. Contrib. Mineral. Petrol., 28: 310—318.

Chappell, B.W. and White, A.J.R., 1974. Two contrasting granitic types. Pac. Geol., 8: 173—174.

Condie, K.C. and Hunter, D.R., 1976. Trace element geochemistry of Archean granitic rocks from the Barberton region, South Africa. Earth Planet. Sci. Lett., 29: 389—400.

de Albuquerque, C.A.R., 1977. Geochemistry of the tonalitic and granitic rocks of the Nova Scotia southern plutons. Geochim. Cosmochim. Acta, 41: 1—13.

de Albuquerque, C.A.R., 1978. Rare earth elements in "younger" granites, northern Portugal. Lithos, 11: 219—229.

Dickinson, W.R., 1968. Circum-Pacific andesite types. J. Geophys. Res., 73: 2261—2269.

Dickinson, W.R., 1970. Relations of andesite, granites, and derivative sandstones to arc—trench tectonics. Rev. Geophys. Space Phys., 8: 813—860.

Eby, G.N., 1972. Determination of rare-earth, yttrium and scandium abundances in rocks and minerals by ion-exchange-X-ray fluorescence procedure. Anal. Chem., 44: 2137—2143.

Eskola, P., 1932. On the origin of granitic magmas. Tschermak's Mineral. Petrogr. Mitt., 42: 455—481.

Ewart, A., Taylor, S.R. and Capp, A.C., 1968. Trace and minor element geochemistry of the rhyolitic volcanic rocks, central North Island, New Zealand. Contrib. Mineral. Petrol., 18: 76—104.

Frey, F.A., Chappell, B.W. and Roy, S.D., 1978. Fractionation of rare-earth elements in the Tuolumne intrusive series, Sierra Nevada batholith, California. Geology, 6: 239—242.

Fryer, B.J., 1977. Rare earth evidence in iron-formations for changing Precambrian oxidation states. Geochim. Cosmochim. Acta, 41: 361—367.

Gilluly, J., 1971. Plate tectonics and magmatic evolution. Geol. Soc. Am. Bull., 82: 2383—2396.

Glikson, A.Y., 1976. Trace element geochemistry and origin of early Precambrian acid igneous series, Barberton Mountain Land, Transvaal. Geochim. Cosmochim. Acta, 40: 1261—1280.

Hamilton, W., 1969. The volcanic central Andes — a modern model for the Cretaceous batholiths and tectonics of western North America. In: The Andesite Conference, Oreg. Dep. Geol. Mineral. Ind. Bull., 65: 175—184.

Hanson, G.N., 1978. The application of trace elements to petrogenesis of igneous rocks of granitic composition. Earth Planet. Sci. Lett., 38: 26—43.

Huang, W.L. and Wyllie, P.J., 1973. Muscovite dehydration and melting in deep crust and subducted oceanic sediments. Earth Planet. Sci. Lett., 18: 133—136.

Loiselle, M.C. and Wones, D.R., 1979. Characteristics and origin of anorogenic granites. Geol. Soc. Am., Abstr. Programs, 11: 468.

Masuda, A., Nakamura, N. and Tanaka, T., 1973. Fine structures of mutually normalized rare-earth patterns of chondrites. Geochim. Cosmochim. Acta, 37: 239—248.

Nagasawa, H. and Schnetzler, C.C., 1971. Partitioning of rare earths, alkali and alkaline earth elements between phenocrysts and acidic igneous magma. Geochim. Cosmochim. Acta, 35: 953—968.

Stern, C.R., Huang, W.L. and Wyllie, P.J., 1975. Basalt—andesite—rhyolite—$H_2O$: crystallization intervals with excess $H_2O$ and $H_2O$-undersaturated liquidus surfaces to 35 kilobars, with implications for magma genesis. Earth Planet. Sci. Lett., 28: 189—196.

Streckeisen, A.L. (Chairman) and I.U.G.S. Subcommission, 1973. Plutonic rocks: classification and nomenclature recommended by Int. Union Geol. Sci. Subcomm. on the Systematics of Igneous Rocks. Geotimes, 18(10): 26—30.

Sun, S.S. and Hanson, G.N., 1976. Rare earth element evidence for differentiation of McMurdo volcanics, Ross Island, Antarctica. Contrib. Mineral. Petrol., 54: 139—155.

Taylor, S.R. and Gorton, M.P., 1977. Geochemical application of spark source mass spectrography, III. Element sensitivity, precision and accuracy. Geochim. Cosmochim. Acta, 41: 1375—1380.

Taylor, S.R., Ewart, A. and Capp, A.C., 1968. Leucogranites and rhyolites: trace element evidence for fractional crystallization and partial melting. Lithos, 1: 179—186.