THE PETROLOGY AND GEOCHEMISTRY OF THE NORDESTE VOLCANIC COMPLEX, SAO MIGUEL, AZORES

by
LOUIS A. FERNANDEZ
Department of Earth Sciences
University of New Orleans
New Orleans, LA 70148

ABSTRACT

Sixty samples from the Nordeste Volcanic Complex, São Miguel, Azores, have been analyzed for major elements and fifteen for LIL and other trace metals. Analysis of magnesia and alkali-silica variation diagrams show the bulk of the Nordeste volcanics to be a potassic, mildly alkaline, alkali basalt → trachybasalt → tristanite → trachyte series. The oldest flows of the complex, characterized by low TiO_2 and high SiO_2, are interpreted as representative of compositions transitional between tholeiitic and alkalic suites.

All of the Nordeste samples are enriched in lighter REE relative to Mid-Atlantic Ridge Basalts from the Azores Plateau. Light REE enrichment factors range through a factor of $\sim$ 5 between the basaltic types and the tristanites and trachytes. The younger Nordeste volcanics, when compared to the transitional basalts, are distinguished by higher concentrations of

Ce, Rb, Ba, Eu, Lu, Hf, and Yb and higher La/Sm ratios. The transitional basalts are characterized by high T/Th and Ta/Hf ratios.

Using major, minor and trace element compositions and microprobe analyses of phenocrystic and groundmass phases, least-squares calculations support a crystal fractionation model. The magnesian aphyric to ankaramitic alkali basalts represent magmas from which minor amounts of olivine and pyroxene were either removed from or incorporated into while residing in shallow crustal reservoirs. The trachybasalt → trachyte series represent fractionated liquids generated by the removal of titanaugite, plagioclase, olivine, titanomagnetite, and ilmenite in the early stages followed by removal of abundant plagioclase, augite and minor opagues in the late stages. The dominance of plagioclase in the latter fractionation scheme and its rarity as an xenocrystic phase suggests fractionation in deeper reservoirs, now represented by gabbroic and dioritic layered complexes underlying the Azores Platform. The major and minor element composition of the transitional basalts precludes their being the parent of the alkali basalt sequence, but rather indicate two magma series geenrated by diferrent degrees of partial melting in the mantle.

INTRODUCTION

The Azores archipelago comprises nine islands trending obliquely across the Mid-Atlantic ridge between latitudes 27° and 40° N and marks the western terminus of the Eurasian-African plate boundary (LAUGHTON and WHITMARSH, 1975). The islands straddle the Mid-Atlantic rift from ESE to WNW with: an eastern group São Miguel, Santa Maria and the Formigas Banks; a middle group, Faial, Terceira, São Jorge, Graciosa and Pico and a western group, Corvo and Flores which lie just west of the of the median-rift of the Mid-

Atlantic ridge. The Nordeste Volcanic Complex, an 85 km^2 portion of northeastern São Miguel Island (Fig. 1), is one of the oldest exposed alkaline basalt provinces in the eastern Azores (ABDEL-MONEM, et al., 1975). Field mapping at 1:16000 of the Nordeste complex, predominantly alkali basalt and trachybasalt with minor tristanite, and trachyte flows and small inrusive plugs, has provided the framework for a detailed stratigraphic, stuctural and petrochemical analysis (FERNANDEZ, 1980).

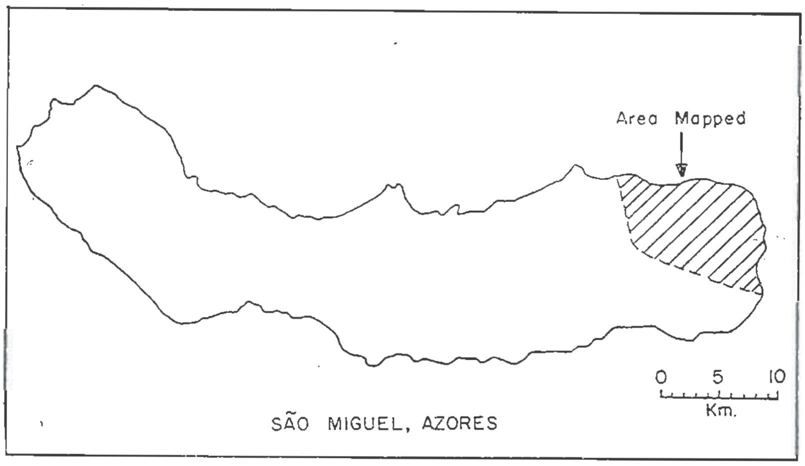

Fig. 1 — Map of São Miguel. Diagonal lines delineate Nordeste volcanic complex.

CHEMISTRY

Major Elements

The Nordeste Volcanics represent a potassic alkali basalt → trachybasalt → tristanite → trachyte series. Positive mineralogical indicators of an alkali parentage are all present: titanaugite, ground-mass olivine and interstitial alkali feldspar.

Plots of 60 chemical analyses of Nordeste samples on a $Na_2O + K_2O$ versus SiO_2 (Fig. 2) diagram shows the majority of the Nordeste suite samples plotting above a line separating Hawaiian tholeiitic and alkalic rocks (MACDONALD and KATSURA, 1964) and below a line which separates the mildly alkaline from strongly alkaline rocks from Tanganyika (SAGGERSON and WILKINSON, 1964). Five samples which lie in or near the hawaiian tholeiite field are the transitional basalts which are the oldest flows in the Nordeste Complex. These are also characterized by low TiO_2, high SiO_2, absence of an interstitial alkali feldspar residuum and by clinopyroxenes which are relatively poor in Al_2O_3 and TiO_2 and rich in SiO_2. These flows are interpreted as representative of chemistries transitional between tholeiitic and alkalic suites.

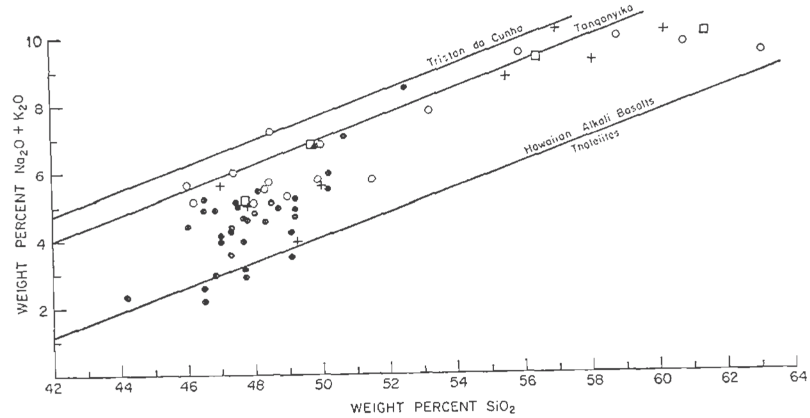

Fig. 2 — Total alkalis versus silica for Nordeste volcanics. Open circles filled circles, and crosses represent aphyric, porphyritic, and feldsparphyric samples, respectively. Line separating alkalic and tholeiitic rocks of Hawaii taken from MACDONALD and KATSURA, 1964 ; line separating mildly alaline from strongly alkaline rocks of Tanganyika based on data from SAGGERSON and WILLIAMS, 1964 ; the generalized trend for Tristan da Cunha rocks taken from Baker and others, 1964. Squares are average Nordeste alkali basalt, trachybasalt, tristanite, and trachyte.

The mildly alkaline, mildly undersaturated Nordeste volcanics, generally hypersthene-olivine normative (slightly nepheline normative when Fe_2O_3 values are normalized to 1.5 % as suggested by Coombs, 1963) differ markedly from the more alkalic, strongly undersaturated (nepheline normative without the Fe_2O_3 correction) volcanics representative of the younger provinces on São Miguel (ASSUNÇÃO, 1961 ; SCHMINCKE and WEIBEL, 1972). Comparison of the Nordeste volcanics with the mildly alkaline but nepheline normative suite of Terceira (SELF and GUNN, 1976 ; SCHMINCKE and WEIBEL, 1972) shows the Nordeste volcanics to be of similar total alkali content but less undersaturated. Previous reports that the São Miguel volcanics were in general more alkalic and more undersaturated that the Terceira suite (SCHMINCKE, 1973 ; SELF and GUNN, 1976) apply only when comparing Terceira to the younger volcanic provines of São Miguel.

In terms of alkalinity and degrees of silica saturation the São Miguel suite, both the Nordeste (transitional basalts excluded and the younger volcanic provinces, can be classed, using the lineages recognized by COOMBS and WILKINSON (1969), as high-Fe variants of the moderately potassic, alkali basalt → trachyte series. The idea that the Azores suite, São Miguel in particular, was relatively low in K_2O (Le MAITRE, 1962 ; BAKER et al., 1964) was appaarntly based on dubious analysis (FERNANDEZ, 1969 and SCHMINCKE and WEIBEL, 1972). Compared to other Atlantic islands São Miguel is most similar to Gough Island differing in having higher Ti, K, Fe and P contents, lower Ni and Mg and late differentiates which are characteristically quartz normative in lieu of nepheline normative.

Figure 3 shows the Nordeste chemical data plotted on magnesia variation diagrams. Na_2O and K_2O both increase proportionately with difefrentiation, K_2O increasing at a greater rate than Na_2O in the salic late differentiates. In the case of the sodic Terceira lavas Na_2O increases at a greater rate than K_2O (see Fig. 2, SELF and GUNN, 1976). In both the

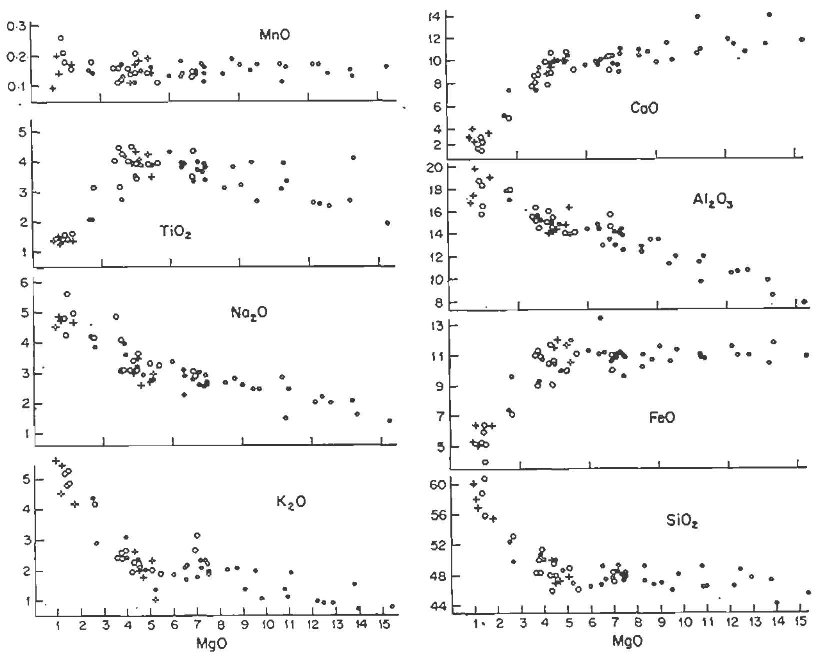

Fig. 3 — MgO variation diagrams for major elements in Nordeste volcanics. Symbols as in Figure 2.

Nordeste and Terceira suites, Na_2O shows a greater degree of scatter at the salic end. CaO decreases slightly with initial differentiation and then decreases rapidly at the salic end. FeO is essentially constant at the mafic end and decreases rapidly in the salic late differentiates. TiO_2 shows considerable scatter at high MgO values, increases slightly and then decreases rapidly as do FeO and CaO. Similar variations are seen in FeO, CaO and TiO_2 plots for the Terceira lavas. Al_2O_3 displays an almost linear variation increasing steadily with increased differentiation, showing only a minor inflection at $\sim 5\%$ MgO. This trend contrasts strongly with the Terceira laavs which show almost constant Al_2O_3 values down to $\sim 4\%$, they then increase and finally decrease with increased differentiation. SiO_2 in the Nordeste samples is essentially constant down to $\sim$ 5 % MgO and then increases with increased differentiation. A similar trend is displayed by the Terceira lavas. P_2O_5 (Fig. 4) increases either linearly or exponentially (the limited number of analyses make interpretation tenuous at most) with increased differentiation and then drops off drastically ($< \sim$ 2 % MgO) in the late differentiates. P_2O_5 variation in the Terceira lavas shows considerable scatter, generally increasing slightly with increased differentiation and finally decreasing in the late differentiates.

Trace and LIL Elements

All of the Nordeste samples are enriched in the lighter REE relative to Mid-Atlantic Ridge Basalts from the Azores Plateau (Fig. 5). Light REE enrichment factors range through a factor of $\sim$ 5 between the basaltic types and the tristanittes and trachytes.

The younger Nordeste volcanics, when compared to the transitional basalts, are distinguished by higher concentrations of Ce, Rb, Ba, Eu, Lu, Hf and Yb and higher La/Sm ratios. The transitional basalts are characterized by high U/Th and Ta/Hf ratios.

The distinct inter-island variations reported for the major elements are also apparent in the trace eleemnt contents. White et al. (1979) have reported that São Miguel lavas are characterized by high concentrations of K, Rb, Cs, Ti, Ba and the light rare-earths, and slightly higher Cr, Hf, Ta, Th and Sr when compared to other Azores islands. Although the data from White et al. (1979) pertains to the younger volcanic provinces of São Miguel, comparison with the Nordeste lavas (transitional basalts excluded) shows this pattern to be generally true with the only notable exceptions being that the

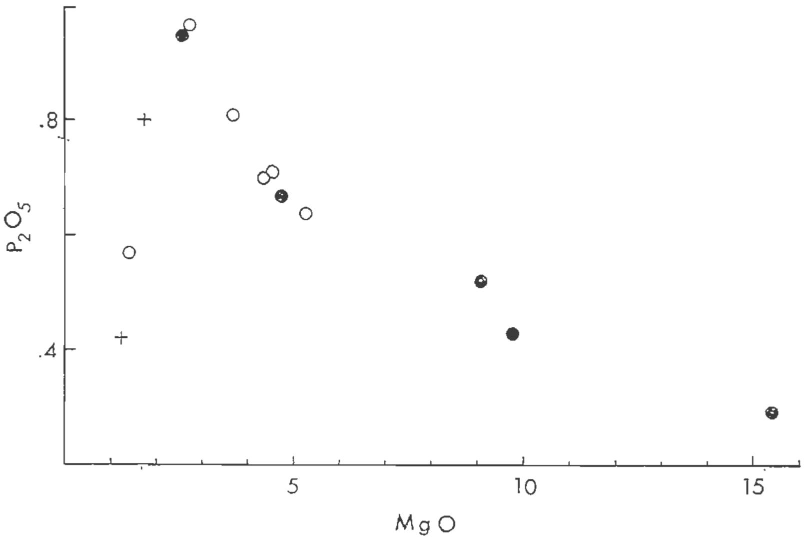

Fig. 4 — MgO versus P_2O_5 variation diagram for Nordeste volcanics. Symbols as in Figure 2.

Nordeste lavas are even more enriched in Rb, have even higher La/Sm ratios but slightly lower Ce and Sm values.

Selected trace and LIL elements are shown as a function of Mg in figure 6. Sc and Ni, as well as Cr and Co, decrease with decreasing Mg. The LIL elements Rb, Ba, Hf and Th increase with decreasing Mg, while La, Eu and the other rare earths increase, reach a maximum and then decrease in the most Mg-poor rocks.

PETROGENESIS

The characteristics of the Nordeste chemical data, as interpreted from the magnesia variation diagrams of both the major and minor elements, are consistent with a model of crystal fractionation of «parental» alkali basalt magma. The

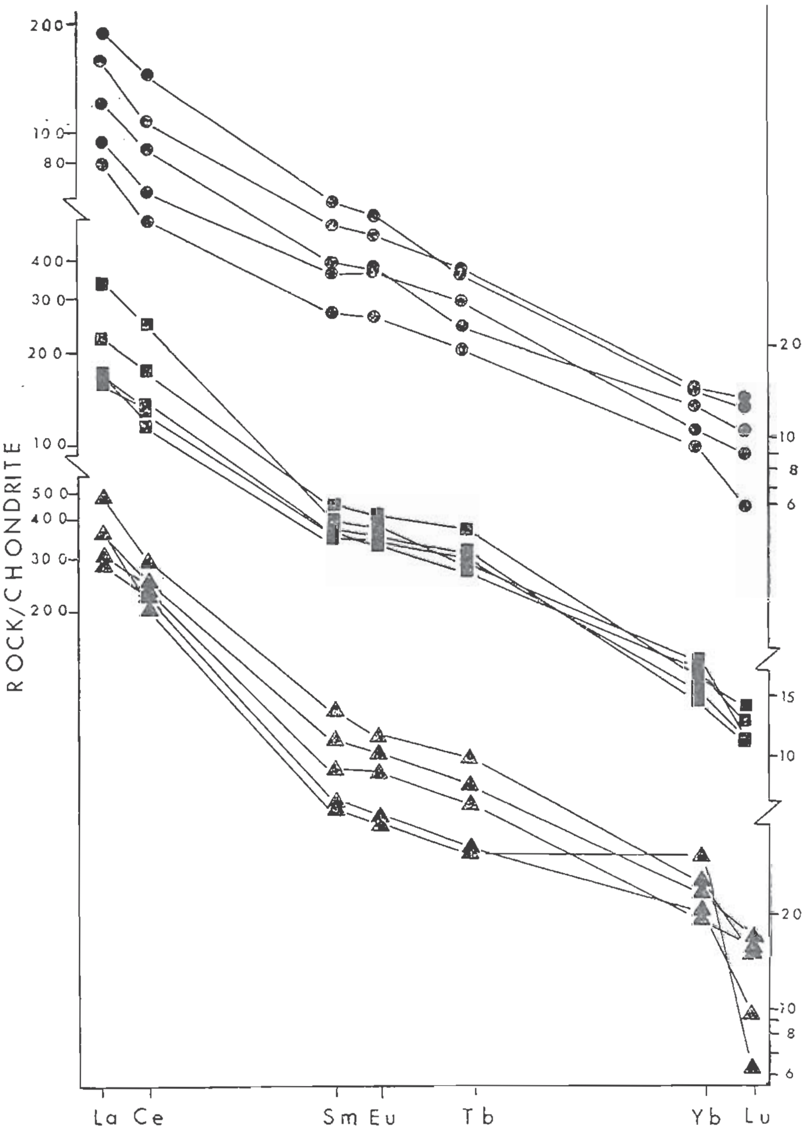

Fig. 5 — Rare earth abundance patterns of Nordeste volcanics. Upper, middle and lower data sets represent alkali basalts, trachybasalts and tristanites-trachytes, respectively.

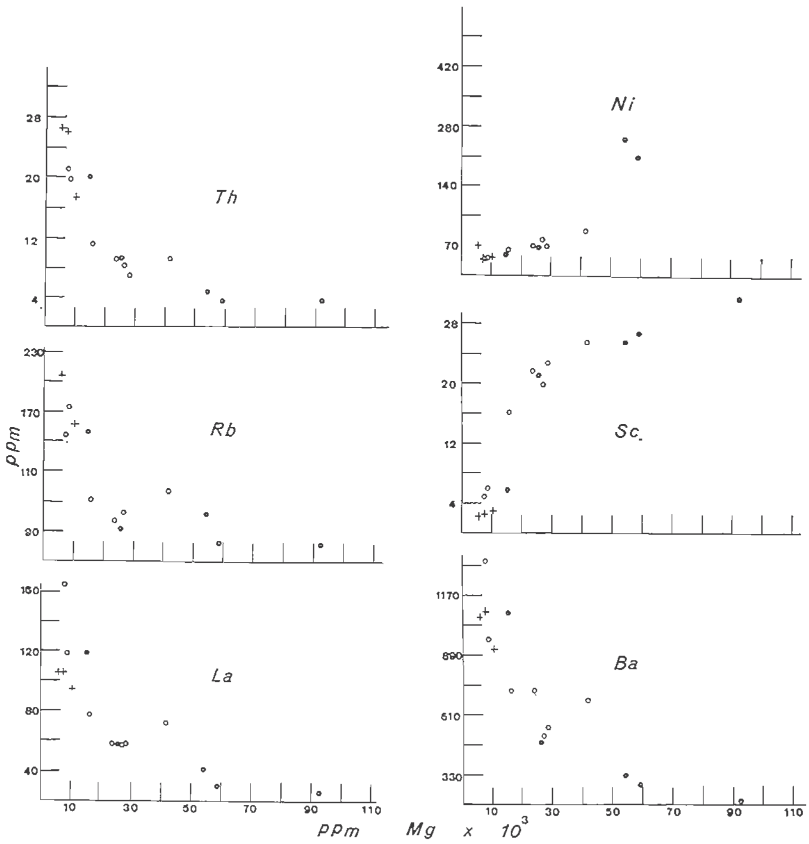

Fig. 6 — MgO variation diagrams for selected trace elements in Nordeste volcanics. Symbols as in Figure 2.

more magnesia (> 7.0 MgO) porphyritic and ankaramitic samples represent accumulative rocks. The latter have correspondingly high values of CaO, MgO, FeO, Ni, Cr, and relatively low contents of TiO_2, Na_2O K_2O, Al_2O_3, and incompatible elements, reflecting the high and variable contents of pyroxene and olivine. Trachybasalt, tristanite and trachyte represent fractionated liquids generated by the removal of predominantly, titanaugite, plagioclase and olivine in the early stages (5 to 7 % MgO), followed by abundant plagioclase, augite, and minor opaques in the late stages (< 5 % MgO). The removal of plagioclase, titanomagnetite and limenite would account for the marked decrease in CaO, FeO, and SiO_2 and for the increases in Na_2O, K_2O, SiO_2 and incompatible elements. The very marked decrease in P_2O_5 and light REE at very low MgO contents suggests that apatite is an important phase in the very late stages of fractionation.

The proposed crystal fractionation model was tested using the Wright and Doherty (1970) least squares computer method for solving petrologic mixing problems. Liquid line of descent tests were performed using average compositions of major rock types (alkali basalt, trachybasalt, tristanite and trachyte) as parent magma — residual liquid pairs, and using microprobe analyses of representative microphenocrysts for the mineral assemblages relating the parent to the differentiated liquid. The results of these tests support the view that the trachibasalts tristanites, and trachytes were derived from «parental» alkali olivine basalt by the process of crystal fractionation. The chemical variability of alkali basalt is attributed to the incorporation of varying amounts of cumulus pyroxenes and olivines plus possible fractionation of the parental alkali basalt melt on passing from source regions to storage regions (sub-volcanic magma chamber). Trial and error runs attempting to relate the alkali basalts to the transitional basalts were unsuccessful, suggesting that the latter are not related by any low pressure fractionation scheme.

The petrochemical trend on the island of São Miguel as a whole: (1) transitional basalts, the hypersthene-olivine normative anomalous basalts of Nordeste (~ 4 m.y.) ; (2) followed by the slightly undersaturated Nordeste alkali basalt-trachyte series (0.95 < x < 4 m.y.) ; (3) in turn followed by the strongly undersaturated suite of the younger volcanic provinces of São Miguel, is attributed to different degrees of partial melting occurring in the mantle. The increasing abundance of tristanitic and trachytic lavas in the younger volcanic provinces and the abundant evidence against partial melting or volatile transfer processes for generating large amounts of salic melts (ZIELINSKI and FREY, 1970; BAKER et al., 1964; WHITE et al., 1979) support fractional crystallization processes as the dominant mechanism for their origin. The absence of any systematic relationship between the degree of silica undersaturation and the REE and the incompatible element contents of the Nordeste lavas (less undersaturated but richer in Rb and with higher La/Sm ratios) and lavas from the younger volcanic provinces of São Miguel, support the view that both within and between island variations (FLOWER et al., 1976) are probably dependent on the conditions of melting and/or differences in the composition of the source material.

REFERENCES

ABDEL-MONEM, A. A., FERNANDEZ, L. A. and BOONE, G. M., 1975 : K-Ar Ages from the Eastern Azores Group (Santa Maria, São Miguel and the Formigas islands) : Lithos, 8, p. 247-254.

ASSUNÇÃO, C. F., TORRE DE, 1961 : Estudo petrográfico da ilha de S. Miguel (Azores) : Com. dos Serv. Geol. Portugal, 45 pp. 80-176.

BAKER, P. E., GASS, I. G., HARRIS, P. G., and LE MAITRE, R. W, 1964 : The Volcanological Report of the Royal Society Expedition to Tristan da Cunha, 1962 : Royal Soc. London Philos. Trans. Ser. A, no. 256, p. 439-578.

COOMBS, D. S. and WILKINSON, J. F. G., 1969 : Lineages and Fractionation Trends in Undersaturated Volcanic Rocks from the East Otago Volcanic Province (New Zealand) and Related Rocks : Jour. Petrol. 10, p. 440-501.

FERNANDEZ, L. A., 1969 : Chemical Petrology of the Basaltic Complex of Nordeste, São Miguel, Azores : Unpubl. Ph.D. dissert. Syracuse University, 134 pp.

FERNANDEZ, Louis A., 1980 : Geology and Petrology of the Nordeste Volcanic Complex, São Miguel, Azores, Geol. Soc. Amer. Bull., Part II, 91, p. 2457-2557.

FLOWER, M. F. M., SCHMINCKE, H.-U., BOWMAN, H., 1976 : Rare Earth and Other Trace Elements in Historic Azorean Lavas : Jour. Volcano. Geother. Res., 1, p. 127-147.

LAUGHTON, A. S. and WHITMARSH, R. B., 1975 : The Azores-Gibraltar Plate Boundary, in Kristjansson, L., ed., Geodynam. of Iceland and the North Atlantic Area : Reidel, Dordrecht, p. 63-81.

LEMAITRE, R. W., 1962 : Petrology of Volcanic Rocks. Gough Island South Atlantic : Geol. Soc. Amer. Bull. 73, p. 1309-1340.

MACDONALD, G. A. and KATSURA, T., 1964 : Chemical Composition of Hawaiian Lavas : Jour. Petrol., 5, p. 82-133.

SAGGERSON, E. P. and WILLIAMS, L. A. J., 1964 : Ngurumanite from Southern Kenya and its Bearing on the Origin of the Rocks in the Northern Tanganyika Alkaline District : Jour. Petrol. 5, p. 40-81.

SCHMINCKE, H.-U. and WEIBEL, M., 1972 : Chemical Study of Rocks from Madeira, Porto Santo, São Miguel and Terceira. Neues Jahrb. Mineral. Abh., 117, p. 253-281.

SELF, S. and GUNN, B. M., 1976 : Petrology, Volume and Age Relations of Alkaline and Saturated Peralkaline Volcanics from Terceira, Azores : Contrib. Mineral. Petrol., 54, p. 293-313.

WHITE, W. M., TAPIA, D .M. M. and SCHILLING, J.-G., 1979 : The Petrology and Geochemistry of the Azores Islands. Contrib. Mineral. Petrol., 69, p. 201-213.

WRIGHT, T. L. and DOHERTY, P. C., 1970 : A Linear Programming and Least Squares Computer Method for Solving Petrologic Mixing Problems. Geol. Soc. Amer. Bull., 8, p. 1195-2008.

ZIELINSKI, R. A. and FREY, F. A., 1970 : Gough Island : Evaluation of a Fractional Crystallization Model : Contrib. Mineral. Petro., 29, p. 242-254.