Geology and petrology of the Nordeste volcanic complex, São Miguel, Azores: Summary

LOUIS A. FERNANDEZ   *Department of Earth Sciences, University of New Orleans, New Orleans, Louisiana 70122*

INTRODUCTION

The Azores archipelago is comprised of nine islands trending obliquely across the Mid-Atlantic Ridge between latitudes 37°N and 40°N; it marks the western terminus of the Eurasian-African plate boundary (Laughton and Whitmarsh, 1975). The islands straddle Mid-Atlantic rift from east-southeast to west-northwest with an eastern group — São Miguel, Santa Maria, and the Formigas Bank; a middle group — Faial, Terceira, São Jorge, Graciosa, and Pico; and a western group — Corvo and Flores, which lie just west of the median-rift of the Mid-Atlantic Ridge. The Nordeste volcanic complex, underlying an 85-km² portion of northeastern São Miguel Island, is one of the oldest exposed alkaline basalt provinces in the eastern Azores. Field mapping at 1:16,000 of the Nordeste complex (Fernandez, 1969), which consists predominantly of alkali basalt and trachybasalt with minor tristanite and trachyte flows and small trachyte plugs, has provided the framework for a detailed stratigraphic, structural, and petrochemical analysis (Fig. 1).

STRATIGRAPHY AND STRUCTURE

The 1,300-m-thick exposed volcanic rocks which make up the bulk of the Nordeste complex have been subdivided into five stratigraphic sequences, from oldest to youngest: lower basalts, Nordeste ankaramites, upper basalts, tristanites, and trachytes. The lower basalts (~ 1,000 m thick) are composed of a generally conformable sequence of lavas varying from ankaramites to alkali basalts to trachybasalts which does not show any simple relationship between the compositions of the flows and their sequence of extrusion. The only exception to this is at the base of this sequence, best exposed along the eastern coastline, where a thin series of five to ten flows overlies some small scoria cones of similar chemistry. These lowermost units are the oldest exposed rocks on São Miguel, 4.01 m.y. old (Abdel-Monem and others, 1975), and are characterized chemically by exceptionally low K_2O, Na_2O, and TiO_2 relative to the rest of the complex. These lowermost units are termed "transitional" basalts because their chemistry and mineralogy is intermediate to those of oceanic tholeiites and alkali basalts.

Unconformably overlying the lower basalts is the Nordeste ankaramites sequence, the most distinctive of the complex. This unit consists of two widespread, thick flows (~200 m maximum thickness) of ankaramite and plagioclase-rich ankaramite. Conformably overlying the Nordeste ankaramites is a sequence of relatively thin, commonly aphyric, alkali basalts and trachybasalts totaling ~150

m. The rock types of this sequence grade upward from slightly porphyritic olivine alkali basalt to aphyric trachybasalt. A K-Ar date of 1.86 m.y. on the basal unit of the upper basalts and 4.01 m.y. for the lowermost unit of the lower basalts gives a time span of 2.15 m.y., during which most of the exposed Nordeste complex was emplaced.

The two youngest volcanic sequences, the tristanites and the trachytes, constitute the thinnest units and have the least areal extent. The tristanites consist of short, stubby flows as much as 10 m thick. The trachytes consist of flows which are similar to the tristanites and also appear as small, plug-like intrusives. Cutting the complex are a multitude of dikes, both simple and multiple, varying in composition from ankaramite to alkali basalt to hornblende-bearing trachybasalt. The three youngest isotopic dates, 1.28, 1.23, and 0.95 m.y., were obtained on a trachyte plug, a trachybasalt dike, and a tristanite flow, respectively. The dates are consistent with the field interpretations and support the hypothesis, based on the mapping, that different portions of the complex were fed by magma chambers which were in different stages of differentiation.

PETROGRAPHY

The Nordeste volcanics constitute a K-rich, alkali basalt–trachybasalt-tristanite-trachyte series. Modal quartz and feldspathoids are absent, but alkali feldspar patches, interstitial to groundmass minerals, are common. In addition to their essentially silica-saturated chemistry, the mafic rocks of the complex, which account for more than about 90% of the rock series, are strikingly rich in phenocrysts of olivine and clinopyroxene.

More than one-half of the analyzed rocks are alkali basalts. They are simple mineralogically but extremely variable in texture. Aphanitic textures are the least common, and porphyritic and strongly porphyritic (ankaramitic) textures are extremely common. A typical porphyritic alkali basalt is characterized by abundant, strongly zoned titanaugite and olivine phenocrysts, and plagioclase microphenocrysts set in a mesostasis of plagioclase, pyroxene and minor olivine, iron-oxides, biotite, alkali feldspar, and apatite. The ankaramites differ in being very rich in phenocrysts (30% to ~50%) and in having complexly zoned and mantled pyroxenes (diopside cores rimmed by titanaugite) and olivines (Fig. 2).
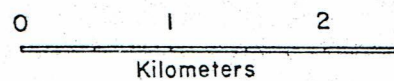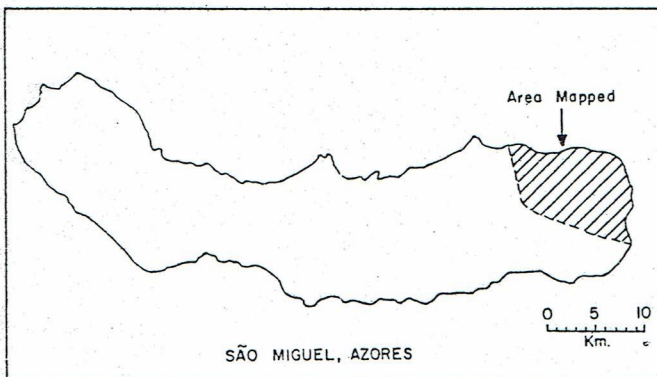
The trachybasalts differ from the alkali basalt group by being much poorer in ferromagnesian minerals and more variable in texture and mineralogy. They vary from those which contain pyroxene, olivine, and plagioclase phenocrysts, set in an essentially

L. A. FERNANDEZ

N
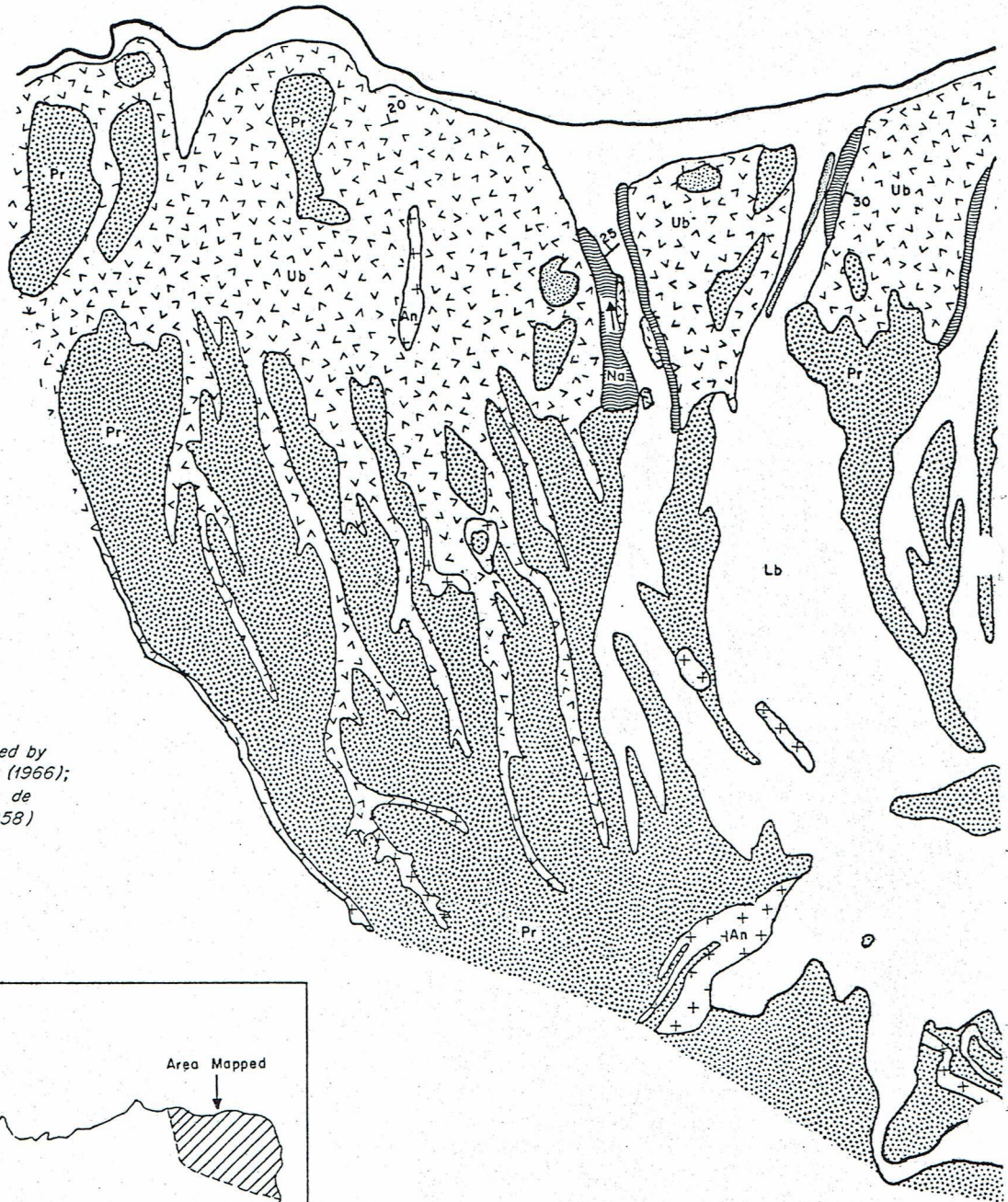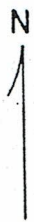
Geology by L. A. Fernández assisted by
R. A. Isaacs (1965) and J. F. Childs (1966);
based in part on Carta Geologica de
São Miguel (Zbyszewski et al., 1958)

Area Mapped

SÃO MIGUEL, AZORES

0   5   10
Km.

0   1   2
Kilometers

. Geologic map of the Nordeste volcanic complex, São Miguel, Azores.

Figure 1. *(Continued).*

EXPLANATION

Recent
- Ql — Alluvium

Late Pleistocene or Recent
- Bt — Beach and Terrace Clastic Sediments
- Pr — Pyroclastics

Late Pliocene or Pleistocene
- Sc — Scoria Cones
- Ty — Trachytes
- An — Tristanites (Tristanite flows, plugs and minor trachybasalt flows)

Pliocene
- Ub — Upper Basalts (Alkali basalt and trachybasalt flows)
- Na — Nordeste Ankaramites
- Lb — Lower Basalts (Alkali basalt and trachybasalt flows)

10 — Strike and dip of flow banding or foliation

→ Generalized flow direction
(Petrography and structure of individual flows and groups of flows in each series cannot be unambiguously characterized into groups of rock types. See text for details of variation.)
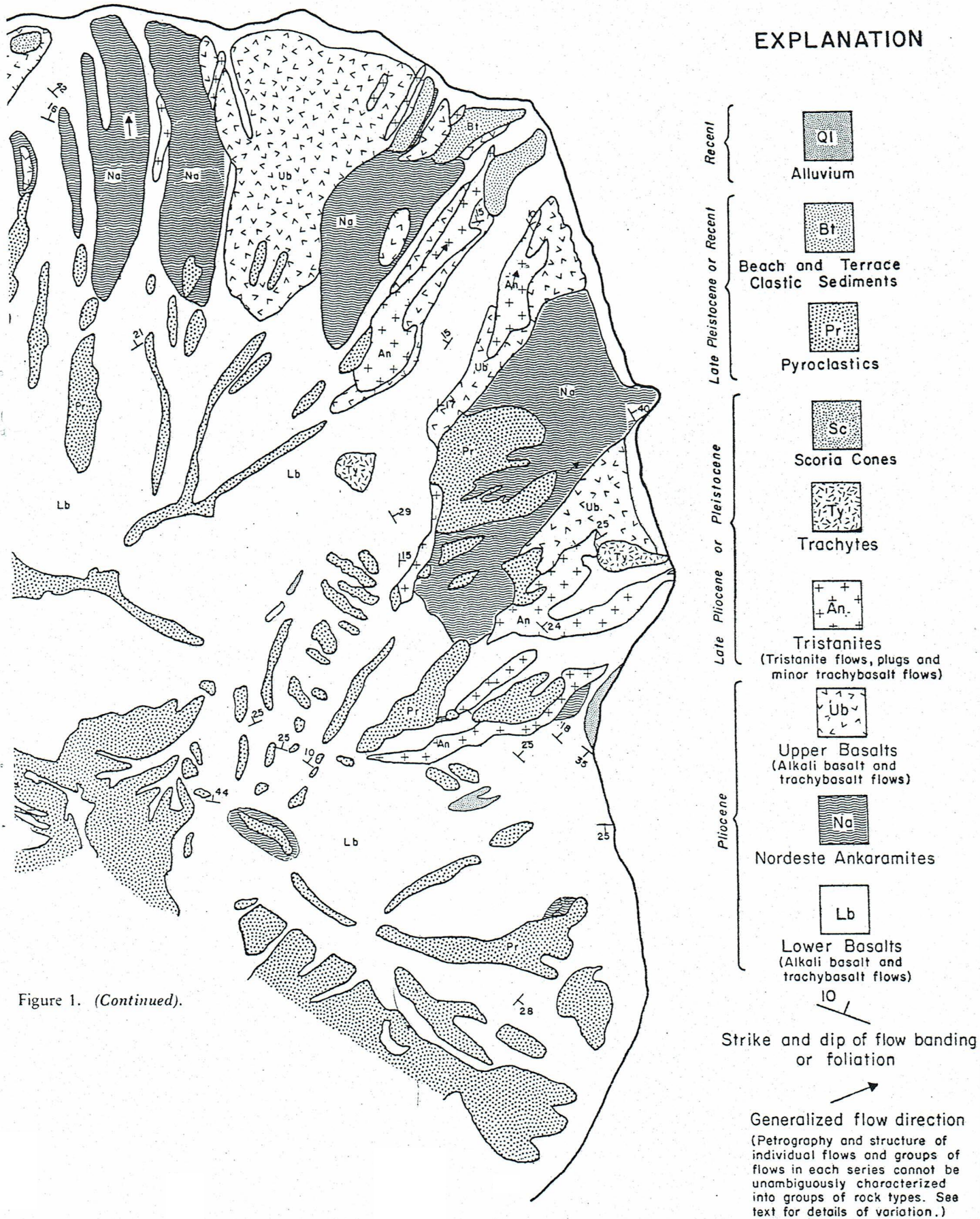
678   L. A. FERNANDEZ

made with major- or minor-element variations and the sequence of extrusion of the lavas (Boone and Fernandez, 1971). These observations, with corroborating data on pyroxenes, support the view that batches of cumulus crystals were frequently incorporated in successively differentiated liquids.

Clinopyroxene, the most common ferromagnesian phase, ranges from diopsidic augite → aluminous titanaugite → augite → aegirine augite. Comparison of the Nordeste clinopyroxene trend with the three pyroxene trends proposed by Gibb (1973) suggests that the Nordeste pyroxene trend is a variant of the strongly alkaline trend. On the basis of the behavior of Al in the clinopyroxenes, the Nordeste lavas are divided into two groups: high-silica transitional basalt with clinopyroxenes enriched in Si, Ca, and Cr, and a low-silica ankaramite → trachyte series with pyroxenes enriched in Al and Ti.
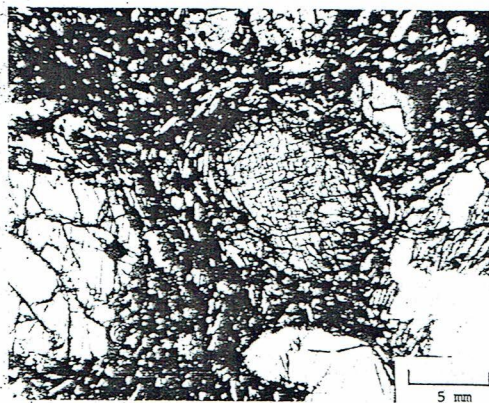

Figure 2. Ankaramite (no. 100). Large xenocrysts and phenocrysts of augite and olivine and microphenocrysts of plagioclase set in a fine-grained groundmass of augite, plagioclase, olivine, and iron oxides. Large crystal of pyroxene in center has a diopsidic augite core rimmed by mauve titanaugite (plane light).

Titanomagnetite and ilmenite occur as groundmass phases and less frequently as microphenocrysts. The compositions of coexisting titanomagnetite and ilmenite were used to determine temperatures of equilibration and the fugacity of oxygen (Buddington and Lindsley, 164). Two assemblages in basalts plot very close to the quartz-fayalite-magnetite (QFM) buffer, as is generally the case for high-temperature mafic extrusives (Haggerty, 1976). Two assemblages in more siliceous samples (trachybasalt dike and tristanite intrusive plug) plot below the QFM buffer (lower fO_2) and give temperatures of 803 and 783 °C, respectively. The latter are comparable to values reported for intermediate and felsic intrusives (Haggerty, 1976). One groundmass assemblage gave very low temperature and fO_2 values (695 °C and $10^{-19.2}$) relative to its phenocrystic counterpart, suggesting an absence of equilibrium between phenocryst and groundmass phases during subsolidus cooling.

Biotite is a ubiquitous phase but never attains the status of an essential mineral. Its color and pleochroic formula indicate relatively high Ti^{4+} to Fe^{3+} ratios. The amphiboles are restricted to intermediate and late differentiates. Their pleochroism and $2V_x$ values indicate basaltic hornblendes or kaersutites. The one microprobe analysis is that of a low-TiO_2 kaersutite.

CHEMISTRY

The Nordeste volcanic rocks represent a potassic, mildly alkaline, mildly undersaturated to saturated alkali basalt → trachybasalt → tristanite → trachyte series. All positive mineralogical indicators of an alkali parentage are present: titanaugite, groundmass olivine, and interstitial alkali feldspar. Plots of 60 chemical analyses of Nordeste samples on a K_2O-versus-Na_2O scatter diagram show that the Nordeste suite, in addition to the volcanics from the younger provinces on São Miguel (central and western parts), are characteristically potassic, comparable to the potassic Tristan da Cunha and Gough Island alkali basalt → trachyte series. On a $(Na_2O + K_2O)$ versus SiO_2 diagram, the majority of the samples plot above a line separating Hawa 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). Plots for five samples which lie in or near the Hawaiian tholeiite field are the "transitional" basalts which make up 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 those of tholeiitic and alkalic suites.

Comparison of the Nordeste complex with the island of Terceira (Self and Gunn, 1976) shows that the Terceira volcanic rocks are also mildly alkaline but more undersaturated and are sodic instead of potassic. Compared to rocks of other Atlantic islands, São Miguel is most similar to Gough Island. It differs in having higher Ti, K, Fe, and P contents: lower Na and Mg; and late differentiates which are characteristically quartz normative instead of nepheline normative.

PETROGENESIS

The Nordeste chemical data, as interpreted from magnesia variation diagrams (Fig. 3) are consistent with a model of crystal fractionatin of "parental" alkali basalt magma. The more magnesian (>7.0% MgO) porphyritic and ankaramitic samples represent accumulative rocks. The latter have correspondingly high values of CaO, MgO, FeO, and relatively low contents of TiO_2, Na_2O, K_2O, and Al_2O_3, reflecting the high and variable contents of pyroxene and olivine. Trachybasalt, tristanite, and trachyte represent fractionated liquids generated by the removal of titanaugite, plagioclase, and olivine in the early stages (5% to 7% MgO), followed by abundant plagioclase and augite and then minor opaques in the late stages (>5% MgO). The removal of plagioclase, titanomagnetite, and ilmenite would account for the marked decrease in CaO, FeO, and SiO_2.

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
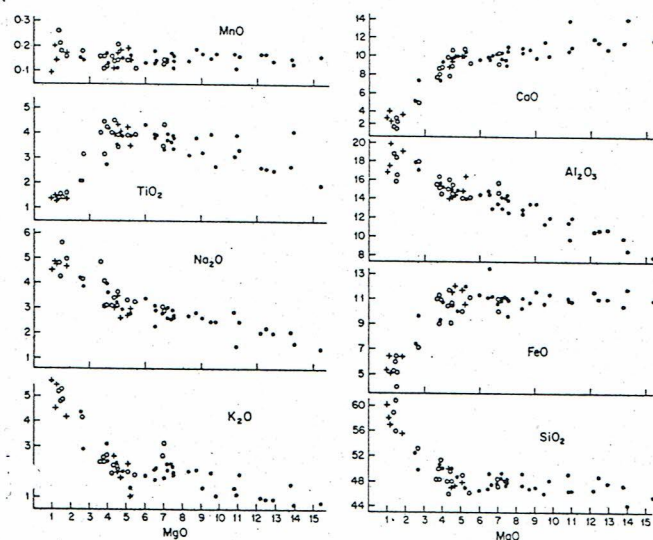
Figure 3. Magnesia variation diagrams for major elements in Nordeste volcanics. Open circles, filled circles, and crosses represent aphyric, porphyritic, and feldsparphyric samples, respectively.
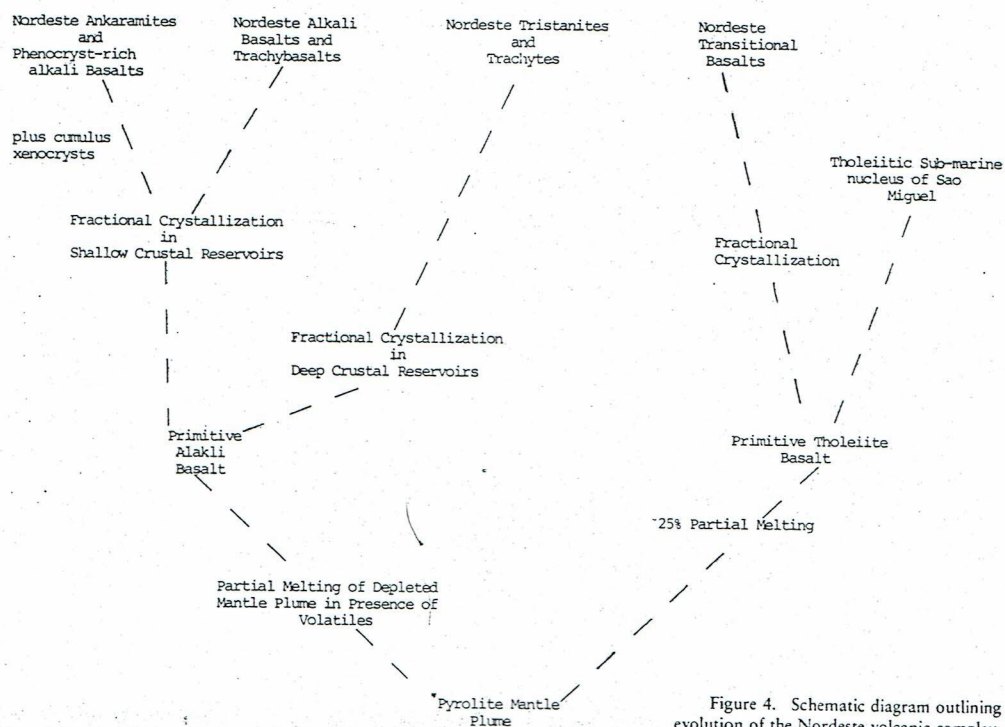

Figure 4. Schematic diagram outlining evolution of the Nordeste volcanic complex.

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, although only a first approximation due to the absence of positively identifiable parent magma–residual liquid pairs, support the view that the trachybasalts, tristanites, and trachytes were derived from "parental" alkali olivine basalt by the process of crystal fractionation. The chemical variability of the alkali basalts is attributed to the incorporation of varying amounts of cumulus pyroxene and olivine crystals plus possible fractionation of the parental alkali basalt melt on passing from source regions to storage regions (subvolcanic magma chamber). Trial-and-error runs, in an attempt to relate the alkali basalts to the transitional basalts, were unsuccessful, suggesting that the latter are not related to the other rocks by any low-pressure fractionation scheme.

A model for the evolution of the Nordeste Volcanic Complex (Fig. 4), one consistent with the available chemical and mineralogical data and which can accommodate any of the proposed tectonic models for the Azores (Krause and Watkins, 1970; Schilling, 1975; Flowers and others, 1976; White and others, 1979), is similar to the model proposed by Wright (1971) for the evolution of Kilauea. Partial melting (>20% to 25%) of a dipairic uprise (mantle plume) of low-velocity mantle at depths of 35 to 70 km would generate the tholeiite submarine nucleus of São Miguel (tholeiitic submarine lavas have been dredged from the Terceira Rift; White and others, 1979) and the subsequent transitional basalts of Nordeste. The alkali basalts which constitute the bulk of the Nordeste complex, are attributed to smaller amounts of partial melting at similar depths, possibly in the presence of volatiles (Mysen and Holloway, 1977). Possible high-pressure fractionation of these melts may have occurred during their slow ascent to the main storage regions at depths of 5 to 10 km. Magmas periodically ascended from the main storage region into shallow crustal reservoirs, minor fractionation occurring during their ascent as well as during storage at these upper-crustal levels. Periodic eruption of the upper parts of the shallow reservoirs produced alkali-basalt melts from which minor amounts of olivine and pyroxene were removed. These are represented by the abundant and variable Nordeste aphyric and porphyritic alkali basalts. During vigorous eruptions, or during periods when new inflxues of melt were introduced into the shallow chambers, previously settled olivine and pyroxene were incorporated into magmas prior to their eruption. This would account for the chemical and petrographic variability of the ankaramites and porphyritic alkali basalts and for the common presence of relatively low pressure pyroxenes (high total Al, low Al^{VI}) and olivine xenocrysts. The trachybasalt-tristanite-trachyte series was produced by plagioclase-pyroxene crystal fractionation of alkali-basalt melts in the deeper reservoirs (5 to 10 km). The dominance of plagioclase in the fractionation scheme and its rarity as a xenocrystic phase

suggest that the representatives of these deeper accumulating phases were not brought to the surface and probably are represented by gabbroic and dioritic layered complexes underlying the Azores Platform.

REFERENCES CITED

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, v. 8, no. 4, p. 247–254.

Boone, G. M., and Fernandez, L. A., 1971, Phenocrystic olivines from the eastern Azores: Mineralogical Magazine, v. 38, p. 165–178.

Buddington, A. F., and Lindsley, D. H., 1964, Iron-titanium oxide minerals and synthetic equivalents: Journal of Petrology, v. 5, p. 310–357.

Fernandez, L. A., 1969, Chemical petrology of the basaltic complex of Nordeste, São Miguel, Azores [Ph.D. dissert.]: Syracuse, New York, Syracuse University, 134 pgs.

Flowers, M.F.M., Schmincke, H.-U., and Bowman, H., 1976, Rare earth and other trace elements in historic Azorean lavas: Journal of Volcanology and Geothermal Research, v. 1, p. 127–147.

Gibb, F.G.F., 1973, The zoned pyroxenes of the Shiant Isles Sill, Scotland: Journal of Petrology, v. 4, p. 203–230.

Haggerty, S. E., 1976, Opaque mineral oxides in terrestrial igneous ro. in Rumble, D., III, ed., Oxide minerals: Mineralogical Society of America Short Course Notes, v. 3, p. Hg-101–300.

Krause, D. C., and Watkins, N. D., 1970, North Atlantic crustal genesis in the vicinity of the Azores: Royal Astronomical Society Geophysical Journal, v. 19, p. 261–283.

Laughton, A. S., and Whitmarsh, R. B., 1975, The Azores-Gibraltar plate boundary, in Kristjansson, L., ed., Geodynamics of Iceland and the North Atlantic area: Reidel, Dordrecht, p. 63–81.

MacDonald, G. A., and Katsura, T., 1964, Chemical composition of Hawaiian lavas: Journal of Petrology, v. 5. p. 82–133.

Mysen, B. O., and Holloway, J. R., 1977, Experimental determination of rare earth fractionation patterns in partial melts from peridotite in the upper mantle: Earth and Planetary Science Letters, v. 34, p. 231–237.

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: Journal of Petrology, v. 5, p. 40–81.

Schilling, J. G., 1975, Azores mantle blob: Rare earth evidence: Earth and Planetary Science Letters, v. 25, p. 103–115.

Self, S., and Gunn, B. M., 1976, Petrology, volume and age relations of alkaline and saturated peralkaline volcanics from Terceira, Azores: Contributions to Mineralogy and Petrology, v. 54, p. 293–313.

White, W. M., Tapia, D. M. M., and Schilling, J. G., 1979, The petrology and geochemistry of the Azores Islands: Contributions to Mineralogy and Petrology, v. 69, p. 201–213.

Wright, T. L., 1971, Chemistry of Kilauea and Mauna Loa lava in and time: U.S. Geological Survey Professional Paper 735.

Wright, T. L., and Doherty, P. C., 1970, A linear programming and least squares computer method for solving petrologic mixing problems: Geological Society of America Bulletin, v. 91, p. 1995–2008.

Zbyszewski, G., and others, 1958, Carta geológica da Portugal na escala de 1:50,000. Noticia expliciva da Folha "B", S. Miguel (Azores): Lisboa, Serviços Geológicos de Portugal, 37 p.