



SECTION 2

PETROLOGY AND GEOCHEMISTRY OF OCEANIC VOLCANOES

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MANTLE HETEROGENEITY IN THE NORTH ATLANTIC — EVIDENCE FROM OCEANIC ISLANDS

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ABSTRACT

Geochemical domains in the North Atlantic have been based upon major element composition of island basalts such as the K/Na-ratio with potassic islands such as São Miguel (Azores) distinguished from highly sodic provinces (Madeira group) (Schmincke, 1973) :

- ocean floor basalt glasses from the Mid-Atlantic Ridge with Ti-rich and K-poor provinces, south of ca. 32° N, distinguished from areas richer in K (north of ca. 32° N) (Melson, Dimitriev, 1979) ;
- highly incompatible elements such as Th and La which show characteristic ratios for several ocean floor provinces in the northern North Atlantic (Tarney, Treuil, Wood, 1979).

New major and trace element and $^{87}\text{Sr}/^{86}\text{Sr}$ -data at hand and presently obtained from the Azores, Madeira and Canary Island groups show that

- 1) ratios of incompatible elements are more highly dispersed in island than in sea floor basalts ;
- 2) neighbouring oceanic islands of the same group can each show characteristic trace element ratios that do not overlap between adjacent islands.
- 3) Higher K/Na-ratios are also reflected in higher incompatible element contents and higher $^{87}\text{Sr}/^{86}\text{Sr}$ -ratios.
- 4) Island groups close to major tectonic boundaries such as triple junctions and fracture zones are chemically more diverse than those away from major tectonic boundaries.
- 5) The mantle beneath the North Atlantic north of about 35°N appears chemically more heterogeneous than that south of ca. 35°N , possibly reflecting a more complex subduction — related history resulting from formation of the Protoatlantic.

(This paper was not read at the Symposium)

FRACTIONATION, PARTIAL MELTING, AND MIXING IN NORMAL BASALTS FROM 22-25° N, MID-ATLANTIC RIDGE

by

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INTRODUCTION

Much of the recent work on ocean ridge basalts has been directed toward supposedly «abnormal» sections of spreading ridges associated with inferred «mantle plumes». Such samples are especially well represented in the successful deep drilling accomplished by DSDP leg 37 (Aumento, Melson, et al., 1977) and in the data set from FAMOUS (White and Bryan, 1977; Langmuir et al., 1977; Bryan, 1979). The Mid-Atlantic Ridge near 22° N has been the source of many of the basalt samples on which our concepts of «normal» sea floor are based. As a result of a series of cruises associated with study of a «normal» oceanic crustal section in and near the Kane Fracture Zone at 24° N, about 150 new glass and whole rock major element analyses and trace element analyses of selected samples have been completed, representing dredge stations between 22° and

25° N. The data are discussed in detail by Bryan et al., 1981. These dredge data are supplemented by extensive published data for DSDP sites 395 and 396 located nearby (Melson, Rabinowitz et al., 1978 ; Dmitriev, Heirtzler et al., 1978).

In both quantity and compositional diversity, these samples approach those from leg 37 and FAMOUS. However, some important differences do exist, both in absolute element abundances and in the nature of inter-element co-variances of both major and trace element data.

MAJOR ELEMENT VARIATION

Using glass data from the Woods Hole collections near the Kane Fracture Zone and from other locations along the Mid-Atlantic Ridge from 0-37° N, Melson and O'Hearn (1979) showed that important major element differences exist between modern ocean ridge basalts located north or south of about 29° N. The northern group of samples include those from leg 37 and FAMOUS and are relatively enriched in Al_2O_3 , MgO and CaO. The southern group, of which those near Kane and 22° N are typical, are relatively enriched in FeO, TiO_2 , and Na_2O . Bryan and Dick (1981) have shown that these data sets define distinct liquidus trends which may be represented as regression lines in the normative plagioclase-pyroxene-olivine ternary (Fig. 1). Because existing experimental data indicate that both the FAMOUS and 22° N liquidus trends are consistent with low-pressure phase equilibria, Bryan and Dick (1981) argue that these trends must reflect differences in mantle source major element compositions rather than different depths of origin or different melting histories.

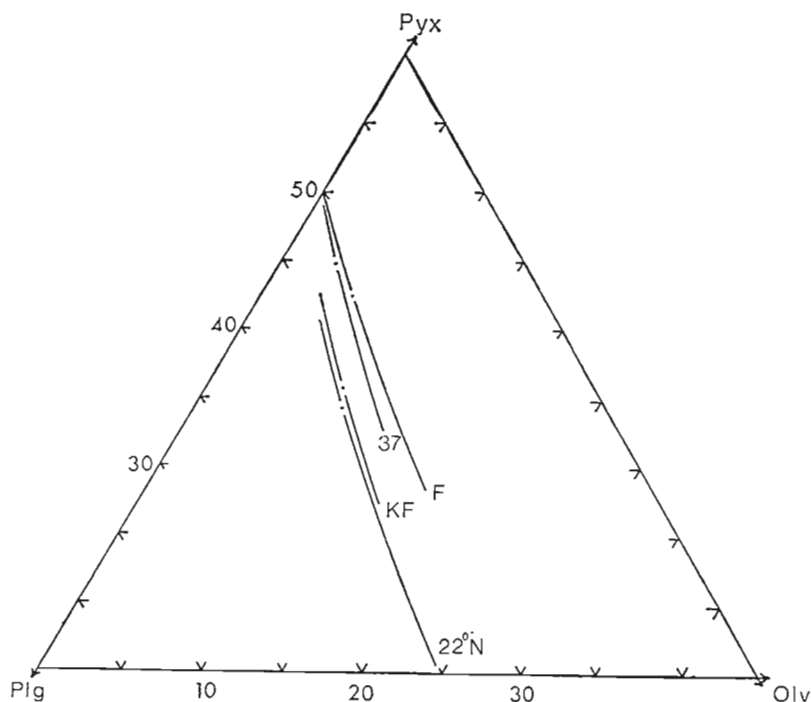


Fig. 1 — Comparison of basalt glass variation trends in the normative ternary plagioclase-pyroxene-olivine. F = FAMOUS, 37 = leg 37, KF = Kane Fracture Zone; 22°N = other samples south of Kane Fracture Zone. After Bryan and Dick, 1981.

TRACE ELEMENT VARIATION

Basalts near 22° N all show the depletion in large-ion lithophile elements that is considered typical of «normal» ocean ridge basalt. Chondrite-normalized rare-earth patterns show characteristic depletion in La and Ce relative to Sm and heavy rare earths, and all patterns are sub-parallel. In contrast to

FAMOUS and leg 37 (Langmuir et al., 1977; Bryan and Thompson, 1977) there is little variation in relative incompatible element enrichments and crossing rare earth patterns have not been observed. Trace element data, as well as major element data, are very similar in overall abundances and ranges to data for DSDP sites 395 and 396, although the modern ridge basalts extend both to somewhat more «primitive» and somewhat more «evolved» compositions than have been reported from those drill sites. It is of particular interest that no special basalt compositions are associated with the Kane Fracture Zone, and there are no significant major or trace element differences between the basalts erupted north and south of the fracture zone.

PETROGENESIS

In detail, the basalts near 22° N show many of the same genetic problems as do those from the FAMOUS area. However, unlike FAMOUS, the consistency in incompatible element depletion levels makes it unnecessary to appeal to complex melting models. Probably all the basalts were ultimately derived by similar degrees of melting from a relatively homogeneous source. That source must differ in both major and trace element compositions from the source of the FAMOUS and leg 37 basalts, and possibly also in mineralogy, to account for specific differences between FAMOUS and 22° N basalts.

Various subsets of the basalt data document the importance of low-pressure crystal-melt equilibria in accounting for much of the compositional variation. Significant variation exists within individual samples of phyric basalts. The quenched glass rims of these basalts represent some of the most fractionated composition in the data set, while their bulk compositions (glass plus phenocrysts) are very similar in composition to some of

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the least fractionated glasses (Fig. 2). Modal analyses and materials balance calculations (Table 1) confirm that differences between glass rim and bulk rock compositions are accounted for by the phenocryst assemblages, and that this difference mimics the variation trend in the glass data set as a whole, reflecting up to about 30 % crystallization. This within sample variation is interpreted to represent varying degrees of crystallization within vents and/or temporary storage chambers as these individual magma batches ascended to the surface. Apparently, both magma ascent and the rate of crystallization were sufficiently rapid that there was no opportunity for selective separation of crystals from liquid.

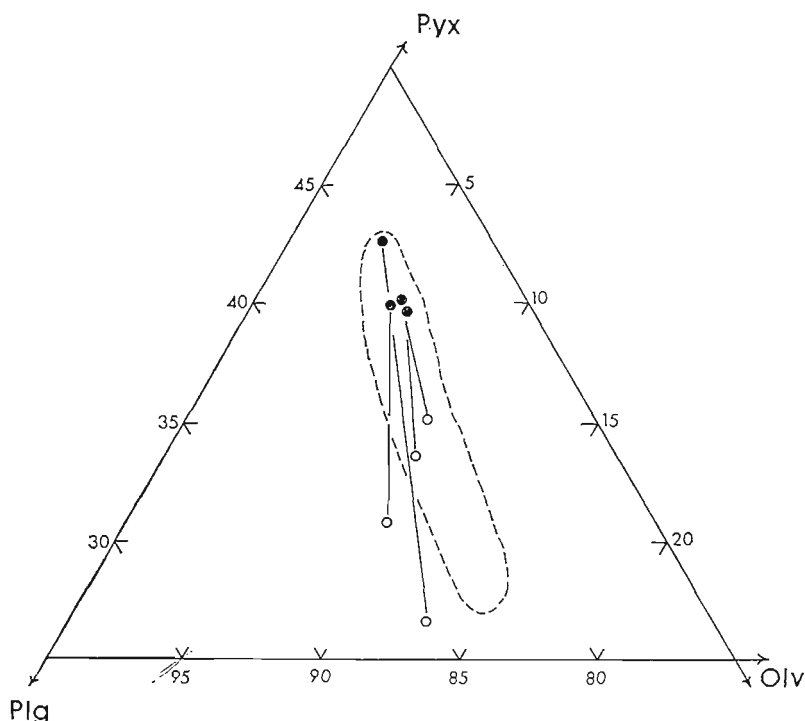


Fig. 2 — Normative plagioclase-pyroxene-olivine ternary, showing relation between quenched glasses (solid circle) and their corresponding whole rock compositions (open circles); tie lines connect compositions from individual samples.

Similar fractionation schemes can be shown to account for compositional differences among different aphyric basalt samples, both within single dredge collections, or selected from more widely separated sites (Bryan et al., 1981). In these cases, it is inferred that more prolonged fractionation took place in shallow chambers where crystal settling was effective; such a process is also supported by the layered gabbros collected from deeper crustal exposures in or near the Kane Fracture Zone (Dick et al., 1980). In several data subsets, the residual liquid is enriched in incompatible elements in excess of what can be accounted for by simple fractionation; such relations evidently are not limited to «abnormal» basalts. In all of these fractionation schemes, pyroxene plays a significant role, a role also supported by its presence as microphenocrysts in the more fractionated basalts.

Certain data subsets are best explained by low-pressure fractionation followed by simple mixing of new parental liquid and the fractionated liquid remaining in an evolving magma chamber. The resulting «intermediate» liquids are characterized by relatively high concentrations of both compatible and incompatible elements. These relations are illustrated graphically in figure 3, and are further supported by materials balance calculations (Bryan et al., 1981). However, as is also shown in the figure, other «intermediate» basalts appear to be the normal products of simple low-pressure fractionation, while others appear to require mixing of more extreme «residual» or «parental» liquids than have so far been recognized in the collection.

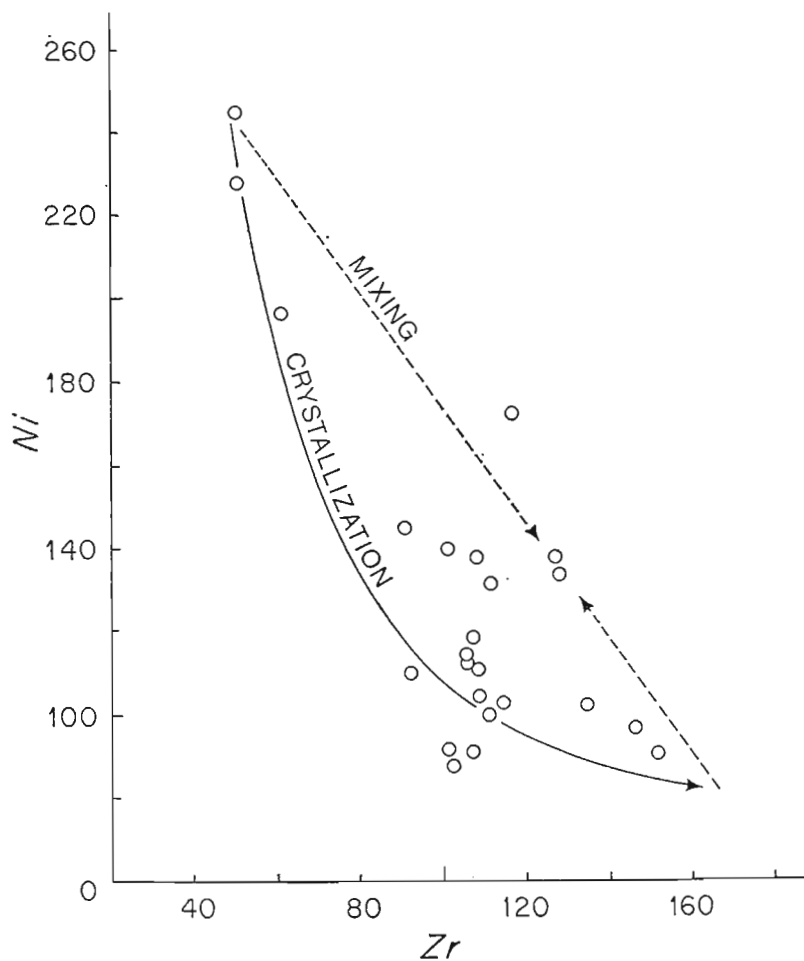


Fig. 3 — Variation in Ni vs Zr, showing theoretical crystallization trend (solid line) and mixing trend (dashed line). Crystallization curve computed assuming equilibrium crystallization and distribution coefficients of 3.5 for Ni, 0.1 for Zr.

SUMMARY

Basalts near 22° N all show the incompatible element depletion considered to be «typical» of ocean ridge basalts remote from sites of mantle plumes or other «abnormal» mantle sources. Basalts in or near the Kane Fracture Zone show no special compositional features; all seem to have originated in the median valley north or south of the Kane by similar degrees of melting of a homogeneous source. Both major and trace element data suggest, however, that this mantle source differs in composition from that in the FAMOUS area. A large part of the compositional variation in the data can be accounted for by low pressure fractionation in combination with simple mixing. Small differences in initial degree of partial melting seem adequate to explain remaining discrepancies between trace and major element variation.

ACKNOWLEDGEMENTS

Basalt glass analyses by T. O'Hearn (Smithsonian Institution) and modal analyses by J. G. Moore (U.S. Geological Survey) have contributed substantially to this study. Major and trace element analyses of whole rock samples were obtained in a co-operative analytical program between the Dept. of Chemistry, Woods Hole Oceanographic Institution, and the Department de Geologie, Universite de Montreal. This research was supported by the National Science Foundation through grant OCE 77-26842.

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TABLE 1

COMPARISON OF GLASS RIM, CALCULATED, AND OBSERVED BULK ROCK COMPOSITIONS OF BASALT

AII 96-6-44, and a natural glass from basalt AII 96-8-21

	A	B	C	D
SiO ₂	51.34	50.45	50.51	50.47
TiO ₂	1.86	1.52	1.51	1.52
Al ₂ O ₃	14.79	16.23	16.17	16.02
FeO ₂ *	10.65	9.40	9.28	9.38
MgO	6.54	7.37	7.37	7.69
CaO	11.36	11.71	11.63	11.32
Na ₂ O	3.07	2.76	2.90	2.92
K ₂ O	.15	.15	.12	.15
P ₂ O ₅	.17	.13	.13	.14
Total	99.93	99.72	99.62	99.61

A Glass rim, phyric basal sample AII96-6-44.

B Bulk rock, phyric basalt sample AII96-6-44.

C Bulk rock composition calculated as a linear combination of glass plus phenocrysts.

D Glass rim, basalt sample AII96-8-21. Data from Bryan et al., 1981.

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

by

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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 \rightarrow trachybasalt \rightarrow tristanite \rightarrow 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 ~ 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 \rightarrow trachyte series represent fractionated liquids generated by the removal of titanite, plagioclase, olivine, titanomagnetite, and ilmenite in the early stages followed by removal of abundant plagioclase, augite and minor opaques 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 generated by different 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 km² 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 intrusive plugs, has provided the framework for a detailed stratigraphic, structural and petrochemical analysis (FERNANDEZ, 1980).

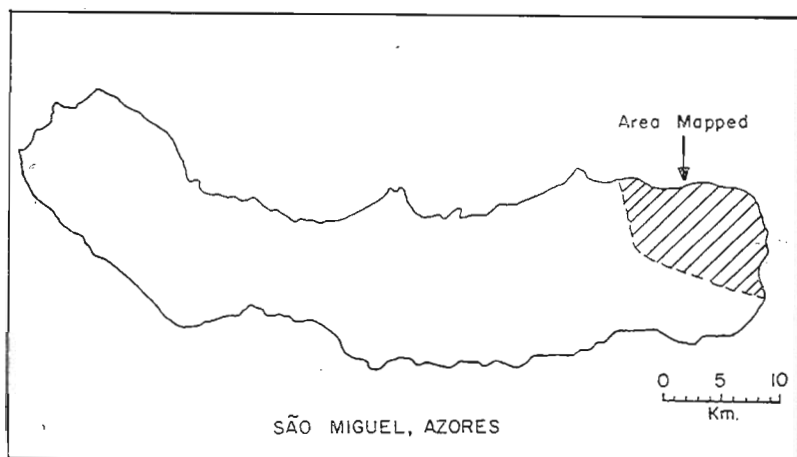


Fig. 1 — Map of São Miguel. Diagonal lines delineate Nordeste volcanic complex.

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: titanite, ground-mass olivine and interstitial alkali feldspar.

Plots of 60 chemical analyses of Nordeste samples on a $\text{Na}_2\text{O} + \text{K}_2\text{O}$ 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.

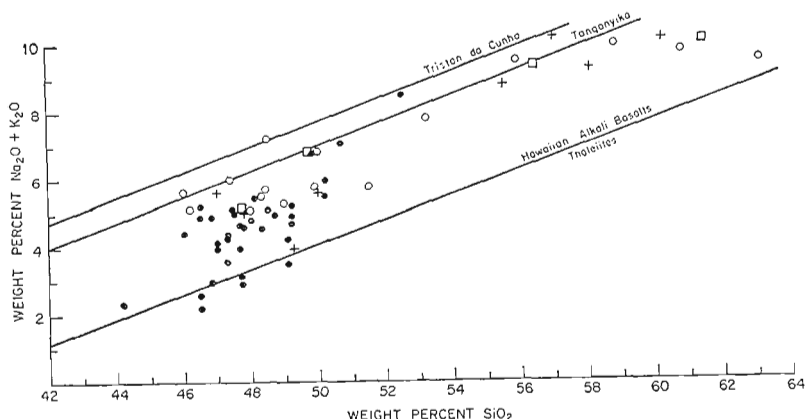


Fig. 2 — Total alkalis versus silica for Nordeste volcanics. Open circles filled circles, and crosses represent aphyric, porphyritic, and feldsparphyric samples, respectively. Line separating alkalic and tholeiitic rocks of Hawaii taken from MACDONALD and KATSURA, 1964; line separating mildly alkaline 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 than the Terceira suite (SCHMINCKE, 1973 ; SELF and GUNN, 1976) apply only when comparing Terceira to the younger volcanic provinces 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 \rightarrow 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 apparently 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 differentiation, 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

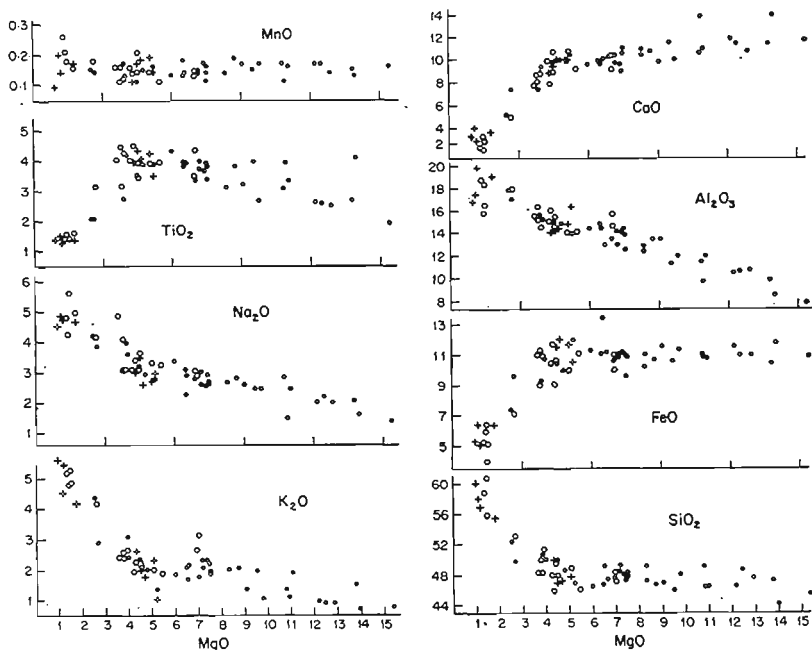


Fig. 3 — MgO variation diagrams for major elements in Nordeste volcanics. Symbols as in Figure 2.

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 lavas 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 ~ 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 U/Th and Ta/Hf ratios.

The distinct inter-island variations reported for the major elements are also apparent in the trace element 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

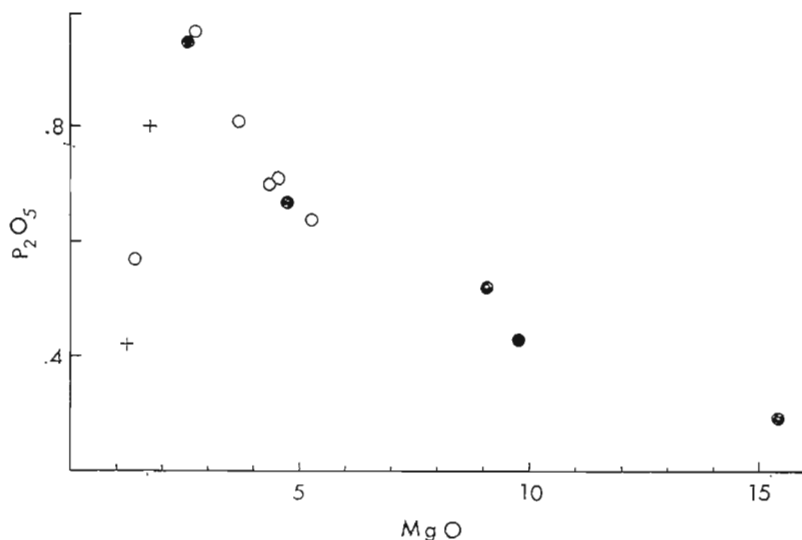


Fig. 4 — MgO versus P₂O₅ variation diagram for Nordeste volcanics. Symbols as in Figure 2.

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

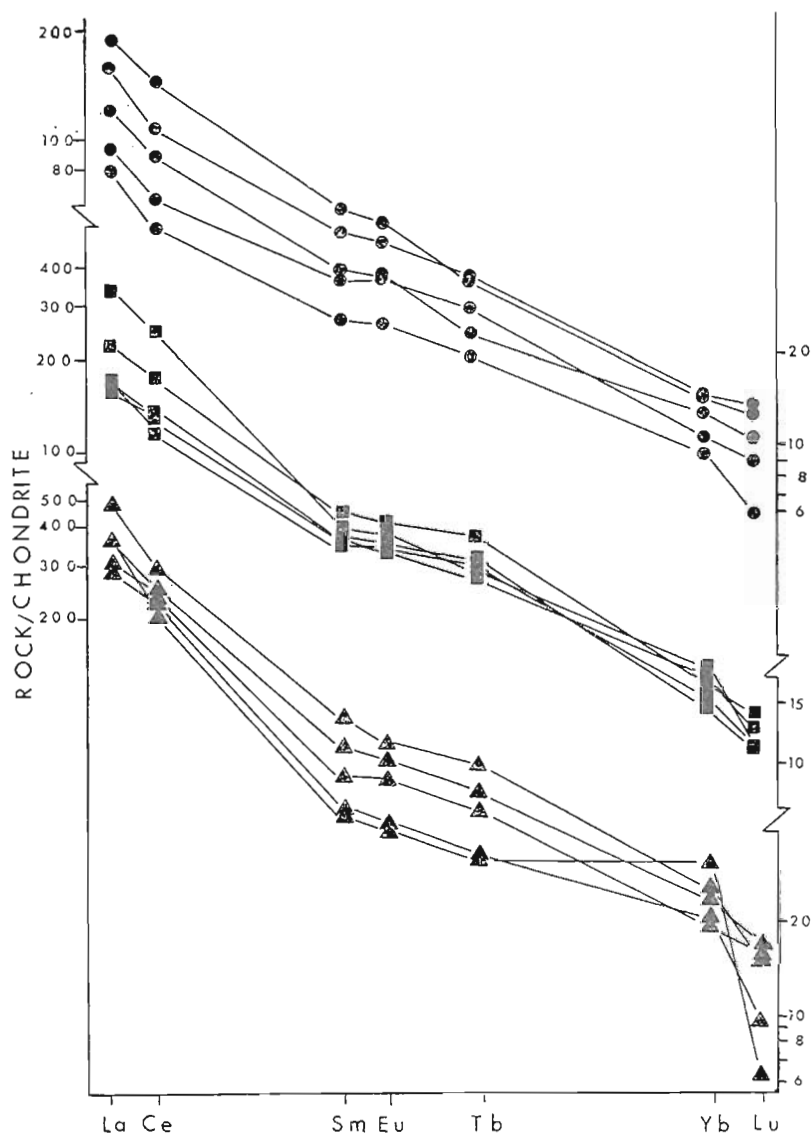


Fig. 5—Rare earth abundance patterns of Nordeste volcanics. Upper, middle and lower data sets represent alkali basalts, trachybasalts and tristanites-trachytes, respectively.

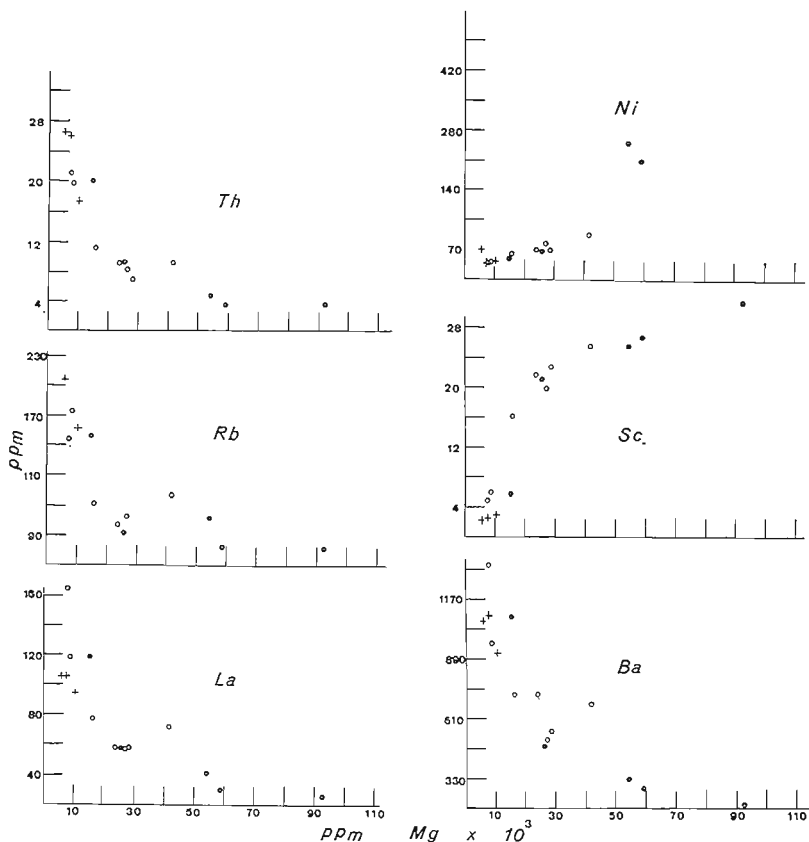


Fig. 6 — MgO variation diagrams for selected trace elements in Nordeste volcanics. Symbols as in Figure 2.

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 SiO₂ and for the increases in Na₂O, K₂O, SiO₂ and incompatible elements. The very marked decrease in P₂O₅ 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.

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THE PETROLOGY AND GEOCHEMISTRY OF THE AGUA DE PAU VOLCANO, SAO MIGUEL, AZORES

by

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and I. L. GIBSON³

INTRODUCTION

During recent years several geochemical investigations have centred upon the Azores (Schmincke 1973, Schmincke and Weibel 1973, Flower et al., 1976, White et al., 1979) with particular emphasis being laid upon inter island differences. Islands have been characterised as being relatively potassic (São Miguel) less potassic (Flores and Santa Maria) and sodic (Pico, Fayal, São Jorge, Graciosa and Terceira) (Flower et al., 1976). However, several of these islands are complex, consisting of several centres displaying multiple compositional trends. In this study we have concentrated upon lavas erupted from one volcano, that of Agua de Pau on the island of São Miguel (Fig. 1).

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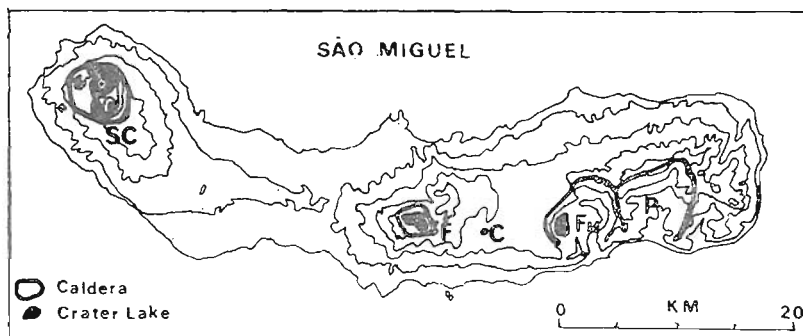


Fig. 1 — São Miguel Island. Symbols: SC = Sete Cidades, F = Furnas (Água de Pau) C = Congra, Fu = Furnas, P = Povoação Vulcânica.

The volcano consists of a central cone from whose caldera explosive trachytic eruptions have taken place. Basic and intermediate subsidiary cones are situated on its flanks, which have produced both lava flows and pyroclastics (Booth et al., 1978).

PETROGRAPHY

The lavas from the Água de Pau volcano belong to the alkali-olivine basalt-hawaiite-trachyte series. They are almost invariably porphyritic and frequently contain syenite nodules.

Olivine-basalts: The basalts contain phenocrysts of euhedral olivines $[Fo_{76-90}]$ and buff coloured clinopyroxenes containing up to 3.4 % TiO_2 , with ore (mainly titan magnetite with occasional ilmenite) and rare plagioclase $[An_{86} Ab_{13} Or_1 - An_{80} Ab_{38} Or_2]$, the whole being set in a groundmass of plagioclase laths, clinopyroxene, olivine and ore. In contrast some of the basalts contain numerous large rounded very magnesian olivines $[Fo_{87} +]$ and pale buff clinopyroxenes, which frequen-

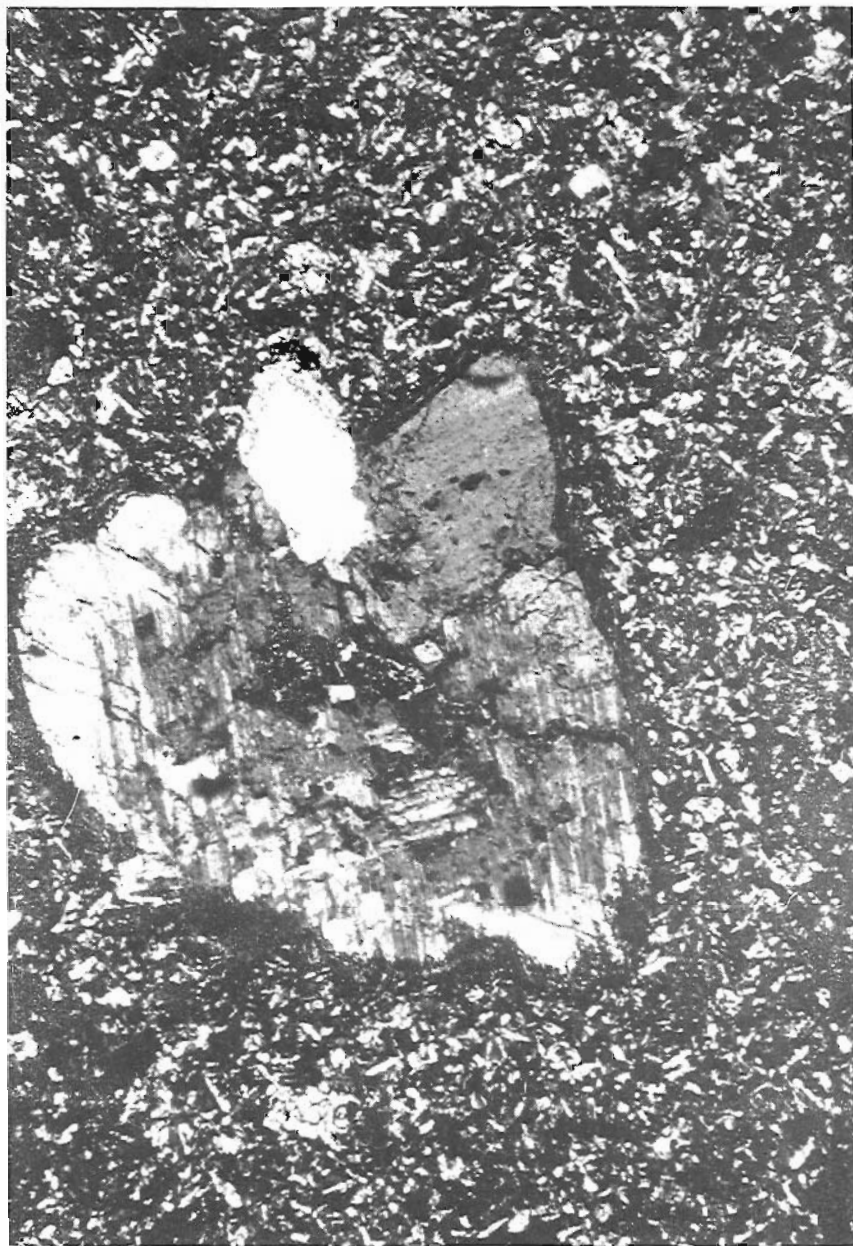


Plate 1 — Resorbed anorthoclase in hawaiite.

Field of view.

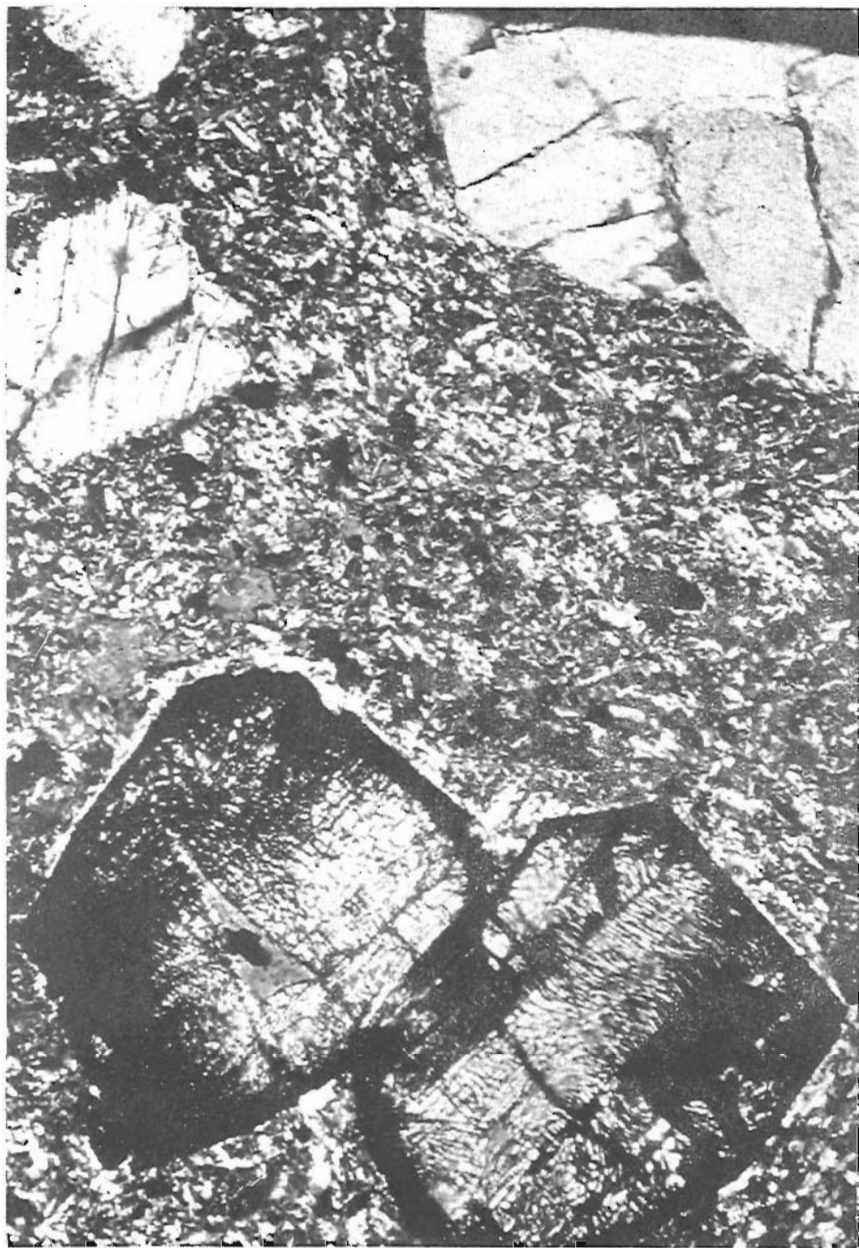


Plate 2 — Decorated olivine with exsolved magnetite.

tly occur in aggregates. Such xenoliths may represent pieces of sub-volcanic cumulate sequence or portions of wall rock.

Hawaiites: The most prominent feature of the hawaiites is the almost ubiquitous appearance of large, anhedral, strongly resorbed anorthoclases [around $An_{31}Ab_{56}Or_{13}$] which often exhibit cross hatched twinning on a fine scale (Plate 1). These anorthoclases are often associated in aggregates with or without large pale green clinopyroxenes and often have overgrowths and show evidence of polygonisation into smaller grains. Other feldspar phenocrysts consist of large carlsbad twinned alkali feldspar laths [$An_6Ab_{39}Or_{55}$], which again are usually rounded and partially resorbed. In addition to the large, pale buff clinopyroxenes, there are smaller, darker augites containing up to 3.9 % TiO_2 which are often hollow ended. Biotites are fairly comon, but tend to be resorbed and rimmed with iron ore. The groundmass consists of buff clinopyroxene, plagioclase laths varying amounts of ore.

Trachytes: Phenocrysts in the trachytes consist mainly of large alkali feldspars, either fresh, euhedral and carlsbad twinned [$An_2Ab_{61}Or_{38}-An_6Ab_{46}Or_{48}$] or ,to a lesser degree, large subhedral feldspars with resorption and polygonised textures and may show cross hatch twinning [$An_{17}Ab_{63}Or_{21}$]. Both types of feldspar may show overgrowths and contain frequent inclusions of biotite and pale green clinopyroxene.

Pale green euhedral aegirine occurs, occasionally altered to pale brown amphibole. Biotite is common, but is almost invariably oxidised with magnetite rims. Occasional pale brown, pleochroic amphibole is present.

Some trachytes contain rounded olivine crystals always altered in some degree, either being rimmed with iddingsite or ore, or in extreme cases, rimmed with a thick border of magnetite with more magnetite exsolved from the interior into a lace pattern (Plate 2). The magnetite was exsolved on too fine a scale to be resolved by the electron probe beam,

and the resulting analyses were those of stoichiometric olivines ($\text{Fe}_{0.90}$). X ray diffraction showed the presence of magnetite plus magnesian olivine, but no quartz from which we conclude that the silica required to maintain the stoichiometry in the reaction is amorphous.

CHEMISTRY

In a plot of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 it can be seen that the lavas of Agua de Pau fall distinctly on the alkaline side of the dividing line between tholeiitic and alkalic lavas (Mac-

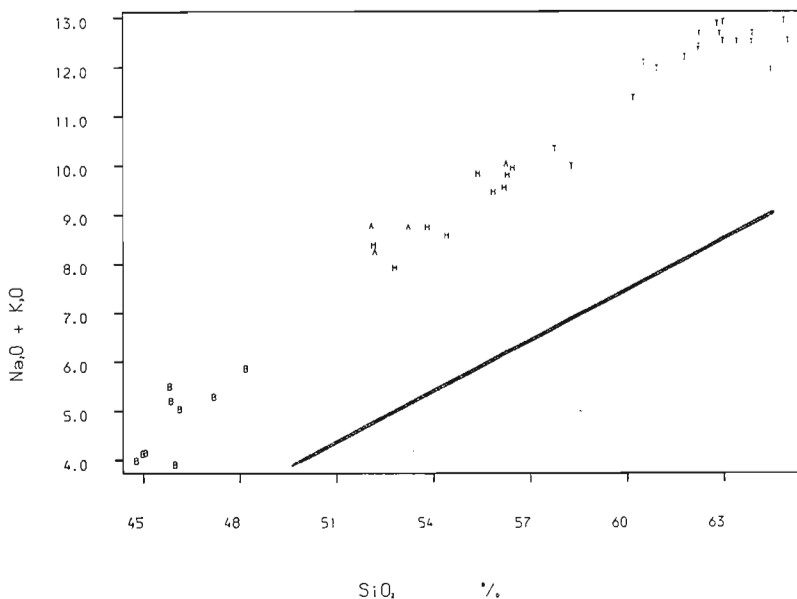


Fig. 2 — SiO_2 vs $\text{Na}_2\text{O} + \text{K}_2\text{O}$, Mac-Donald-Katsura plot. Symbols :T — trachytes, H — hawaiïtes, B — basalts, A — aphyric hawaiïtes.

donald & Katsura, 1964) (Fig. 2). It can also be seen that there are two pronounced gaps on the plot between the most basic lavas, the basalts ($< 50\% \text{SiO}_2$), the hawaiites ($50\text{--}59\% \text{SiO}_2$) and the trachytes ($> 59\% \text{SiO}_2$). It is realised that the feldspar composition should be used to justify the term hawaiite and split the group into hawaiite, benmoreite, mugearite etc. but the feldspar chemistry in these lavas is complex as has already become apparent and it is advantageous for our present purposes to give a single name to this intermediate group of rocks so as to emphasise the chemical coherence.

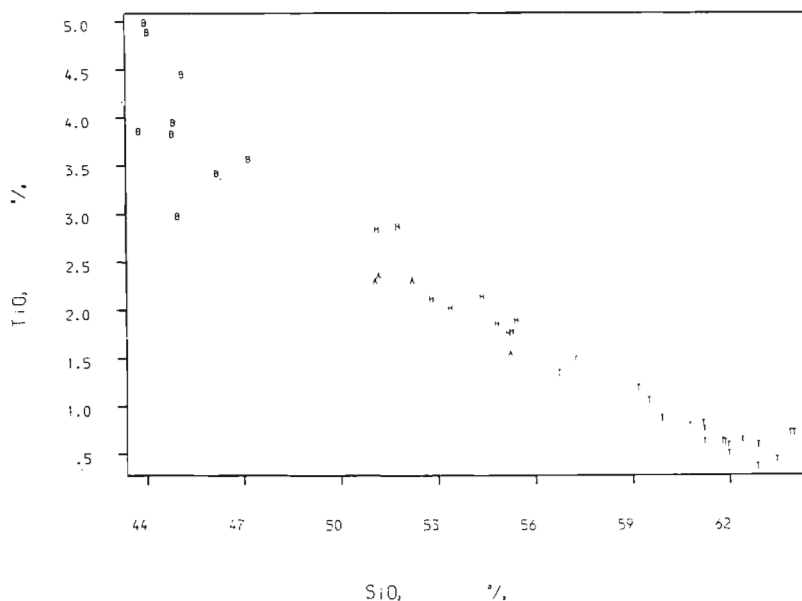


Fig. 3 — SiO_2 vs TiO_2 — symbols as for Figure 2.

Most of the other major element and many of the trace element versus SiO_2 diagrams also plot as smooth trends, for example, SiO_2 vs CaO , TiO_2 or Fe_2O_3 (total Fe) (Figs. 3 & 4) all form straight line graphs which is qualitatively consistent

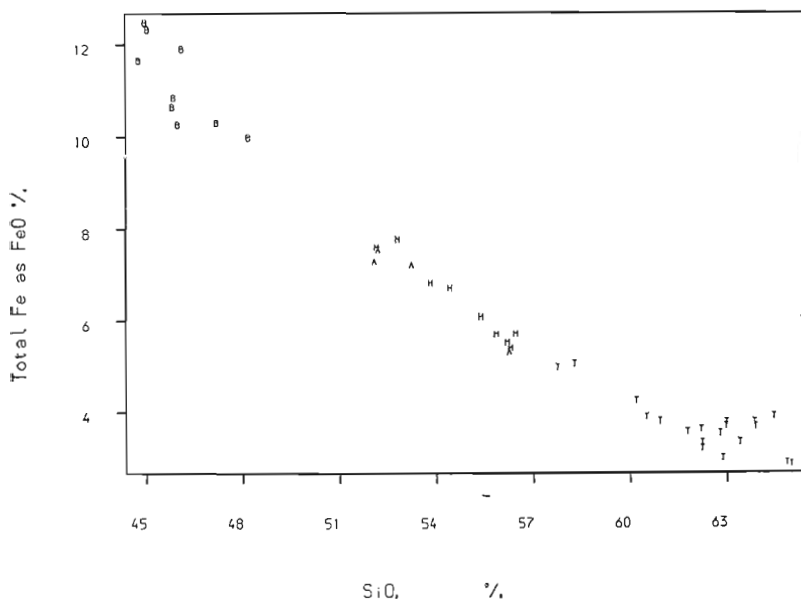


Fig. 4 — SiO₂ vs total iron as Fe₂O₃ — symbols as for Figure 2.

with the fractionation of plagioclase, clinopyroxene, olivine and ore. The suite as a whole is unusual in that Fe + Ti start decreasing in abundance with the first increase in SiO₂, so that there is no period of Fe or Ti enrichment. This pattern is suggestive of high oxygen fugacity, and oxide phenocrysts can be seen among the earliest crystallising phases.

Another feature of the chemical variation of the lavas is the late stage depletion of K₂O and Al₂O₃ (Fig. 5), commencing at approximately 62% SiO₂. This is consistent with the onset of fractional crystallisation of K feldspar from the trachytes.

Plots of SiO₂ vs MgO, Cr, Ni, P₂O₅ and the incompatible elements however do not follow the above simple patterns.

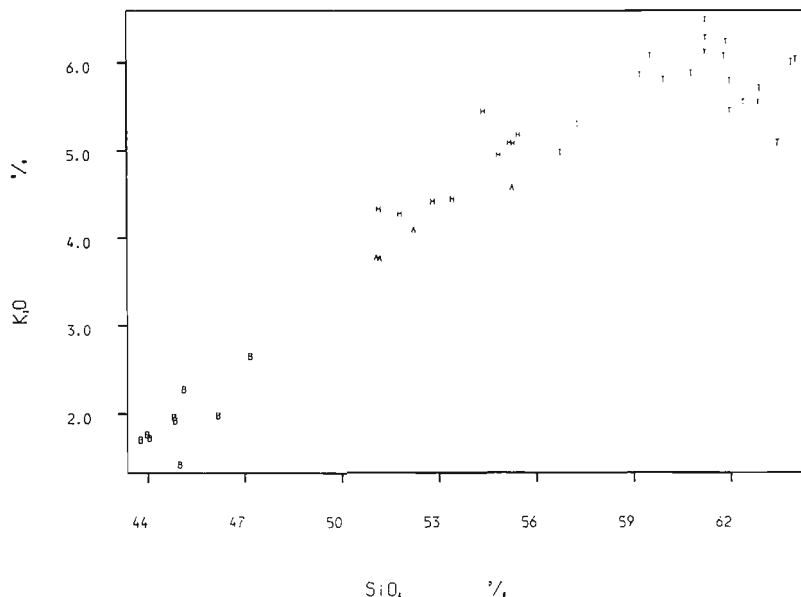


Fig. 5 — SiO_2 vs K_2O — symbols as for Figure 2.

For MgO vs SiO_2 (Fig. 6) the majority of the lavas form a smooth curve. However, the noteworthy part about this diagram is the group of lavas that plot on the MgO enriched side of the main trend. Petrographically these rocks contain the large, rounded olivine phenocrysts, which in the more acid samples become rimmed with iddingsite or ore, or which in extreme cases appear to have exsolved iron as an ore-rich rim, and a net-like pattern throughout the crystals. This exsolution implies that the trachytic lavas containing xenocrysts are oxidising with respect to the silica liquid-olivine-magnetite oxygen buffer reaction whereas the basic lava which precipitated the original olivine was reducing (Thompson 1975).

SiO_2 plotted against the trace elements Cr and Ni show similar trends, and chrome spinel can often be seen included in the olivines.

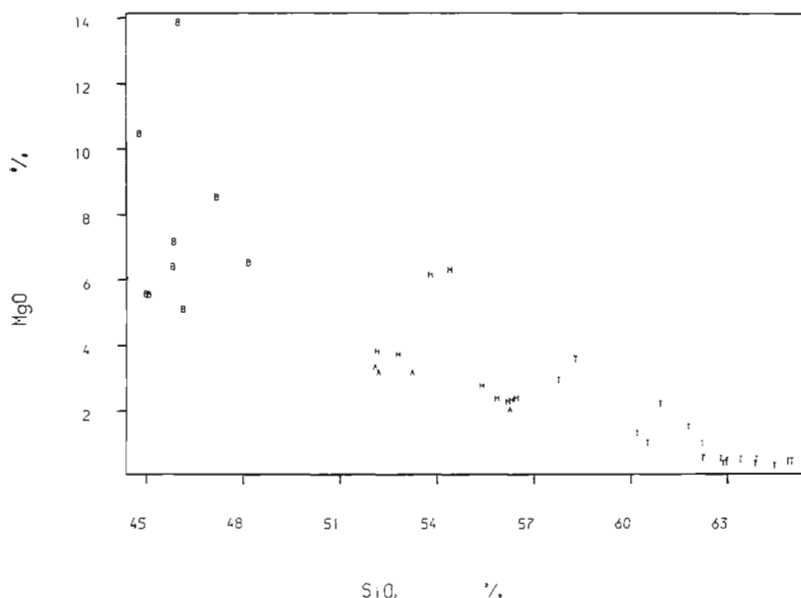


Fig. 6 — SiO₂ vs MgO — symbols as for Figure 2.

This MgO, Cr, Ni enriched group of lavas are also geographically distinct, and occur in the NE part of the volcano. It seems that this group have been enriched in olivine xenocrysts — as a cumulate phase.

Another distinct group of rocks are shown up on variation diagrams of SiO₂ versus Zr, Rb, Nb and the REE. The main trends of the data form curved patterns with higher concentrations of incompatible elements with increasing SiO₂ (Fig. 7), but with little enrichment in the incompatible elements at SiO₂ levels less than about 60 %. One group of hawaiitic lavas however, falls on the incompatible rich side of the main trend (marked A in Fig. 7). These lavas occur on the SE corner of the volcano, near Villa Franca do Campo, and are almost completely aphric — in particular they are the only hawaiites without resorbed anorthoclase and/or alkali feldspars.

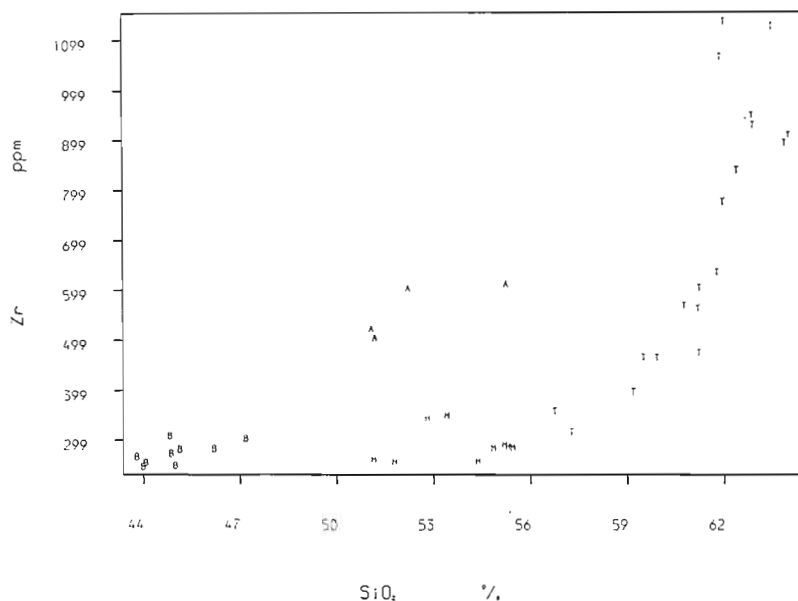


Fig. 7 — SiO₂ vs Zr — symbols as for Figure 2.

RARE EARTH ELEMENT CHEMISTRY

The chondrite normalised REE patterns of the Agua de Pau lavas are all steep, light REE enriched patterns with Ce_N/Yb_N ratios in the range 40-60. There is progressive enrichment of all the REE in the more evolved rock, but with no change in slope of the patterns. The most noteworthy feature of the chondrite normalised REE patterns are the Eu anomalies. The basalts (Fig. 8) have smooth patterns, while the trachytes (Fig. 9) have strong negative Eu anomalies ($Eu/Eu^* \approx 0.3$) consistent with plagioclase (or Ca bearing feldspars) fractionation. The hawaiites fall into two distinct groups (Fig. 10) the aphyric group with slightly more enriched, smooth patterns,

and the porphyritic group with small but consistent positive Eu anomalies ($\text{Eu}/\text{Eu}^* \approx 1.5$). Petrographically it can be seen that these lavas contain large, rounded, partially resorbed anorthoclases and alkali feldspars, while the aphyric hawaiites do not.

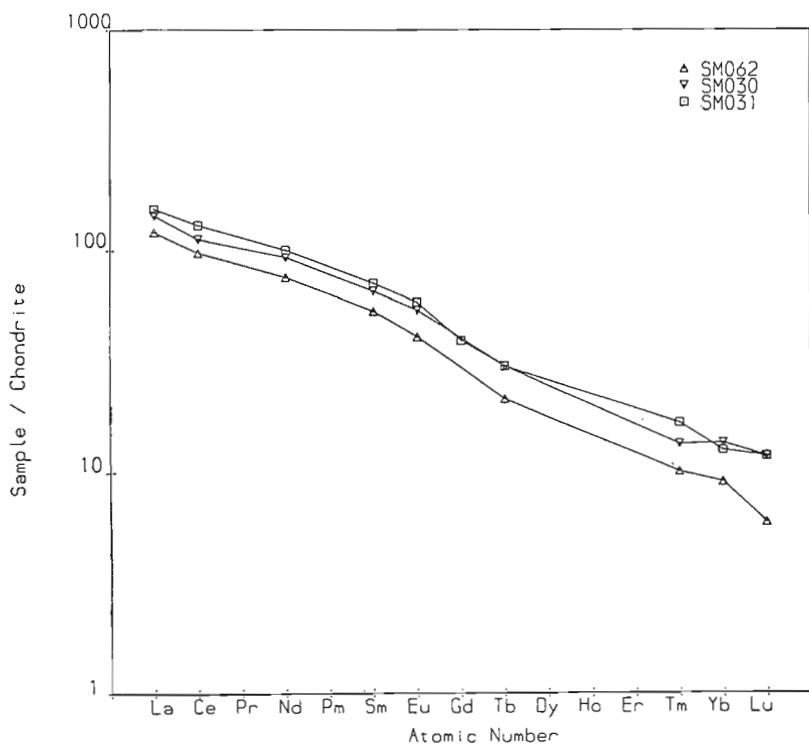


Fig. 8 — Chondrite normalised plot of REE for basalts.

When K/Rb ratios are plotted against Eu anomaly (Fig. 11), it can be seen that the hawaiites with their positive Eu anomaly also have high K/Rb ratios, while the trachytes with negative Eu anomalies also have K/Rb ratios relative to the basalts

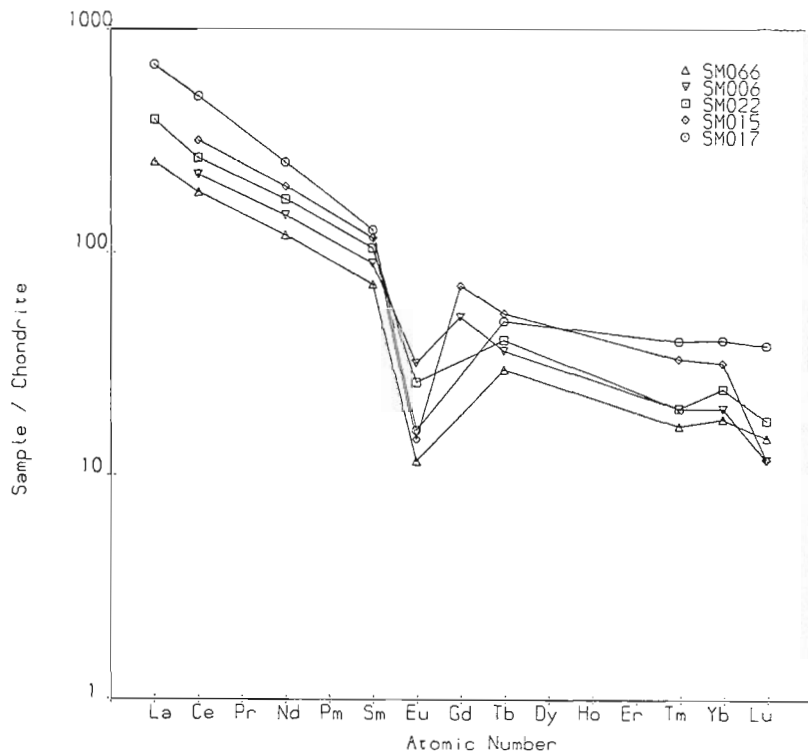


Fig. 9 — Chondrite normalised plot of REE for trachytes.

and aphyric hawaiites. As alkali feldspars are known to have very high K/Rb ratios this is consistent with loss of Eu, and K relative to Rb in feldspar during fractionation in the latter case, while in the former case the increased K/Rb ratios and positive Eu anomaly can be readily explained by addition of alkali feldspar and anorthoclase both which can be seen in a highly resorbed state in the hawaiites.

It is noteworthy that the small group of aphyric hawaiites without resorbed feldspars show neither positive Eu anomalies nor increased K/Rb ratios relative to the basalts. Furthermore,

they have higher absolute concentrations of the rare earth and other incompatible elements over the phyric hawaiites, consistent with the latter having been considerably diluted by non-incompatible element bearing phases e.g. feldspars. Thus in Fig. 7 the aphyric hawaiites may represent the main liquid line of descent, while the hawaiites on the main trend are not liquid compositions at all, but represent liquids which have been enriched in cumulus alkali feldspar and anorthoclase.

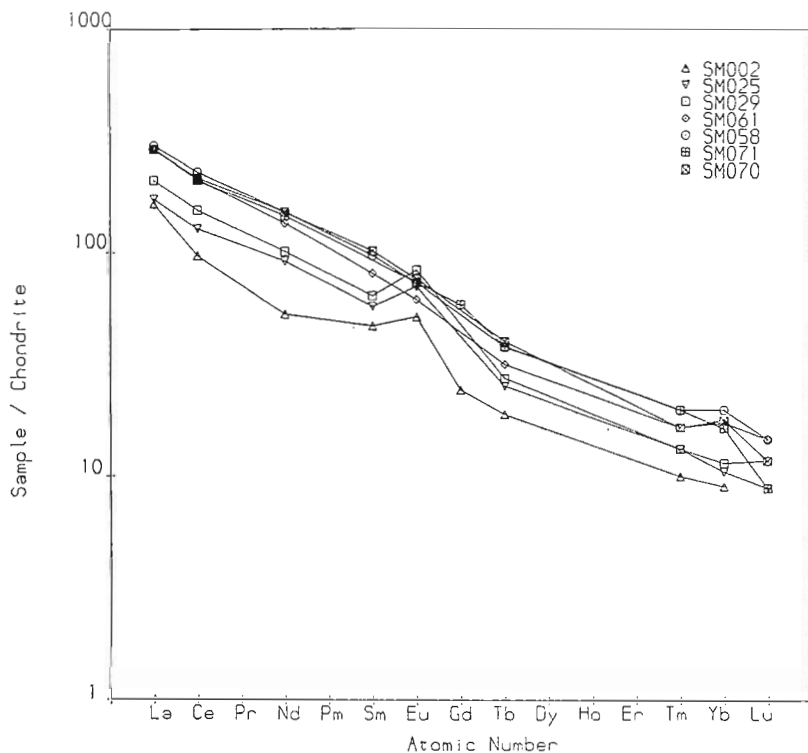


Fig. 10 — Chondrite normalised plot of REE for hawaiites :
 SM002, SM025, SM029 = hawaiites
 SM061, SM058, SM070, SM071 = aphyric hawaiites.

SYMPOSIUM ON THE ACTIVITY OF OCEANIC VOLCANOES

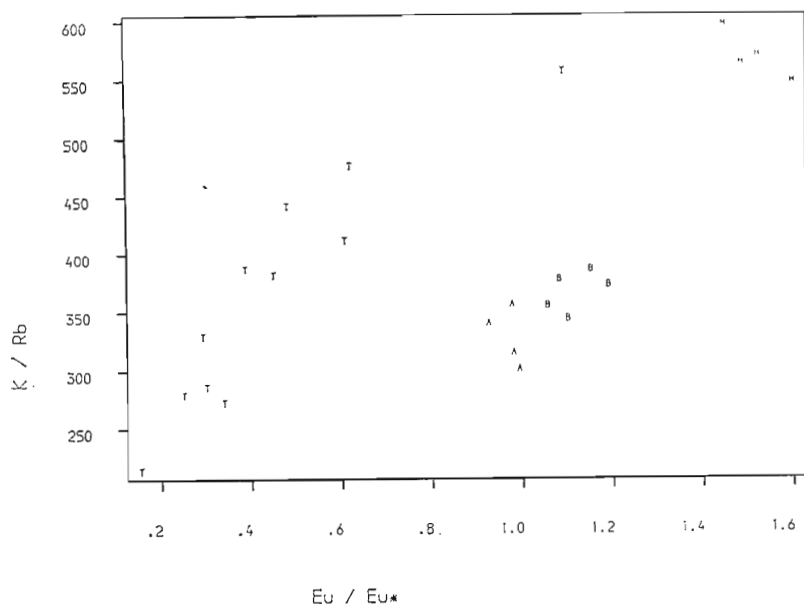


Fig. 11 — K/Rb plotted against Eu/Eu* symbols as for Figure 2.

The only lavas in the suite which appear to precipitate alkali feldspar as an equilibrium phase are the trachytes. Therefore it is tempting to think that alkali feldspars in the hawaiites were originally precipitated by the trachytes. Consideration of Sr and Ba data reinforce this conclusion. That the feldspar-phyric hawaiites can be generated by simple mixing of trachyte and basalt liquids is precluded by the low levels of incompatible elements and the Eu anomaly data. Consequently the only explanation remaining is that the feldspar xenocrysts in the hawaiites have sunk from overlying trachytic magma.

CONCLUSIONS

In conclusion, the most satisfactory explanation for the presence of resorbed feldspars in the hawaiites and the trace element geochemistry, particularly the REE distributions in the lavas, is the existence of a vertically zoned magma chamber beneath the Agua de Pau volcano. In this vertically zoned magma chamber fractionation has occurred to produce basalt, hawaiite and trachyte magma layers, one above the other. During the fractionation process, alkali and anorthoclase feldspars have settled from the trachyte layer into the hawaiite layer, thus supplying the hawaiite with positive Eu anomalies, depleting the incompatible elements (e.g. Zr, Nb and the REE) and increasing the K/Rb ratios. New batches of magma entering the magma chamber are presumed to cause turbulence and may be responsible for the frequent occurrence of olivine /clinopyroxene and syenite xenoliths.

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PETROGENESIS OF THE RECENT TRACHYTIC PYROCLASTIC SUCCESSION OF AGUA DE PAU VOLCANO, (SAO MIGUEL, AZORES)

by

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ABSTRACT

The recent stratigraphy of São Miguel records large numbers of trachytic pyroclastic deposits produced by plinian to sub-plinian eruptions. Tephrochronological studies by Booth, Croasdale and Walker (1978) have shown that in the last five thousand years there have been five such eruptions from Agua de Pau, one of three active stratovolcanoes on São Miguel.

A geochemical and electron microprobe study made on the resultant pyroclastic succession, revealed significant variations in pumice clast chemistry and mineralogy between the individual deposits. For example, Sr and Eu/Eu^* decrease in value through the succession, whereas 'incompatible' elements such as La, Zr and Nb show stepwise enrichment attaining highest concentrations in the most recent deposit. The individual pyroclastic deposits are interpreted as representing

successive samples of a body of trachyte magma undergoing appreciable crystal fractionation.

However not all of the observed chemical and mineralogical variations of the pyroclastic deposits are consistent with simple differentiation. For example, evidence is presented that trachyte magma has periodically mixed with intermediate and basaltic magmas. Magma mixing has found to be a recurrent feature of many of the lavas and pyroclastic deposits from Agua de Pau.

Associated lavas possessing REE patterns with positive Eu anomalies and mineralogical peculiarities are also discussed.

A case is made for the existence of a compositionally zoned magma chamber beneath Agua de Pau volcano.

(This paper was not read at the Symposium)

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GEOCHEMISTRY OF EYJAFJÖLL, A VOLCANO IN SOUTHERN ICELAND

by

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ABSTRACT

Eyjafjöll is a central volcano in the eastern neo-volcanic zone of southern Iceland. Its last eruption occurred from 1821 to 1823. Most of the volcano is composed of transitional alkali basalt and basaltic andesite. Rhyolites and dacites have been erupted only from the central, glacier capped, caldera. Good stratigraphic coverage was obtained from three traverses from the base of the mountain to the ground moraine on top. The best section was sampled on the deeply dissected southern side of the volcano.

Major element whole-rock analysis of 64 samples and microprobe determined compositions of selected phenocryst phases have been used to develop a fractionation model relating the various rock types produced by the volcano. Considerable subtraction of olivine from a hypothetical primary magma is required to produce even the least silicic compositions observed

at the surface. More silicic compositions can be derived from one of two «parent» compositions, chosen from the least differentiated rocks sampled, by further subtraction of plagioclase, clinopyroxene, and magnetite with minor ilmenite and olivine. No separate source or mechanism is required to produce the small quantities of rhyolite found, as they can be derived by fractionation. There is some evidence that the magmas of Eyjafjöll have become less alkalic and more silica-saturated with time.

(This paper was not read at the Symposium)

MAGMA MIXING AND HYBRIDISM : A PRELIMINARY STUDY FROM SOUTHERN ICELAND

by

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ABSTRACT

The importance of magma-mixing in the generation of intermediate rock types is discussed in the light of two occurrences of mixed rocks found in the Tindfjallajökull silicic centre, S.-Iceland. The first being a minor mafic part of the large Thorsmörk ignimbrite (Jørgensen, 1980), demonstrates the formation of non-linearly derived hybrids through differential interdiffusion of elements, in connection with resorption/crystallization of phenocryst phases, demonstrated by the occurrence of abundant xenocrysts of feldspar and pyroxene and new crystallization of pyroxene and magnetite in the hybrids. The

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second occurrence is a mafic lava of benmoreitic composition, containing xenocrysts of acid and basic feldspars and pyroxenes in addition to unresorbed phases in equilibrium with the melt. Several other rocks show disequilibrium features which may indicate mixing of two contrasting magma types, though other rock types contain phases which may be remnants from partial melting of crustal material, as well as of fractional crystallization.

INTRODUCTION

The contemporaneity of acid and basic magmas in Iceland has challenged petrologists since the days of Bunsen, and explanations of the relationship have changed several times. Since the early sixties two contrasting schools of thought have evolved, the first explaining the phenomenon in the terms of fractional crystallization best illustrated by the Thingmuli (Car-michael 1964, 1967) and the Setberg centres (Sigurdsson 1970), or in terms of partial melting of crustal material as proposed by Walker (1966) and further evolved by Grønvold (1973), Sigvaldasson (1974), Johannesson (1975) and recently in a comprehensive model by Oskarsson et al. (in press).

The present study is mainly concerned with the importance of magma-mixing in the formation of intermediate rocks exemplified by the late Pleistocene Tindfjallajökull silicic center in S.-Iceland, and an associated pyroclastic flow deposit, the Thorsmörk ignimbrite.

THE THORSMÖRK IGNIMBRITE

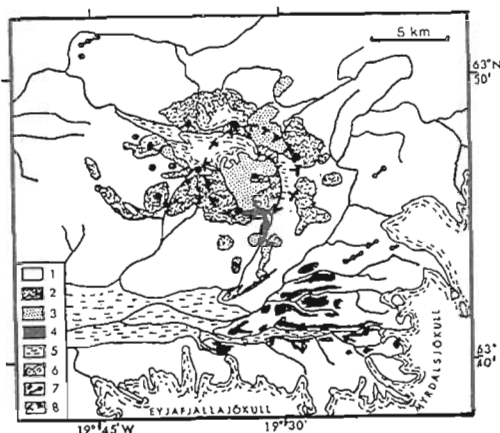


Fig. 1 — Simplified geologic map of the Tindfjallajökull silicic center and surroundings. 1 : basalts undifferentiated. 2 : evolved rock types, basaltic andesites to benmoreites. 3 : rhyolites. 4 : The Thorsmörk ignimbrite. 5 : alluvium. 6 : icefields. 7 : late to postglacial vents. 8 : inferred caldera fault. Rocks of neighbouring centers undifferentiated.

The Thorsmörk ignimbrite (Fig. 1) was originally described by Thorarinsson (1969), and in more detail by Jørgensen (1980a, b). The mapping of the ignimbrite demonstrated that it originated within the caldera-region of the Tindfjallajökull silicic center during the penultimate interglacial of the region (approx. 200.000 years old). It was emplaced as a series of low energy pyroclastic flows which buried the surrounding low-land to a max. depth of > 200 m in a prolonged eruption sequence. The lower part of the ignimbrite is welded and crystallized after emplacement, producing a compound cooling

unit. The present outcrop are aof 80 km² must have contained an original volume of 6 km³ ignimbrite (4 km³ dense rock equivalents) indicating a probable original total volume of the order of 6-8 km³ dense rock.

Petrologically 95 % of the juvenile material is a rather homogeneous comendite showing small, but significant, variations in the phenocrysts. Variations in the feldspar phenocryst compositions indicate a small, but permanent thermal gradient in the magma-chamber prior to eruption, while trends in the pyroxenes indicate falling fO₂ during crystallization, stabilizing the formation of fayalite in the upper part of the magma-chamber. Exsolution phenomena and large ranges in haematite and ulvöspinel contents in the oxides from the uppermost part of the ignimbrite indicates disequilibrium conditions in the magma-chamber at this stage of the eruption, probably resulting from external heating of the magma-chamber.

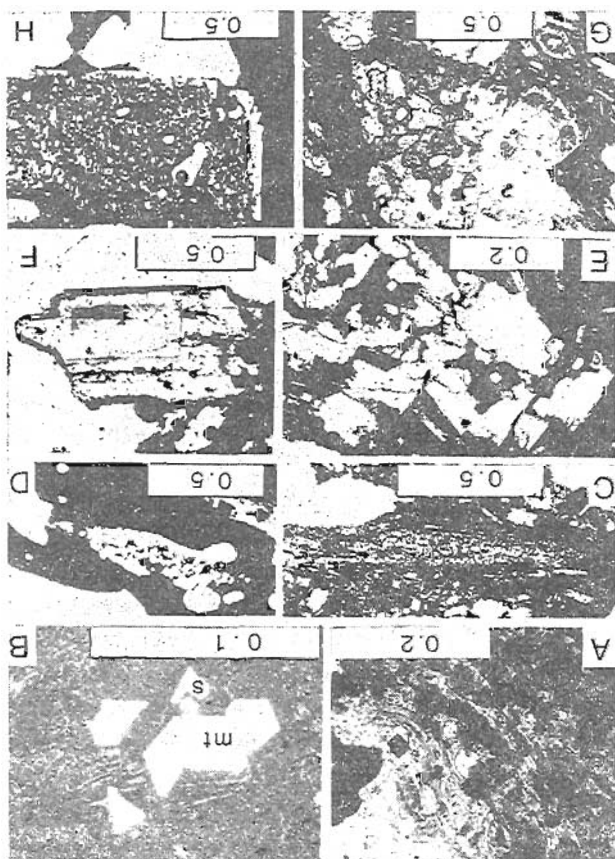
In addition to the comendite, the ignimbrite contains a suite of mafic glasses constituting approximately 5 % of the juvenile material. This material ranges in composition from transitional basalt (in the sense of Jakobsson, 1972) through mugearite and benmoreite to subcalciic rhyodacite, spanning the whole silica range from 46 to 71 % SiO₂.

The material occurs as glass shards and lapilli fragments, which are often transparent, especially the more silica rich varieties, but larger clasts are often tachylitised, due to crystallization of a fine web of feathery pyroxene and skeletal magnetite, Fig 2 B.

The material is compositionally rather heterogeneous even within single fragments, Fig. 3. The heterogeneity is often seen as colour banding in the transparent glasse, Fig. 2A, as lighter or darker patches, or various different shades of brown or grey, probably a function of different oxidation ratios. True banded pumices with alternating dark and light bands occur throughout the ignimbrite, but change in character from bottom to top, the mafic bands becoming more siliceous with increasing height in the ignimbrite and interdiffusion becoming more

Fig. 2 — Microphotographs from the Thorsmörk ignimbrite and Tf 13. A. Transition from dark basalt to light basaltic andesite (with magnetite microcrysts). Lower part of Thorsmörk ignimbrite. B. Magnetite (mt) and sulfide globules (s) in matrix of feathered pyroxene and glass of mugearitic composition. Middle part of THI. Reflected light. C. Fe-hedenbergite with abundant glass inclusions. Tf 13. D. Fe-hedenbergite with abundant glass inclusions in benmoreitic glass. Uppermost part of THI. E. Strongly resorbed basic plagioclase. Tf 13. F. Slightly resorbed oligoclase mantled by anorthoclase in mugearitic glass. Lower part of THI. Partly crossed N. G. Fingerprint textured anorthoclase with oligoclase rim. Hollow ferrosalite microcryst in lower left. Tf 13. (Dark amoeboid patch in anorthoclase is artifact). H. Strongly resorbed anorthoclase with oligoclase rim in benmoreitic glass. Uppermost part of THI.

Bar scale in mm.



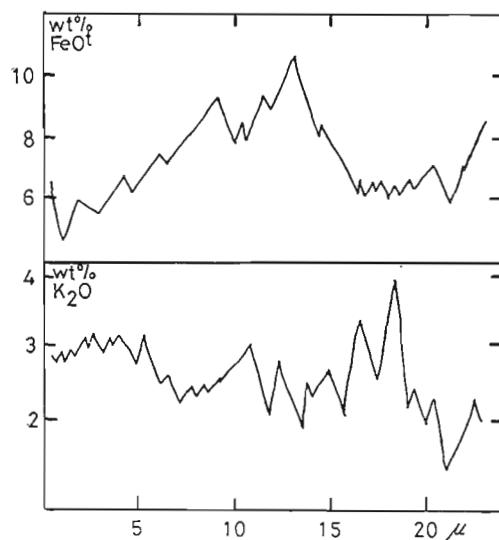


Fig. 3 — Tracings of elemental scans across heterogeneous glass, for Fe and K. Uppermost part of TH1.

pronounced. The banded pumices indicate mechanical, incomplete mixing, while large mafic clasts of benmoreitic composition, Table 1: Th2, represents a much more advanced stage of diffusional mixing where the more acid glasses only occur as occasional small patches more or less digested in the large mass of mafic benmoreite.

The most basic material is homogeneous and may occur as spheres of the type formed during Hawaiian fountaining, Heiken (1972) but is mainly found as shards and subrounded, vesiculated lapilli, of the type mainly found strombolian deposits, Walker and Croasdale (1972). The mugearitic material is mainly found as strongly vesiculated clasts of reticulite type, Heiken (1972). The benmoreitic material is very massive and little vesiculated while more siliceous material becomes increasingly more vesiculated becoming true pumices around 70 % SiO_2 .

The mafic glasses contain a number of minerals displaying a wide range of textures. The basic glass apparently contained rare phenocrysts of olivine, augite and labradorite plagioclase, which all occur more or less resorbed. The intermediate glasses crystallized ferrosalitic pyroxenes (Fig. 4), oligoclase plagioclase, magnetite and sulphide globules as phenocrystal phases, while Fe-hedenbergitic pyroxene (Fig. 4), and magnetite occur as microcrystal phases. The phenocrysts are inevitably resorbed (Fig. 2F), but not as much as the abundant xenocrystal phases from the comendite, mainly Fehedenbergite with abundant glass-inclusions (Fig. 2D), and anorthoclase commonly displaying finger-print textures, or even higher degrees of resorption (Fig. 2H).

The mixing apparently took place between the temperature of the comendite, 915° C (Fe-Ti oxide temperature after Buddington and Lindsley, 1964) and 1100° C for the basalt (olivine/liquid temperature after Roeder (1974) and Bender et al. (1978)). The magnetites of the intermediate compositions are very high in ulvöspinel content indicating rather reduced conditions.

THE TINDFJALLAJÖKULL SILICIC CENTER

The Thorsmörk ignimbrite originated within the Tindfjallajökull silicic center, and a major question was then whether intermediate rocks comparable to hybrid compositions found in the ignimbrite, was present as independent rock units within the center.

The Tindfjallajökull silicic center was mapped in detail by Larsen and Jørgensen (personal communication), and initial results show that the center is mainly composed of transitional basalt with abundant sub-calcic to peralkaline rhyolite (Table I), with minor intermediate rocks of mainly basaltic-andesites with

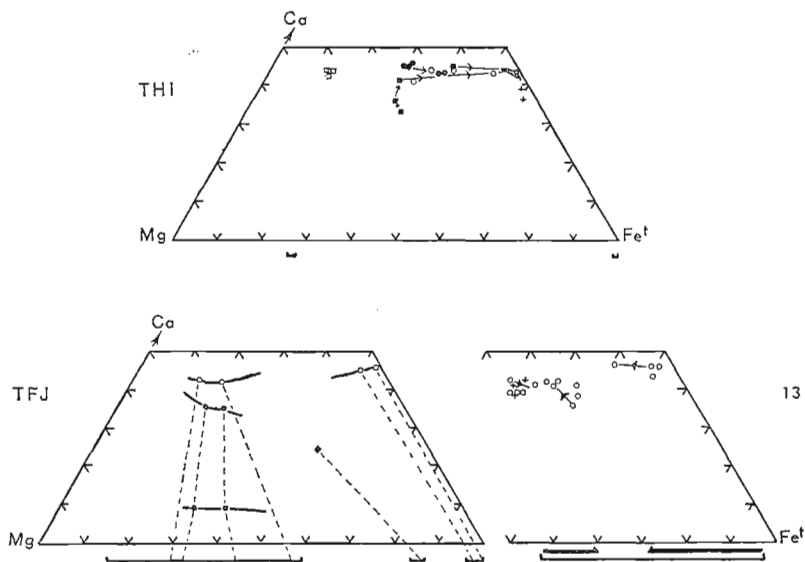


Fig. 4 — Pyroxene quadrilaterals (preliminary) for the Thorsmörk ignimbrite (THI), the Tindfjallajökull igneous suite (TFJ) and sample TF 13 (13). Symbols: *THI*. hatched area: general field of comenditic pyroxenes. Filled squares and circles: zoned pyroxenes. Filled squares and circles: zoned pyroxenes in comendite. Crosses: microcrysts in quenched rhyodacite. Open triangle: microcryst from mugearitic glass. Open circles: phenocrysts from various hybrid glasses. Open squares: phenocrysts in basic glass. Lower bars: associated olivines. *TFJ*. Heavy lines: generalised pyroxene trends for the igneous suite. Dashed lines: connects coexisting cpx, olivine and opx for different assemblages. Open circles: basalt. Closed circles: intermediate rocks. Open squares: acid rocks. Diamond: hornblende bearing rhyolite. 13. Heavy arrows at bottom: shows direction of zoning in olivines. Crosses: microcrysts in glomerocryst.

marked alkaline affinities (Fig. 5). The intermediate rocks show several complexities, some of them looking very much like ordinary icelandites, while others seem to be true mugearites. One of the rocks, Tf. 13, seemed to be a rather homogeneous

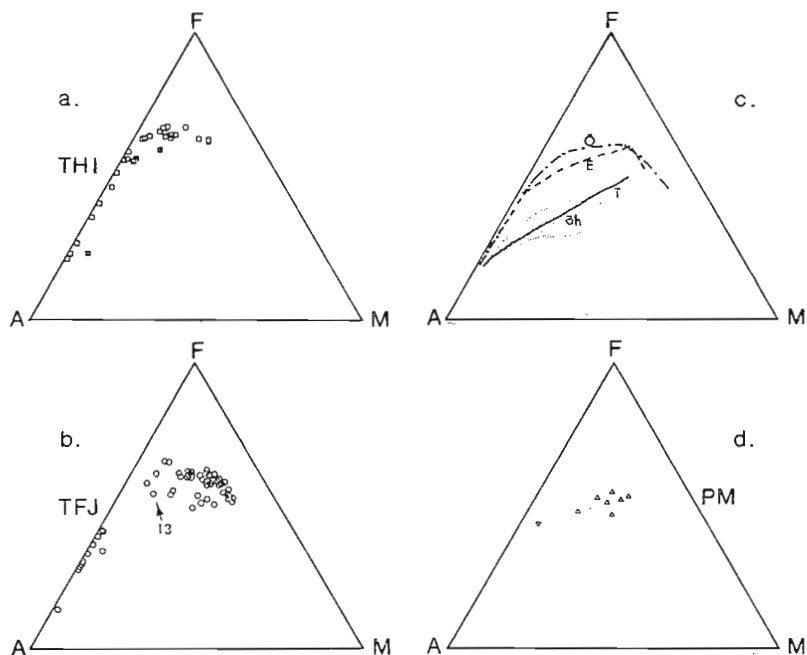


Fig. 5 — Representative AFM diagrams, (wt. % $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{FeO}^t - \text{MgO}$). *a.* The Thorsmörk ignimbrite suite. Open squares : single spot microprobe analyses. Filled squares : whole rock analyses. *b.* The Tindfjallajökull igneous suite, whole rock analyses. Arrow points to sample Tf 13. *c.* Comparative trends. O : Örfajökull main trend, (Prestvik, 1980). E : Eyjafjallajökull, (Arney, 1978). T : Torfajökull mixed trend, (Grønvold, 1973). öh : Örfajökull hybrid field, (Prestvik, 1980). *d.* Partial melts from gabbro-standing triangle) and granophyre (inverted triangle) xenoliths from Tindfjallajökull hyaloclastites, (Larsen, 1979 and personal communication).

benmoreite, but microprobe investigation proved it to be very heterogeneous, containing phenocrysts of both Fe-hedenbergitic and augitic compositions zoned to ferrosalite, while similar trends are found in the olivines, (Fig. 4) and in the feldspars, which show finger-print textures, (Fig. 2G) and strong disinte-

gration (Fig. 2E). Microcrysts in vesicular glomerocrysts have compositions comparable with the most basic pyroxenes, while the microcrysts in the groundmass are ferrosalites. This mineralogic evidence indicates that the rock resulted from mixing of approximately equal amounts of comendite and transitional basalt, and thus is very similar to the benmoreitic compositions found in the Torsmörk ignimbrite. Many other rocks in the Tindfjallajökull centre shows disequilibrium relationships, but many of these are not as readily interpreted as magma-mixing as was the Tf 13. It appears as though two parental basaltic compositions are present, a dominant low magnesium transitional basalt type and a subordinate high magnesium tholeiitic type, (Fig. 5). The transitional basalt type seems to grade continuously into rocks of basaltic andesite composition, an evolution most probably resulting from fractional crystallization. More evolved rocks inevitably show disequilibrium features, and in more finegrained varieties two sizegrades commonly appears thoroughly mixed, indicating mixing of two magmas not very different in composition. The comendites only rarely shows disequilibrium features, indeed many of them are only sparsely porphyritic and the minerals present shows only very restricted compositional ranges. The subcalic rhyolites on the other hand commonly shows disequilibrium features in the shape of resorption of phenocrysts as well as clots of quenched mafic material, even for the most evolved rhyolite, a hornblende-fayalite-ore-allanite-oligoclase-phyric, high silica rhyolite. The tholeiitic basalt type does not seem to have any direct successors, but a scattered selection of rocks falling off the main trend of evolution for the center, (Fig. 5) and generally showing abundant disequilibrium textures, may be more or less associated with this type. The abundance of more or less melted xenoliths of gabbroic or granophyric composition found in the frequent hyaloclastites of the center, Larsen (1979), presents a further complication. Partial melts formed from these, Fig. 5 (Larsen, 1979) plot in the scattered field of compositions described above. The occurrence of pyro-

xene phenocrysts with partly exsolved orthopyroxene lamellae, characteristic of slowly cooled plutons, in some very plagioclase-rich rocks, seems further evidence of the importance of contamination from wall rocks.

DISCUSSION

The data presented above show that magma-mixing is an important, though not the only, operative process in the formations of the intermediate rocks of the Tindfjallajökull. One may then question the importance of this observation on the regional scale. Silicic hybrid rocks have recently been described from the Öræfajökull center in SE-Iceland, Prestvik (1980), and many of the features described are comparable with those of the present work. Grønvold (1973) described and gave analyses of hybrid rocks from the Torfajökull silicic center S-Iceland, and so did Wetzel et al. (1978). The origin of the Hekla andesites have variously been attributed to fractional crystallization of basalt, Baldrige et al. (1973), partial melting of crustal material, Sigvaldasson (1974) and magma-mixing Wetzel et al. (1978). The Eyjafjallajökull igneous series (Arney, 1978), on the other hand was claimed to be solely a product of fractional crystallization, in spite of the occurrence of mechanically mixed lavas and abundant disequilibrium features, Arney (1978). The important difference between the earlier described occurrences of hybrid rocks and those of the present study is, however, the marked deviation from a linear mixing line of the hybrid composition, especially for elements such as Na, Fe, P, Mn (enriched) and Ca, Mg, Ti (depleted). This is a clear indication that processes other than mechanical mixing were operative, of which differential interdiffusion, as observed on a micro-scale, and, resorption/crystallization of phenocrysts, of the type proposed by Aderson (1976), were the most important,

while both fractional crystallization and partial melting of crustal material, definitely were important in the formation of several rock types present in the TFJ center. Similar complex processes undoubtedly operated in the formation of rocks from the neighbouring gsilic centers described above, though more detailed studies are needed to establish to what degree.

Eichelberger (1978), proposed that thorough mixing of magmas to produce intermediate rocks were characteristic of subduction zone situations, due to thick crust and thus long residence time for magmas in this environment, while rift areas were characterised by scarce intermediate rocks and a pronounced bimodality, due to thin crust and correspondingly short residence time for magmas. The present data corresponds well to this model, the amount of intermediate material being insignificant against the abundant basalts and rhyolites. Further the data presented corresponds extremely well to the model presented for southern Iceland by Oskarsson et al. (in press), the Tindfjallajökull actually being placed in the middle of their zone most favourable of mixing, the transitional basalt corresponding to their wet alkali basalt, and the tholeiitic type being injected from the Eastern Rift Zone proper, and through mixing/crystallization resulting in the other observed rock types. The melted xenoliths could then be remnants after melting of amphibolite, though amphiboles are extremely rare, even in unmelted samples. The composition of the partial melts is further more similar to tholeiites, but this may not be significant, as it could be a function of very local conditions with the liquid later being modified during collection.

CONCLUSIONS

The present study has demonstrated the importance of magma-mixing in the production of intermediate rocks in the Tindfjallajökull silicic center, supplementary to other petrogenetic processes, and implied this probable importance in the case of several other centers, though the origin of the parental composition remains unresolved. The wide range of compositions present in the Tindfjallajökull center, however, indicates that this center remains a key area to the understanding of the fundamental petrogeentic processes operating in this region, and is thus important to the understanding of oceanic island volcanism in general.

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TABLE I
REPRESENTATIVE ANALYSES

	Tf 1	Tf A1	Th 1	Tf 13	Th 2	Tf 236	Th 3
SiO ₂	47.12	45.28	46.15	57.64	61.65	72.29	74.28
Al ₂ O ₃	13.92	14.93	12.70	13.17	12.77	11.51	11.41
TiO ₂	2.97	3.96	4.10	1.83	1.31	.23	.17
FeO. ¹	12.35	14.20	15.66	10.78	10.80	3.36	2.73
MnO	.19	.20	.32	.29	.33	.10	.07
MgO	8.13	6.57	4.98	1.83	.65	.06	.02
CaO	10.57	10.16	9.64	4.87	3.83	.46	.42
Na ₂ O	2.83	2.92	3.13	5.66	5.42	5.89	4.82
K ₂ O	.54	.53	.73	1.59	2.41	3.80	4.17
P ₂ O ₅	.35	.38	1.03	.64	.36	.01	.01
Sum	98.97	99.13	98.46	98.30	99.47	97.71	98.10

Explanation :

Tf 1 : basalt from northern part of Tindfjallajökull silicic center

Tf A1 : biotite bearing basalt from SW part of Tfj. center

Tf 13 : mugearite from central part of Tfj. center

Ff 236 : comendite from northern rim of Tfj. caldera

Th 1 : basic shard from middle part of Thorsmörk ignimbrite

Th 2 : benmoreitic shard from uppermost part of THI

Th 3 : average comendite from THI

All Tf : whole rock analyses from G.G.U. Geochemical Lab.

All Th : single point microprobe analyses

All Fe : calculated as FeO for convenience.

KRAFLA LAVAS 1975-1980 — CHEMICAL VARIATION

by

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ABSTRACT

Basaltic magma is continuously being fed into magma reservoirs at about 3 km beneath the Krafla volcano in North Iceland. At the same time the North Iceland plate boundary is undergoing a major rifting episode on a 100 km long fault swarm that intersects the Krafla volcano. Most of the magma resides a short period in the magma reservoirs and is injected into the fault swarm as 10-15 km long segments are rifted.

About $0.6 \times 10^9 \text{ m}^3$ of magma are estimated to have flowed through the magma reservoirs and about 1 % have been erupted in short lived fissure eruptions and injections into boreholes. The lavas show significant chemical variation (MgO 5.2—8.6 %) and clear signs of mixing during eruption and indications of extensive mixing before eruption. The apparent end members are not related by fractionation of minerals observed in the lavas which suggests that at least two separate reservoirs are involved.

The new lavas are erupted from a discontinuous fissure with the more primitive lavas found at the northern end. This reflects the regional distribution of postglacial lavas in the area as basalts erupted north of the Krafla volcano are dominantly more primitive than those associated with the volcano.

FLUORINE IN VOLCANIC ROCKS OF ICELAND

by

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ABSTRACT

The fluorine content of volcanic rocks from different volcano-tectonic environments in Iceland differs systematically in concert with other petrochemical parameters. The lowest abundance of fluorine (45-220 ppm F) is found in the petrochemically primitive ol-tholeiites of the rift zone. Evolved basalts ranging from ol-tholeiite to qz-tholeiite composition occur in the volcanic centers of the rift zone. These rocks contain 220-450 ppm F, while with alkaline affinities found in volcanic centers outside the rift zone contain up to 1600 ppm F. The variation in fluorine within the different rock suites is believed to reflect varying degree of crustal involvement in their genesis. In the rift zone fluorine chemistry of the basalts is believed to result from mixing with silicic magmas formed by anatexis in the rift zone crust. In the non-rifting volcanic centers the high fluorine results from a partial melting of amphibolite, which is believed to be a residual assemblage from earlier anatexis in the rift zone.

(This paper was not read at the Symposium)

MAGMA MIXING AT OCEANIC TRANSFORM FRACTURE ZONES

by

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ABSTRACT

Ocean ridge eruptive chemistry reflects isochronic compositional «gradients», often attributed to the interaction of lithophile element-rich mantle plumes with the relatively depleted asthenosphere. Inspection of Atlantic and Pacific axial gradients shows lithophile-rich eruptions do not correspond exclusively to proposed loci for mantle upwelling. In contrast, transform fracture zones appear to mark the majority of lithophile-enrichment peaks, suggesting relatively superficial tectonic phenomena influence magma chemistry. A general association of lithophile and radiogenic isotope enrichment with increasingly frequent offset spreading culminates at major fracture zone-ridge axis intersections (e.g., Galapagos, Iceland, Azores, Jan Mayen, and Siqueiros, Oceanographer and Romanche fracture zones). Major element and normative compositions show that enrichment also coincides with increased depth of melt segregation in the mantle. This is of interest in view of independent

evidence for a vertical zonation of mantle lithophile and radiogenic constituents, such that magmas of deeper origin would reflect a downward transgression from depleted to enriched sources. On the basis of thermal models it is reasonable to postulate two preferential zones of partial melting at ocean ridge axes: one activated by «normal» rift dilation (high degrees of melting at shallow depth), the other activated by transform fractures (low degrees of melting at greater depth), each environment constrained by characteristic ranges of P & T and relative volumetric contributions to the accreting lithosphere. Deep basement drilling in the vicinity of fracture zones reflects such dual magma provenance and reveals evidence for the partial hybridization of disparate magmas within single offset spreading segments. This is consistent with evidence for extensive linear magma transport in rift-controlled environments. While reserving judgment on the surface effects of mantle plumes it is proposed that ocean ridge eruptives may reflect differential, tectonically controlled, sampling of a vertically zoned upper mantle, essentially as a secondary effect of the offset spreading pattern.

(This paper was not read at the Symposium)

MAJOR ELEMENT CHEMISTRY
OF BASALT GLASSES DREDGED
FROM YOUNG ISOLATED VOLCANOES
AND THE EAST PACIFIC RISE, 10°-14° N

by

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ABSTRACT

Major element electron microprobe analyses of over 100 dredged samples of basalt glass from the East Pacific Rise and nine young isolated seamounts near the Rise are presented along with petrographic data for the samples. These data indicate that most suites of samples from seamounts are fractionated suites of low-K₂O mid-ocean ridge basalt similar to many described previously. In addition, however, some seamount lavas differentiate toward higher K₂O, TiO₂ and other incompatible element enrichment without correlation with Mg/Fe ratios. These two types of chemical abundance variation

trends do not correlate well with size, age or tectonic settings of the seamounts, however, the absolute amount of chemical diversity observed in the lavas of each seamount does correlate with these other variables. The data indicate that location on fracture zones is neither a necessary or sufficient condition for great chemical diversity of seamount lavas, however, seamounts on fracture zones tend to be large in size. On the other hand, relatively great age (> 3.0 m.y.) and great size ($> 200 \text{ km}^3$) are sufficient but not necessary conditions for such seamount lava diversity. These patterns may be interpreted in terms of the evolution of young oceanic central volcanoes.

INTRODUCTION

Geologic and petrologic studies of oceanic islands have added greatly to our understanding of oceanic volcanism (Daly, 1933; Baker, 1973, Sun and Sanson, 1975). However, volcanic islands may not be truly representative of oceanic central volcanism since they are only the very largest of the oceanic central volcanoes. Geologic and petrologic studies of the much more numerous wholly-submerged oceanic central volcanoes are necessary to determine: 1) The proportion of oceanic central volcano seamounts which are presently active. 2) The proportions of intra-plate volcanoes which originate near ridge crests. 3) The mean-active lives of these various types of volcanoes.

Such questions may be partly answered by a combination of field/petrologic studies of wholly-submerged volcanoes complemented by statistical studies of seamount size and abundance distributions on oceanic crust of various ages (Batiza, 1981). Batiza (1977, 1979, and 1980) presented results of studies of small ($< 500 \text{ km}^3$) young and isolated (not-grouped) oceanic central volcanoes which indicate that many such vol-

canoes are composed of basalt chemically similar to mid-ocean ridge tholeiitic basalt. In addition, however, some of these volcanoes are capped by alkalic and transitional basalt suggesting that these volcanoes may evolve petrologically. This evolution could be linked to temporal changes in their mantle source area as young active seamounts are carried away from ridge crests (Batiza, 1980). McNut and Batiza (1981) presented paleomagnetic data for most of these young oceanic volcanoes and showed that such data are helpful for distinguishing between volcanoes and structural features on the sea floor, providing information on their mean active growth periods and for determining eruption chronologies of individual volcanoes.

The purpose of this paper is to present petrographic and major-element composition data for samples from nine small seamounts near the East Pacific Rise (7 volcanoes and 2 structural features) and for samples dredged from the Rise. In addition, we discuss systematic relationships which exist between the petrology of these seamounts and their tectonic settings, size, and paleomagnetic characteristics. The location of these seamounts, bathymetric maps and data on the locations of dredge hauls has been presented previously (Batiza, 1980).

METHODS

The field methods employed as part of this study have been described previously (Batiza, 1979 and 1980). In Table 1 we present a summary of the results of petrographic examination of about 250 thin sections of samples recovered in 27 dredge hauls. Table 2 gives major element compositions and the petrographic type of 135 samples from the nine seamounts and the East Pacific Rise. These analyses are electron microprobe analyses of fresh glass and therefore represent liquid compositions unaffected by crystal accumulation and alteration (Melson et al., 1976).

RESULTS

The samples studied include pieces of submarine hyaloclastites (Fig. 1), pillow lava and sheet flow (submarine pahoehoe: Figs. 2 and 3). The lava flows are mostly aphyric or very sparsely phyric, but some porphyritic types were recovered. Textures within the samples vary from glassy to holocrystalline and the only unusual texture observed consists of segregation vesicles and tubes which are sometimes abundant in the sheet flow samples (Fig. 4). In all other respects, the mineralogy and textures of these samples are similar to those of previously- described submarine basalt lavas (e.g., Bryan, 1971) and pyroclastic rocks (e.g. Schmincke et al., 1979). On the basis of the types of phenocrysts and megacrysts found in the lavas, eleven distinct petrographic types may be distinguished (Table 1).

Most of the samples have megacrysts of plagioclase (An_{60-75}) and/or olivine, but these are abundant ($> 1\%$) in only a few samples. Most of the lavas have rare phenocrysts of plagioclase or plagioclase plus olivine and it is clear from observed textural relationships that for most samples, plagioclase was the first liquidus phase. The only exceptions are from volcano $\neq 3$ where olivine is the first liquidus phase, followed by plagioclase. Many samples also have phenocrysts and microphenocrysts of clinopyroxene. In all cases, this is the latest phase to crystallize and observed assemblages are: Pl + Ol + Cpx and less commonly Pl + Cpx.

The chemical compositions of the lavas vary widely as shown in Figs. 5 and 6. Most volcanoes exhibit some chemical variation, however, the magnitude and trends of this chemical variation are widely different between volcanoes. With some significant exceptions, most of the samples analyzed are low- K_2O mid-ocean ridge tholeiite which are chemically similar to

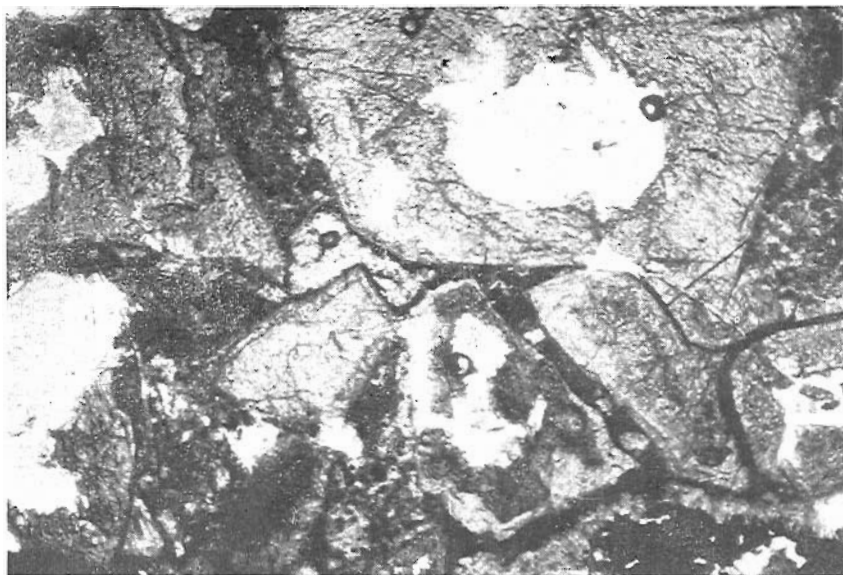


Fig. 1 — Photomicrograph of hyaloclastite 28-7D, width of frame is 2 mm.
Note angular fragments of altered glass with fresh cores which
are loosely cemented by Fe-Mn oxides.

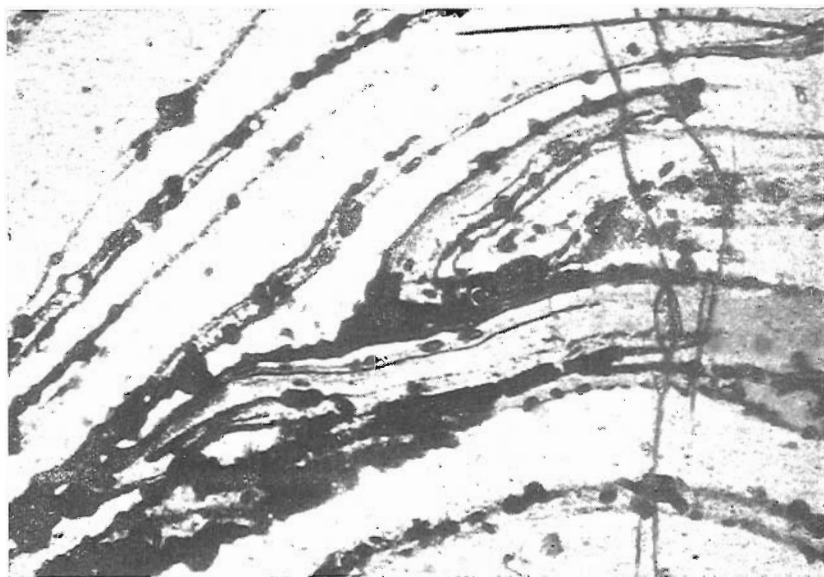


Fig. 2 — Photomicrograph of samples 19-5, width of frame is 0.11 mm.
This sample of sheet flow has a thick glassy rim, pictured here,
with a very pronounced flexion texture defined by tiny crystal-
lites of silicates and opaque minerals.

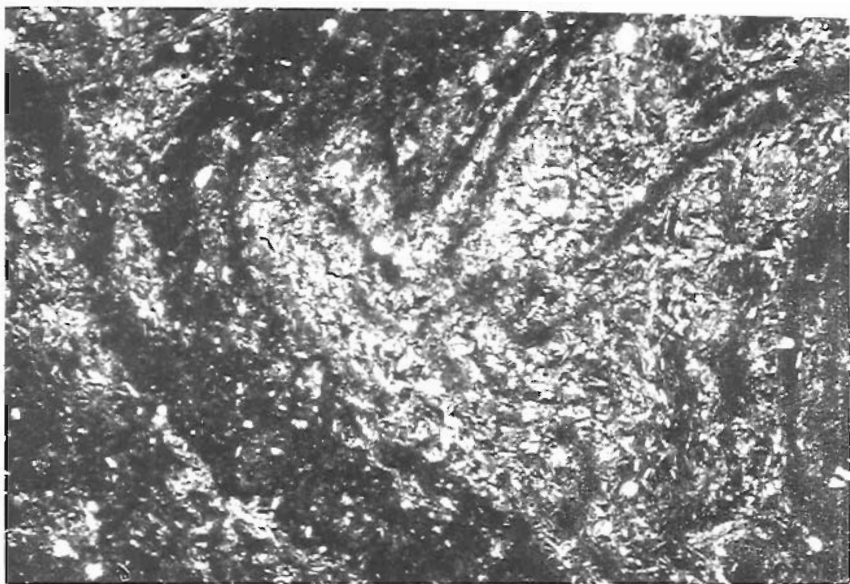


Fig. 3— This rock is similar to the one in Fig. 2 but this photomicrograph is taken of the interior portion of the flow which is almost holocrystalline. Note the very pronounced fluxian texture. Sample is 3-2 and width of frame is 2 mm.

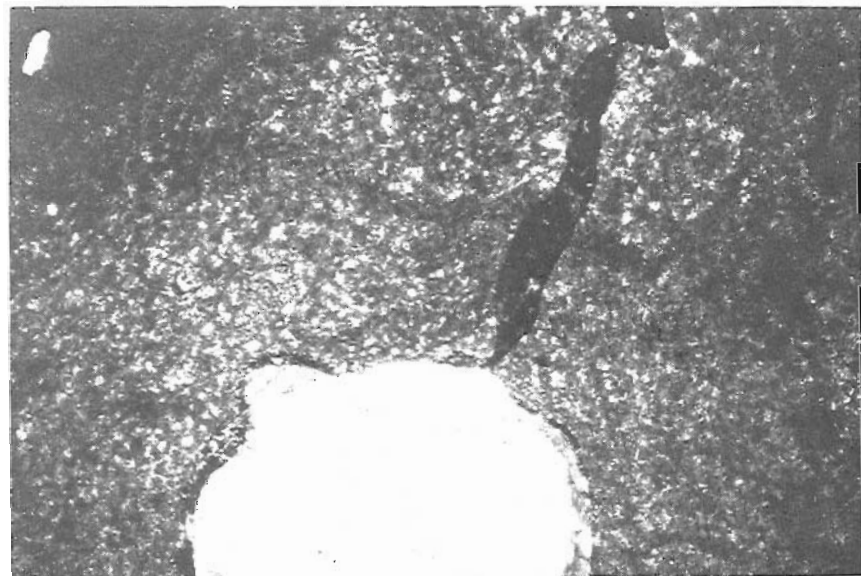
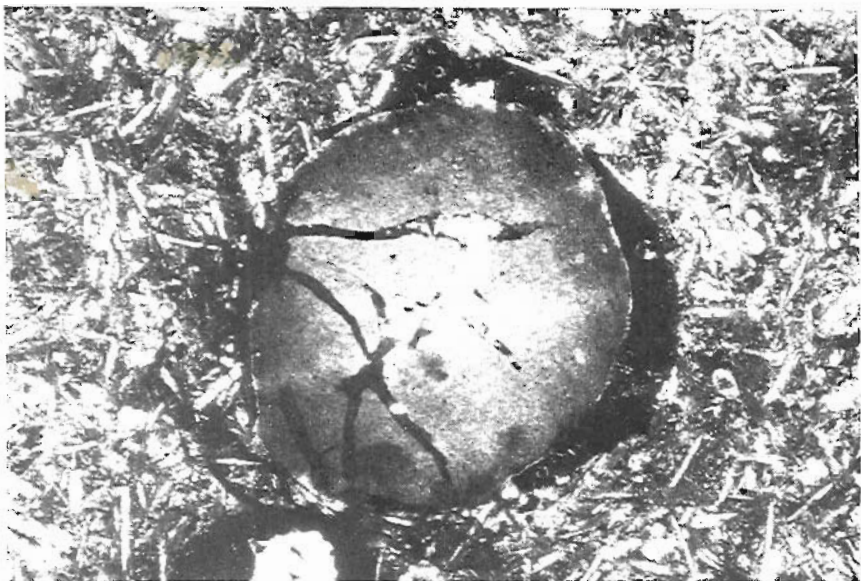


Fig. 4 — Photomicrographs of sample 23-8 which contains abundant segregation vesicles and tubes like the ones shown here. These segregations are thought to form as a result of changing lithostatic pressure during crystallization such as might be caused by extrusion and rapid flow down the steep slopes of a submarine volcano (Smith, 1967). Width of frames is 2 mm.



samples obtained from the active mid-ocean ridge system and from drilling of the oceanic crust. Suites of samples from individual volcanoes generally show a range of $100 \text{ Mg/Mg} + \text{Fe}^{2+}$ (Mg no.) and other element variations characteristic of suites of mid-ocean ridge basalt (Batiza et al., 1977; Melson et al., 1976; Morel and Hekinian, 1980; Byerly, 1980; Clague and Bunch, 1976; Frey et al., 1974; Natland and Melson, 1980).

In addition to these tholeiites and fractionated tholeiites the seamount dredges contain alkalic basalt and transitional basalt. These samples are not depleted in light rare earth element (LREE) and other incompatible trace elements but rather have either flat chondrite-normalized REE patterns or LREE enriched ones (Batiza, 1980). Fig. 6 shows that these transitional and alkalic lavas have distinctive variation trends of major elements as well.

Before a discussion and interpretation of the petrology of the seamounts, the characteristics of each are given:

Seamount 1: This volcano was discussed by Lonsdale and Spiess (1979) and Lonsdale and Batiza (1980). It is a small (47 km^3) tholeiitic volcano located within the central magnetic anomaly of the East Pacific Rise on crust 0.6 m.y. in age. Dredges of its slopes and summit have recovered tholeiitic basalt with Mg no. 60-63. Dredge 3 (Table 2) probably sampled 2 individual flows which have phenocrysts of Pl and Pl + Ol.

Seamount 2: This volcano is also small ($\sim 80 \text{ km}^3$) and is located symmetrically across the East Pacific Rise from seamount 1. Like seamount 1, it is located on normal oceanic crust (i.e., not on a fracture zone). Lavas from its slopes and summit contain only plagioclase phenocrysts but some contain megacrysts of plagioclase and olivine. They have uniformly flat REE abundance patterns (Batiza, 1980) and slightly higher K_2O abundances than depleted mid-ocean ridge basalt (MORB) of comparable Mg no. (61-63).

Seamount 3: This small (62 km^3) bathymetric high is located on normal crust of 1.1 m.y. in age and there is good evidence (Batiza, 1979, 1980) that it is not a volcano, but rather a structural feature. Lavas from 4 dredge hauls show variation in Mg no. of 61 to 68 and belong to two groups: a low- K_2O group and a high K_2O group (Fig. 6). Lavas of the former group have phenocrysts of either Pl or Pl + Ol and sometimes megacrysts of plagioclase. Those of the latter group (high K_2O) have phenocrysts of either olivine or Ol + Pl and lack megacrysts. These two groups differ in La/Sm ratio and other trace element abundances (Batiza 1980).

Seamount 4: This small (74 km^3) bathymetric high is located on normal crust 1.5 m.y. in age. Like volcano 3, there is good morphologic and paleomagnetic evidence to indicate that it is a structural feature rather than a volcanic constructional feature. Three dredges of this feature yielded lavas with Mg no. of 60-64 and a variety of phenocryst assemblages but all are LREE-depleted tholeiitic basalt.

Seamount 5: This seamount is one of the largest of this group ($\sim 300 \text{ km}^3$) and is located on a small fracture zone near crust which is 0.9 m.y. old. Paleomagnetic evidence indicates that this feature is probably a volcano but it has asymmetric slopes and other morphologic features which indicate an unusual growth history or later morphologic modification. Lavas from five dredges have phenocrysts of either Pl + Ol or Pl + Ol + Cpx with occasional megacrysts of both plagioclase and olivine. They show great chemical diversity with Mg no. of 55 to 65 and all have slightly higher K_2O (Fig. 6) and La/Sm ratio (Batiza, 1980) than typical low- K_2O MORB.

Seamount 6: This small ($\sim 70 \text{ km}^3$) volcano is located on crust of 3.0 m.y. age and is located very close (10 km), though not directly on, a small fracture zone. Two dredge hauls of the summit region recovered both transitional basalts with

flat REE abundance patterns and LREE enriched alkali olivine basalt (Batiza, 1980). The former have either Pl or Pl + Ol phenocrysts while the latter have either Pl + Ol or Pl + Cpx phenocrysts and are highly vesicular (10-15 % vesicles). This volcano gives very unusual magnetic paleoinclinations and paleodeclinations which could be due to: 1) its small size, 2) inadequate magnetic data, or 3) unusual chemical composition of the lavas. The transitional lavas have a narrow range of Mg no. (65-67) but a wide range of K_2O and TiO_2 abundances (Fig. 6) and the alkalic lavas have a wider range of Mg no. (as low as 53). While the variation trends exhibited by all the samples are discontinuous, the samples appear to define a

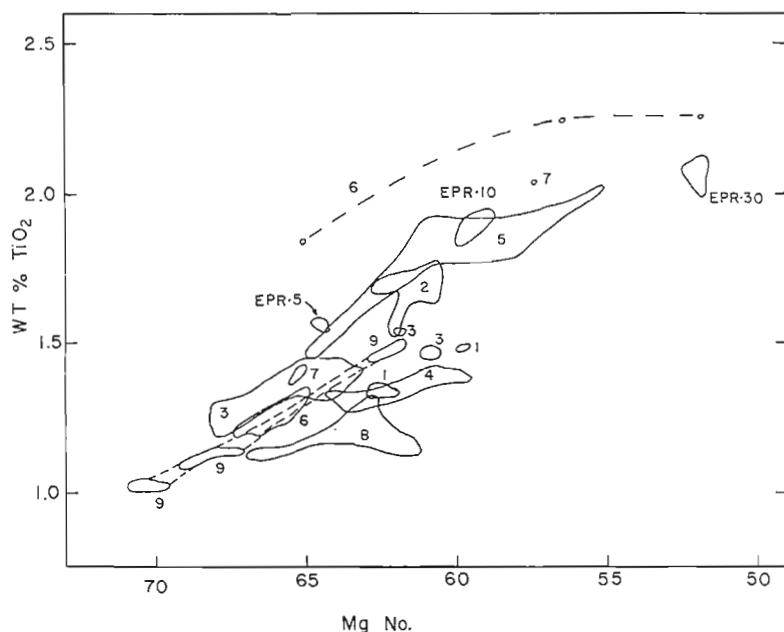


Fig. 5 — Plot of MG no. ($100 \text{ Mg/Mg} + \text{Fe}^{+2}$) versus wt. % TiO_2 content for the glasses analyzed. Fields for samples from each seamount are shown with solid lines. Dashed lines connect groups of samples from the same volcano. Numbers of the fields correspond with the volcano numbers used in the text.

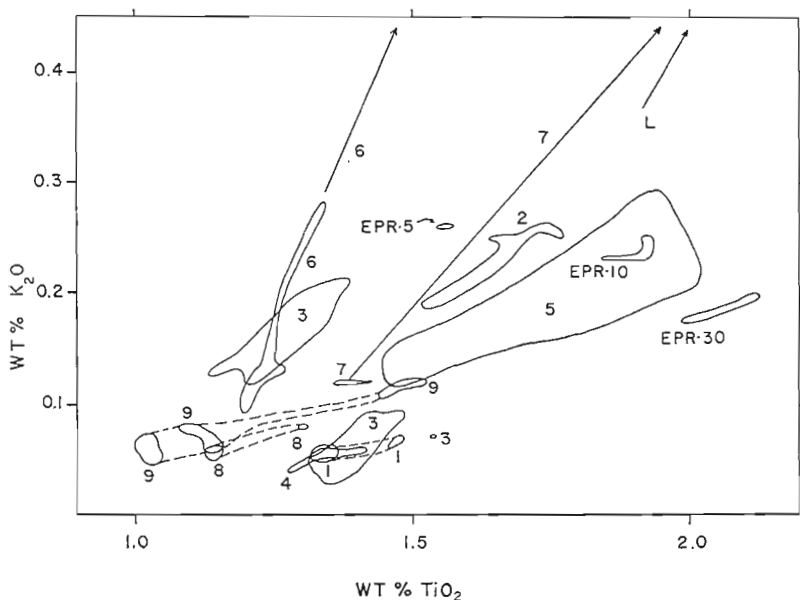


Fig. 6 — Plot of wt. % K_2O versus wt. % TiO_2 for the glasses analyzed. Same conventions as Fig. 5. Also shown is the trend labelled «L» which is from Natland and Melson (1980). Note the variable K/Ti ratios of samples from this study.

single trend toward incompatible element enrichment which is not related to changes in Mg no. (Figs. 5 and 6 and Batiza, 1980).

Seamount 7: This is the largest seamount of the group (540 km^3) and is located on the same fracture zone as seamount 5 adjacent to crust 3.5 m.y. in age. Paleomagnetic results indicate clearly that this seamount is a volcano that is tilted northward about 15° which explains its asymmetric slopes. Rocks from two dredges include both a suite of LREE depleted tholeiites (Mg no. ~ 65 with Pl or Pl + Ol phenocrysts) and LREE enriched transitional basalts with Mg no. ~ 57 , La/Sm = 1.27 (Batiza, 1980) and Pl + Cpx phenocrysts and plagioclase megacrysts.

Seamount 8 : This small (61 km³) volcano is located on the oldest crust of any of the seamounts in this group (6.8 m.y.) and is about 10 km north of a small fracture zone. Paleomagnetic evidence indicates that in contrast to most of the others, it is younger than the crust upon which it is built. Two dredge hauls recovered LREE depleted tholeiitic basalt with Mg no. 61-63 and 67 (two groups) which all have only plagioclase phenocrysts and occasional megacrysts of plagioclase and olivine.

Seamount 9 : This volcano (~ 200 km³ in volume) is located along the same fracture zone as seamounts 5 and 7 near crust 5.5 m.y. in age. It is apparently about the same age as the crust that it is near and grew quickly near the East Pacific Rise. Dredges recovered a suite of LREE depleted tholeiitic basalt (Batiza, 1980) with Mg no. 62-71. The lavas define three distinct groups and a discontinuous trend of chemical variation like many other tholeiitic differentiation trends (Figs. 5 and 6). Phenocrysts and megacryst assemblages are variable (Table 2) and many samples are highly porphyritic with plagioclase or plagioclase plus olivine megacrysts.

East Pacific Rise : Three dredges at the East Pacific Rise yielded lava suites which exhibit a range of La/Sm ratios (Batiza, 1980). Samples from dredges 10 (12° N) and 30 (14° N) are LREE depleted while those of dredge 5 (11.5° N) have nearly flat patterns. The K/Ti ratios of the samples systematically increases and the Mg no. of the samples decrease from south to north along the East Pacific Rise for these three dredge haul. The samples exhibit a great variety of phenocryst and megacryst abundances (Table 2) and were all dredged from portions of the East Pacific which are morphologic horsts (Lewis, 1979).

SUMMARY OF RESULTS

Examination of the data above indicate that several generalizations may be made. However, we caution that the number of seamounts studied is small, and therefore these generalizations may only hold at this locality. Nevertheless, it is clear from this set of data that:

1) The larger volcanoes tend to occur along fracture zones. The three largest volcanoes (5, 7 and 9) occur on the O'Gorman fracture zone. It is also noteworthy that of the seven volcanoes studied, only two (1 and 2) are not either on fracture zones or very near to them such as 6 and 8 (McNutt and Batiza, 1980). The two structural features (3 and 4) are not located on or near fracture zones.

2) All of the relatively large volcanoes show great diversity of lava compositions. However, Figures 5 and 6 show that the volcanoes with the greatest chemical diversity also include volcano 6 ($\sim 70 \text{ km}^3$), showing that great chemical diversity is not a function of size alone. This relationship is not a function of the total number of dredges on each volcano, as volcanoes 9, 7 and 6 had only 2 each whereas volcano 8 had 3 dredges and shows much less chemical diversity.

3) The lavas from all volcanoes located on relatively old crust (3.0 m.y.) exhibit great chemical diversity. The single exception to this generalization is volcano 8, but McNutt and Batiza (1981) have shown that this one is probably much younger than the crust upon which it is built in contrast with the others: volcanoes 9 (5.5 m.y. old crust), 7 (3.5 m.y.) and 6 (3.0 m.y.).

In summary, volcanoes which are either relatively large ($100\text{-}150 \text{ km}^3$), or are located on fracture zones or are greater

than about 3 m.y. in age tend to exhibit greater chemical diversity of lavas than volcanoes which are small (100 km³), young (3.0 m.y. in age) and located at relatively great distance from fracture zones.

DISCUSSION AND INTERPRETATION

Because a great deal more data are yet required in order to critically evaluate the petrogenesis of the lavas from these nine seamounts and the EPR this will not be attempted in this paper. It is clear, however, that while simple low-pressure fractional crystallization may be sufficient to qualitatively explain the chemical variations of the lavas from volcanoes 8, 9, and 1, structural features 3 and 4 and possibly dredge 30 from the East Pacific Rise (Figs. 5 and 6), this mechanism alone is not sufficient to account for the variety of La/Sm ratios and levels of LREE and other incompatible element enrichments of volcanoes 2, 5, 6 and 7, seamount 3 and some of the East Pacific Rise dredged rocks. Electron microprobe, trace element mineral analyses, whole rock major element analysis and isotopic analyses (all in progress) should help to constrain the petrogenesis of these diverse lavas and allow quantitative testing of several possible hypotheses for their origins.

In this discussion we will consider the significance and possible explanations for the observed relationships between the diversity of lava chemistry and the ages, sizes and tectonic settings of the volcanoes summarized before. The observed chemical diversity is of two types: 1) fractionation trends which are very similar to those exhibited by suites of MORB (Type 1) (Figs. 5 and 6). In this case, though, the trends are usually not continuous but are defined by connecting distinct groups of samples; 2) fractionation trends leading to correlated

enrichments of K, Ti, LREE and other incompatible elements without good correlation with $Mg \neq$ (Type 2).

It should be kept in mind that these types of variations could have quite different causes and it is therefore interesting that no correlation between age, size or tectonic setting and the specific type of chemical diversity of lavas is apparent for these volcanoes. For example, type 2 variation is observed for lavas of seamounts 2, 3, 6, 7 and possibly 5 which vary greatly in relative age, size and tectonic setting. Thus it is the absolute magnitude of the chemical diversity rather than its type which correlates well with age, size and tectonic setting.

Because of the small number of volcanoes studied and because of the nature of the observed correlation, it is not possible to tell whether relatively great age, size or location on fracture zones is the most important single factor leading to chemical diversity (of either type). In addition these variables are probably not independent. For example, if growth rates are constant and growth periods exceed 3 m.y., the older the volcano is, the larger it will be.

It is clear from the data that location on a fracture zone is neither a necessary nor sufficient condition for great chemical diversity of lavas. Both relatively great age (> 3.0 m.y.) and relatively great size ($> 200 \text{ km}^2$) are sufficient but not necessary conditions for great diversity. This assumes, of course, that the dredging obtained representative samples of the volcanoes' surfaces.

Relative age could be an important factor either because of increased opportunity for fractional crystallization to occur in sub-volcanic chambers or alternatively because of the increased chances that a volcano drifting away from the accretionary zone of the ridge crest would be fed by diverse magmatic sources different from those which melt beneath the ridge. On the other hand, great lava diversity may only be a function of small average size for individual lava flows. This in turn might be most likely in the waning stages of evolution, but very little evidence bearing on the average volumes of in-

dividual eruptions as a function of time exist for these types of volcanoes. In any case, both fractional crystallization and tapping of multiple and changing source regions are not necessarily age-dependent processes and this may explain why great age is not a necessary condition for great petrologic diversity.

Relatively large size may be an important factor because, as before, the surfaces of relatively large volcanoes may be covered by lavas erupted in the waning stages of evolution. Such activity may be a consequence of the volcano having achieved its maximum attainable height for a given lithosphere thickness (Vogt, 1974) or else its losing contact with a magmatic source from which it is continually being separated by plate motion (Menard, 1969). This assumes, of course, that the small volcanoes studied are still active and in fact volcano 6, though relatively small, shows great chemical diversity. This suggests that location on fracture zones may result in larger average volcano growth rates (volcanoes 5, 7 and 9) but that fracture zones do not otherwise exert important influences on the source region characteristics or chemical diversity of small oceanic central volcanoes.

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TABLE 1

PETROGRAPHIC TYPES

<i>Type</i>	<i>Phenocrysts</i>	<i>Vol. % Vesicles</i>	<i>Megacrysts</i>
1.	Aphyric		
2.	Pl	<5	
3.	Pl + Ol	(a) 10-15 (b) <5	
4.	Pl + Ol + Cpx	(a) 10-15 (b) <5	
5.	Pl + Cpx	(a) 15-20 (b) 5	
6.	Pl	(a) 10 (b) <5	Pl
7.	Pl + Ol	(a) 10 (b) <5	Pl
8.	Ol	<5	
9.	None	>10	Pl (No samples with glass)
10.	Pl + Cpx	>10	Pl
11.	None	(a) 10 (b) <3	Pl + Ol
12.	Hyaloclastite		

TABLE 2

BASALT GLASS ANALYSES

SEAMOUNT 1

	3-1	3-2	3-3	3-4	3-6	3-7	3-9	D-3 Average
SiO ₂	50.42	50.42	50.50	50.53	50.42	50.13	50.54	50.40
TiO ₂	1.32	1.48	1.35	1.49	1.33	1.36	1.33	1.38
Al ₂ O ₃	14.90	15.40	14.75	15.50	15.00	14.84	15.02	15.05
FeO*	9.82	10.05	9.82	10.14	9.91	9.80	9.72	9.89
MgO	7.56	7.05	7.74	7.02	7.60	7.73	7.73	7.49
CaO	12.50	11.85	12.42	11.97	12.40	12.40	12.43	12.28
Na ₂ O	2.61	2.90	2.64	2.87	2.62	2.63	2.63	2.70
K ₂ O	0.05	0.06	0.05	0.07	0.05	0.06	0.06	0.06
P ₂ O ₅	0.11	0.12	0.11	0.11	0.11	0.11	0.10	0.11
TOTAL	99.29	99.33	99.38	99.70	99.34	99.06	99.56	99.36
Mg no.	62.2	60.0	62.8	59.7	62.1	62.8	63.0	61.8
Petrographic Type (P.T.)	3B	3B	3B		3B	1	6B	

BASALT GLASS ANALYSES (*continued*)

SEAMOUNT 2

	4-4	4-8	4-11	4-12	4-13	4-14	4-16	4-17	4-18	4-19	4-20	D-4 Average
SiO ₂	49.13	49.63	49.88	49.62	50.30	49.81	49.87	49.84	50.24	49.61	49.96	49.71
TiO ₂	1.55	1.52	1.64	1.74	1.73	1.77	1.68	1.68	1.64	1.65	1.65	1.65
Al ₂ O ₃	16.22	16.97	16.58	15.96	16.08	16.03	16.16	15.89	16.19	16.17	16.17	16.22
FeO*	9.20	8.89	9.34	9.25	9.22	9.41	9.18	9.23	9.22	9.35	9.25	9.23
MgO	7.11	6.82	6.77	6.91	7.11	6.80	7.25	7.03	6.94	6.98	7.06	6.98
CaO	11.79	11.89	11.89	11.75	11.68	11.95	11.70	11.76	11.78	11.69	11.72	11.78
Na ₂ O	3.08	3.14	3.05	3.08	3.12	3.14	3.08	3.06	3.10	3.11	3.14	3.10
K ₂ O	0.19	0.19	0.22	0.26	0.26	0.25	0.25	0.24	0.25	0.25	0.25	0.23
P ₂ O ₅	0.18	0.19	0.18	0.20	0.17	0.20	0.19	0.18	0.20	0.20	0.21	0.19
TOTAL	98.45	99.24	99.55	98.77	99.67	99.36	99.36	98.91	99.56	99.01	99.41	99.09
Mg no.	62.3	62.1	60.8	61.5	62.3	60.7	62.9	61.9	61.7	61.4	62.0	61.8
P. T.	6A	11B	11B	2	2	11B	2	2	2	2	2	

BASALT GLASS ANALYSES (*continued*)

SEAMOUNT 3

	6-1	6-2	6-3	6-4	6-5	6-6	6-8	6-9	6-10	6-11	6-13	6-14	6-15	D-6 Average
SiO ₂	50.83	50.44	49.95	50.28	50.02	49.77	50.01	50.10	50.16	50.09	50.91	50.93	51.18	50.30
TiO ₂	1.54	1.42	1.44	1.43	1.40	1.42	1.40	1.39	1.43	1.38	1.48	1.46	1.46	1.42
Al ₂ O ₃	14.86	15.67	15.61	15.84	15.80	15.72	15.77	15.63	15.82	15.66	15.03	15.08	15.07	15.53
FeO*	10.10	9.11	9.14	9.02	9.08	9.12	9.08	9.14	9.21	9.04	10.03	10.04	10.08	9.33
MgO	7.42	7.93	7.77	7.96	7.93	8.00	7.93	7.87	7.96	7.97	7.40	7.45	7.33	7.78
CaO	12.01	12.11	12.21	12.07	12.09	11.95	12.02	12.01	11.98	11.99	11.96	12.06	12.16	12.04
Na ₂ O	2.74	3.00	2.94	2.95	2.93	2.97	2.98	2.97	2.97	2.94	2.87	2.55	2.86	2.92
K ₂ O	0.07	0.09	0.07	0.08	0.08	0.07	0.06	0.07	0.06	0.07	0.09	0.08	0.09	0.07
P ₂ O ₅	0.11	0.15	0.14	0.13	0.14	0.15	0.15	0.16	0.12	0.15	0.14	0.13	0.14	0.14
TOTAL	99.68	99.92	99.27	99.76	99.47	99.17	99.40	99.34	99.71	99.29	99.91	99.78	100.37	99.53
Mg no.	62.0	65.0	64.5	65.4	65.1	65.2	65.1	64.6	64.8	65.3	61.0	61.1	60.7	64.0
P. T.	3B	2	2	2	2			2	2	2	7B	2	2	

BASALT GLASS ANALYSES (*continued*)

SEAMOUNT 3

	7-2	7-3	7-4	7-6	7-8	7-9	7-10	D-7 Average
SiO ₂	50.32	50.00	50.57	50.21	50.10	50.13	49.79	50.16
TiO ₂	1.32	1.38	1.40	1.39	1.35	1.33	1.35	1.36
Al ₂ O ₃	15.61	15.58	15.55	15.66	15.82	15.77	15.69	15.67
FeO*	9.37	9.40	9.53	9.46	9.17	9.17	9.28	9.34
MgO	7.91	7.84	7.74	7.74	7.97	7.99	7.98	7.88
CaO	12.16	12.30	12.18	12.27	12.31	12.14	12.10	12.21
Na ₂ O	3.03	3.01	3.00	3.09	2.87	2.99	3.03	3.00
K ₂ O	0.05	0.05	0.04	0.05	0.03	0.04	0.04	0.04
P ₂ O ₅	0.12	0.12	0.11	0.11	0.11	0.11	0.11	0.11
TOTAL	99.89	99.68	100.12	99.98	99.73	99.67	99.37	99.77
Mg no.	64.3	64.0	63.4	63.6	64.9	65.0	64.7	64.3
P. T.	3B	7B	7B	7B	3B	3B	3B	

BASALT GLASS ANALYSES (*continued*)

SEAMOUNT 3

	8-1	8-2	8-3	8-5	8-6	8-7	8-8	8-9	8-10	8-11	D-8 Average
SiO ₂	49.79	49.58	49.72	49.87	49.90	50.19	49.81	50.18	49.79	49.27	49.81
TiO ₂	1.33	1.34	1.24	1.21	1.29	1.26	1.20	1.28	1.21	1.30	1.27
Al ₂ O ₃	16.53	16.66	16.29	16.03	16.74	16.39	16.14	16.68	16.23	16.73	16.44
FeO*	8.77	8.69	7.78	8.80	8.62	8.72	8.89	8.68	8.83	8.55	8.73
MgO	8.10	8.14	8.54	8.66	8.11	8.35	8.79	8.18	8.75	8.50	8.41
CaO	11.85	11.94	11.98	11.98	11.82	12.11	12.04	11.83	1.88	11.78	11.92
Na ₂ O	2.80	2.82	2.59	2.64	2.81	2.62	2.61	2.82	2.62	2.77	2.71
K ₂ O	0.20	0.17	0.13	0.12	0.18	0.14	0.13	0.18	0.14	0.20	0.16
P ₂ O ₅	0.17	0.17	0.17	0.14	0.18	0.16	0.13	0.19	0.16	0.15	0.16
TOTAL	99.54	99.51	99.44	99.45	99.65	99.94	99.74	100.02	99.61	99.25	99.61
Mg no.	66.4	66.7	67.5	67.8	66.8	67.2	67.9	66.8	67.9	68.0	67.3
P. T.	3B	3.B	3B	8	3B	8	8	12	12	12	

BASALT GLASS ANALYSES (*continued*)

	SEAMOUNT 3						SEAMOUNT 4				
	9-1	9-2	9-3	9-4	9-5	D-9 Average	11-1	11-2	12-2	12-3	13-1
SiO ₂	49.68	49.41	49.96	49.32	48.90	49.45	49.82	50.24	50.8	50.41	50.49
TiO ₂	1.38	1.36	1.26	1.31	1.30	1.32	1.33	1.41	1.32	1.38	1.28
Al ₂ O ₃	16.92	17.03	16.74	16.66	16.53	16.78	15.71	14.53	14.90	14.66	15.04
FeO*	8.79	8.83	8.71	8.65	8.72	8.74	9.22	10.20	9.78	10.17	9.49
MgO	7.41	7.52	8.24	8.07	8.16	7.88	7.79	7.51	7.58	7.10	7.83
CaO	12.23	12.12	11.92	11.76	11.98	12.00	12.47	12.43	12.66	12.77	12.45
Na ₂ O	2.87	2.93	2.74	2.81	2.80	2.83	2.75	2.53	2.56	2.62	2.74
K ₂ O	0.21	0.21	0.18	0.18	0.20	0.20	0.06	0.06	0.05	0.05	0.04
P ₂ O ₆	0.18	0.18	0.16	0.18	0.18	0.18	0.11	0.09	0.11	0.10	0.09
TOTAL	99.66	99.59	99.91	98.94	98.77	99.38	99.26	99.00	99.14	99.26	99.45
Mg no.	64.5	64.5	66.8	66.6	66.5	65.9	64.3	60.9	62.2	59.7	63.7
P. T.	3B	8			12		4B	6B	3B	2	2

BASALT GLASS ANALYSES (continued)

SEAMOUNT 5

[illegible]

BASALT GLASS ANALYSES (*continued*)

SEAMOUNT 5

	16-1	17-1	17-2	17-3	17-4	17-5	17-6	17-8	17-9	D-17 Average
SiO ₂	50.04	50.48	50.37	50.22	50.30	50.45	50.69	50.37	50.23	50.39
TiO ₂	1.79	1.71	1.74	1.77	1.64	1.74	1.73	1.68	1.71	1.72
Al ₂ O ₃	14.81	15.52	15.65	15.19	15.74	15.56	15.41	15.47	15.51	15.51
FeO*	10.10	9.03	9.20	9.49	8.96	9.19	9.25	9.13	9.15	9.18
MgO	6.61	7.08	6.97	6.88	7.21	7.03	7.08	7.03	6.97	7.03
CaO	11.57	12.06	11.90	11.93	11.98	12.11	12.10	12.02	12.04	12.02
Na ₂ O	3.18	3.24	3.34	3.30	3.10	3.16	3.23	3.20	3.16	3.22
K ₂ O	0.20	0.17	0.19	0.19	0.17	0.16	0.17	0.16	0.16	0.17
P ₂ O ₅	0.18	0.18	0.19	0.20	0.21	0.19	0.17	0.19	0.20	0.19
TOTAL	99.28	99.47	99.54	99.17	99.31	99.58	99.83	99.25	99.13	99.43
Mg no.	58.1	62.6	61.8	60.7	63.3	62.0	62.0	62.2	61.9	62.0
P. T.			3A	7A	7A	7A	1	4A	4A	

BASALT GLASS ANALYSES (*continued*)

SEAMOUNT 5

SEAMOUNT 6

	18-1	18-3	19-5	19-8	19-11	19-12	19-13	19-15	19-16	19-17	19-19	19-21	19-22	19-23	D-19
SiO ₂	49.77	49.84	50.00	50.94	50.53	50.54	50.26	50.42	50.48	50.14	50.04	48.66	49.52	50.62	
TiO ₂	1.46	1.46	1.24	1.23	1.23	1.23	1.20	1.20	1.22	1.27	1.25	1.84	1.25	2.24	
Al ₂ O ₃	16.44	16.52	16.55	16.49	16.36	16.25	16.60	16.35	16.38	16.51	16.38	18.89	16.66	17.72	
FeO*	8.95	8.95	8.84	8.76	8.77	8.82	8.71	8.79	8.81	8.80	8.77	7.97	8.67	8.14	
MgO	7.68	7.76	8.24	8.18	8.08	8.31	8.12	8.46	8.22	8.10	8.10	6.88	7.84	4.94	
CaO	11.91	11.75	11.97	11.98	12.07	12.01	11.92	11.98	12.00	12.00	12.07	10.20	11.93	9.20	
Na ₂ O	3.07	3.08	2.77	2.75	2.76	2.74	2.78	2.63	2.81	2.74	2.71	3.48	2.79	4.09	
K ₂ O	0.15	0.12	0.13	0.12	0.12	0.12	0.11	0.09	0.13	0.13	0.14	0.93	0.14	1.58	
P ₂ O ₅	0.17	0.16	0.14	0.14	0.13	0.13	0.13	0.12	0.13	0.13	0.12	0.37	0.15	0.53	
TOTAL	99.60	99.54	99.89	100.59	100.05	100.15	99.83	100.04	100.18	99.82	99.58	99.18	98.95	99.06	
Mg no.	64.7	64.9	66.5	66.6	66.3	66.9	66.6	67.3	66.6	66.3	66.3	65.1	65.6	56.5	
P. T.	3,11B	3,11B	3B	3B	3B	3B	3B		3B	3B	3B	3A	2	3A	

* Of low-K₂O samples only.

BASALT GLASS ANALYSES (*continued*)

	SEAMOUNT 6					SEAMOUNT 7					SEAMOUNT 8		
	20-1	20-2	20-4	21-3	21-4	23-6	25-1	25-2	25-3	25-4	25-5	D-25 Average	26-2
SiO ₂	49.30	51.01	49.84	49.92	49.80	51.20	51.33	51.49	50.81	51.74	51.38	51.35	50.69
TiO ₂	1.34	2.25	1.27	1.42	1.36	2.04	1.31	1.15	1.14	1.14	1.30	1.21	1.13
Al ₂ O ₃	16.65	15.54	16.66	16.31	16.21	15.20	14.86	15.59	14.44	14.63	15.00	14.70	16.19
FeO*	8.87	9.95	8.83	8.95	8.84	9.61	9.67	10.42	10.19	10.22	9.71	10.04	8.93
MgO	7.74	5.23	7.84	7.91	7.85	6.04	7.66	7.74	7.85	7.76	7.67	7.73	8.46
CaO	11.75	9.84	11.94	12.11	12.04	11.08	12.58	12.83	12.81	12.72	12.53	12.69	12.59
Na ₂ O	2.94	4.07	2.76	2.85	2.88	3.55	2.65	2.23	2.20	2.23	2.70	2.40	2.54
K ₂ O	0.28	1.00	0.21	0.12	0.12	0.49	0.84	0.06	0.06	0.05	0.08	0.07	0.06
P ₂ O ₅	0.17	0.42	0.16	0.15	0.13	0.27	0.11	0.10	0.10	0.11	0.11	0.11	0.11
TOTAL	99.64	99.31	99.51	99.74	99.23	99.48	100.25	100.61	99.60	100.60	100.48	100.30	100.70
Mg no.	65.1	52.9	65.6	65.1	65.5	57.4	62.9	61.4	62.4	61.9	62.8	62.2	66.9
P. T.	3B	5B	3B	2	3B	10	2	2	11B	11B	2		11 B

BASALT GLASS ANALYSES (*continued*)

SEAMOUNT 9

	27-1	27-2	28-4	28-6	28-7	28-8	28-10	28-11	28-12	28-13	28-14	28-15	28
SiO ₂	50.26	50.06	49.71	49.03	49.16	50.33	49.06	50.37	49.10	49.39	49.23	49.55	49
TiO ₂	1.09	1.14	1.13	1.02	1.03	1.51	1.04	1.48	1.03	1.01	1.03	1.01	1
Al ₂ O ₃	17.32	17.16	16.41	17.30	17.32	15.13	17.28	15.16	17.30	17.37	17.42	17.62	17
FeO*	8.34	8.20	8.42	8.03	8.09	9.46	8.04	9.41	8.05	7.99	8.13	8.02	8
MgO	8.76	7.84	8.49	9.0	9.00	7.16	9.10	7.21	8.81	9.09	9.07	9.05	8
CaO	12.30	12.46	12.17	12.20	12.25	12.10	12.42	12.01	12.34	12.34	12.36	12.35	12
Na ₂ O	2.70	2.75	2.80	2.62	2.61	3.08	2.62	3.07	2.56	2.54	2.54	2.59	2
K ₂ O	0.08	0.07	0.06	0.05	0.06	0.12	0.05	0.12	0.07	0.06	0.06	0.07	0
P ₂ O ₅	0.08	0.10	0.12	0.10	0.12	0.15	0.10	0.15	0.10	0.11	0.10	0.08	0
TOTAL	100.93	99.78	99.31	99.36	99.64	99.04	99.71	98.98	99.45	99.90	99.94	100.34	100
Mg no.	69.2	67.2	68.3	70.6	70.4	61.8	70.8	62.1	69.7	70.9	70.5	70.7	70
P. T.	3B	3B	2	3B	2	12	12	12	12	1	12	2	2,1

BASALT GLASS ANALYSES (continued)

SEAMOUNT 9

	28-17	28-18	28-19A	29-19B	28-21	28-28	1(N-2)	Averages 2(N-13)	3(N-3)
SiO ₂	49.55	49.64	49.85	50.21	50.75	49.74	49.46	49.40	50.48
TiO ₂	1.04	1.02	1.02	1.15	1.45	1.01	1.14	1.02	1.48
Al ₂ O ₃	17.66	17.63	17.57	16.99	15.37	17.80	16.70	17.52	15.22
FeO*	8.04	8.24	8.13	8.53	9.42	8.08	8.48	8.09	9.43
MgO	9.13	8.97	8.80	8.51	7.47	9.01	8.50	8.98	7.28
CaO	12.30	12.37	12.31	12.44	12.23	12.44	12.30	12.32	12.11
Na ₂ O	2.54	2.60	2.60	2.75	3.04	2.59	2.78	2.59	3.06
K ₂ O	0.06	0.06	0.06	0.60	0.11	0.06	0.06	0.06	0.12
P ₂ O ₅	0.08	0.07	0.09	0.08	0.14	0.10	0.10	0.09	0.15
TOTAL	100.40	100.61	100.43	100.72	99.98	100.83	100.02	100.07	99.33
Mg no.	70.8	69.9	69.8	68.1	62.9	70.5	68.2	70.4	62.3
P. T.	11	7B	3B	3B	2	4B			

EAST PACIFIC RISE GLASS ANALYSES

	5-1	5-2	10-2	10-3	10-4	10-5	10-6	10-7	10-8	10-9	D-10 Average	30-1	Averages 30-2
SiO ₂	50.02	50.31	50.32	50.44	49.96	50.05	50.46	50.79	50.11	50.30	50.30	51.15	52.33
TiO ₂	1.55	1.57	1.93	1.87	1.84	1.91	1.92	1.92	1.92	2.06	1.92	1.99	2.07
Al ₂ O ₃	15.84	15.87	15.25	15.24	15.36	15.28	14.99	15.07	15.08	14.88	15.14	14.26	13.78
FeO*	9.10	8.97	10.34	10.24	10.14	10.23	10.23	10.29	10.12	10.09	10.21	11.97	11.78
MgO	7.69	7.68	6.96	6.93	7.10	6.93	6.92	7.00	6.96	7.03	6.99	6.27	6.33
CaO	11.92	12.05	11.25	11.31	11.28	11.36	11.28	11.50	11.35	11.34	11.33	10.76	10.82
Na ₂ O	2.92	2.94	2.96	2.89	2.90	2.91	2.89	2.80	2.84	2.72	2.86	2.79	2.93
K ₂ O	0.26	0.26	0.24	0.23	0.23	0.23	0.23	0.24	0.25	0.24	0.24	0.20	0.21
P ₂ O ₅	0.17	0.19	0.21	0.21	0.21	0.23	0.23	0.20	0.20	0.19	0.21	0.18	0.18
TOTAL	99.47	99.84	99.46	99.42	99.02	99.13	99.15	99.81	99.83	98.85	99.20	99.57	100.43
Mg no.	64.4	64.7	59.0	59.4	59.9	59.2	59.2	59.3	59.5	59.8	59.4	52.8	53.5
P. T.	7B	4B	3B	3B	3B	3B							

HETEROGENEITY OF PHONOLITIC PUMICE DEPOSITS FROM TENERIFE, CANARY ISLANDS

by

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ABSTRACT

The island of Tenerife has an extensive Quaternary phonolitic pyroclastic series, comprising plinian pumice-fall deposits, ignimbrites, and pyroclastic surges. The dominant petrological feature of these pumice deposits is their geochemical and petrographical heterogeneity. Evidence is presented for three causes of heterogeneity: assimilation of roof-rock by the magma, resulting in less evolved compositions of the first-erupted pumice; zonation of the magma chamber, causing a change to intermediate compositions among the last products of an eruption; and magma mixing, where mafic and banded tephra are distributed more or less randomly through a particular pumice deposit.

Evidence for magma mixing is particularly abundant. A detailed petrographic and electron microprobe study has shown that simultaneous mixing of basaltic, intermediate, and phono-

litic magmas has repeatedly occurred in the history of the volcano: for example, phenocrysts representative of the entire magmatic range on Tenerife have been found, together with a compositionally variable glass, *within a single pumice clast*. These relationships are interpreted as the result of the disruption of a stably-zoned magma chamber, containing phonolitic and intermediate liquids, by intruding basaltic magma. The frequent incidence of heterogeneity among the recent phonolitic products of Tenerife volcano, and the occurrence of similar deposits on other island volcanoes, suggests that uncontaminated evolved liquids may be scarce in the oceanic setting.

(This paper was not read at the Symposium)

COARSE-GRAINED ROCKS FROM ASCENSION ISLAND

by

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ABSTRACT

The lavas and pyroclastic rocks of Ascension Island contain a suite of coarse-grained igneous blocks which range in composition from dunite to granite paralleling, but extending beyond, the compositional range of the volcanics. The mineralogy, texture and chemistry of these blocks are discussed, together with their modes of occurrence. More specific features observed include partial melting seen in one suite which suggests that granitic liquids may be formed from blocks of intermediate composition; the occurrence of the rare minerals dalyite ($\text{K}_2\text{ZrSi}_6\text{O}_{15}$) and vlasovite ($\text{Na}_2\text{ZrSi}_4\text{O}_{11}$); and the crystallization *in situ* of a rock type considered to reproduce several of the features displayed by the blocks. The implications of this for the origin of the coarse-grained suite as a whole are considered.

INTRODUCTION

Ascension Island is situated at approximately 8°S 14°W in the South Atlantic. The island is some 92 km² in area and comprises the uppermost 800 m of a 3000 m single cone sited on magnetic anomaly 4 about 120 km west of the median valley of the Mid-Atlantic Ridge and 50 km south of the Ascension Fracture Zone. No explicit connection with either of these major structures has been identified (Van Andel and Heath, 1970).

Ascension Island has attracted the attention of numerous workers since before the visit of Darwin (Darwin 1876). Most prominent for general geology is the work of Daly (1925). A more recent briefer description has been given by Atkins *et al.* (1964). The rare minerals dalyite and vlasovite were identified in ejected granitic blocks by van Tassel (1952) and Cann (1967) respectively, and Roedder and Combes (1967) have carried out fluid inclusion studies on these same blocks.

Ascension Island has features of an oceanic volcano at an advanced stage of evolution. An eccentric main peak, Green Mountain, comprises a basaltic cinder cone built in a caldera-like structure consisting mainly of trachyte and comendite. The latter rock types also form numerous domes and lava and pyroclastic flows elsewhere on the island. Over ninety parasitic centres including lava cones, pyroclastic cones and explosion craters have been located. The lower slopes to the north-west and south are formed of more mafic lava flows ranging from hawaiite to benmoreite in composition. True basalt is relatively rare.

There have been no eruptions verified in historic times.

Bearing in mind that the exposed portion of this volcano is little more than 1 % of its total volume it is worth noting that salic volcanic rocks form a noticeably large proportion of this upper part, possibly as much as 50 %.

DISTRIBUTION AND MINERALOGY OF
COARSE GRAINED BLOCKS

Distribution

- △ Basalt
- ◆ Cones
- Cinders

*In pyroclastics and
other sediments*
+ Middletons facies
x N.A.S.A. facies

Mineralogy

- ▨ Gabbroic cumulates
- ▤ Intermediate
- ▦ Granite

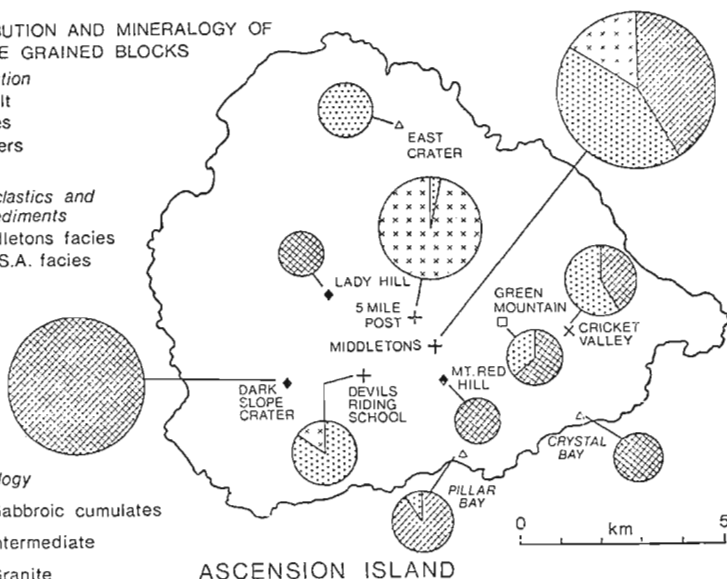


Fig. 1 — Distribution and mineralogy of coarse-grained blocks. The area of the circles is proportional to the number of blocks collected : the Dark Slope Crater circle = 100 blocks.

THE OCCURRENCE OF COARSE-GRAINED BLOCKS

Fig. 1 shows the distribution of blocks.

Coarse-grained rocks may be divided into four categories, (I), grouped phenocrysts, (II), cognate crystal clusters, (III), grouped xenocrysts, and (IV), xenoliths.

In this study, the blocks considered are mainly xenoliths and are found mostly in pyroclastic formations. In lavas the blocks are almost entirely restricted to basalt-intermediate types. A reason for this could be the difficulty of mixing when viscous salic magma passes through a coarse-grained rock body. Four «basaltic» cones have yielded blocks, though Dark Slope Crater is the only prolific source.

By far the most important sources of blocks are the pyroclastic formations and redistributed sediments. Three facies types account for nearly all of these.

- (I) The Middleton's facies — white matrix-dominated sediments up to 70 m in thickness.
- (II) The N.A.S.A. Road facies — poorly sorted red rubble, presumably mass flows.
- (III) Fluvial sediments — mainly alluvial fans, the result of sporadic rainfall.

THE MORPHOLOGY, CHEMISTRY, MINERALOGY AND FABRIC OF BLOCKS FROM SPECIFIC LOCALITIES

Figs. 2 and 3 represent the analyses of individual phases from four important localities.

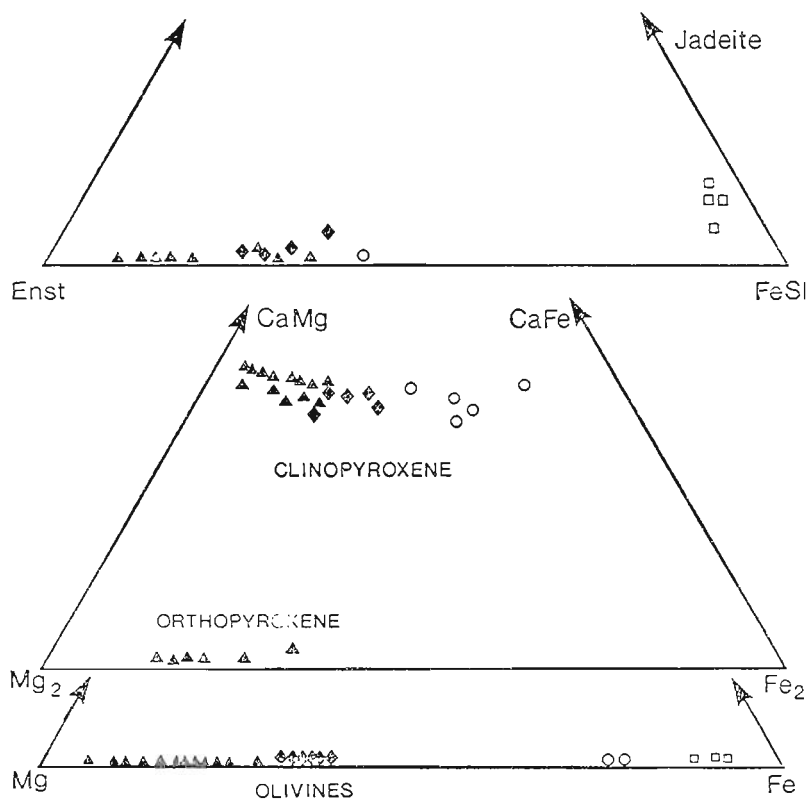
1) *Dark Slope Crater*

The blocks occur as small (few grains) to large (50 cm³) samples, loose or in the wall of the crater. They are invariably coated with scoria and lava and many form the cores of bombs.

Fig. 4 shows the mineralogy in terms of the 3 main phases. Accessories are orthopyroxene, magnetite, ilmenite and chrome-spinel.

These blocks all show good cumulate textures. Preferred orientation of augite and plagioclase is very common and sometimes there is a marked linear alignment of augite crystals. Layering on the hand specimen scale is very rare (only 3 specimens) and is size and modal, rather than chemical pos-

PROBE ANALYSIS OF PYROXENE AND OLIVINE.



- ▲ Dark Slope
- ◆ Middletons
- East Crater
- Five Mile Post

Fig. 2 — Probe analyses of pyroxene and olivine.

PROBE ANALYSIS OF FELDSPARS

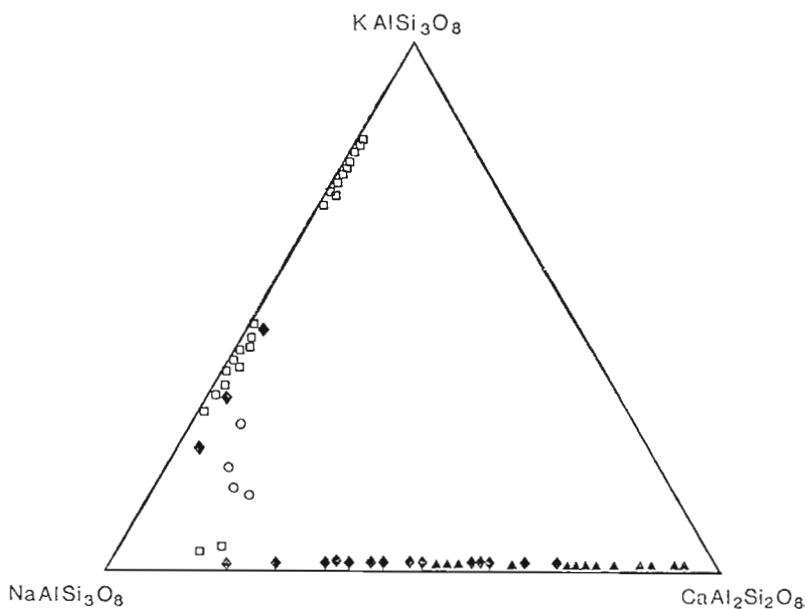


Fig. 3 — Probe analysis of feldspars.

sibly the result of very infrequent current action during otherwise undisturbed crystal settling. Grain size is quite variable but individual blocks are, in general, equigranular. An exception is the large clots (up to 5 cm) of augite sometimes seen in otherwise equigranular blocks (grain size 3-10 mm).

Orthopyroxene occurs as a cumulus phase in only one block, but is common along olivine-plagioclase boundaries in plagioclase-rich rocks (together with augite). Magnetite shows two types of occurrence: as a rare accessory in quite plagioclase-rich rocks and also as a major (up to 80 %) cumulus phase. The latter is seen in two specimens only, suggesting that magnetite crystallised in significant quantity during one or more brief intervals only.

MINERALOGY OF DARK SLOPE XENOLITHS

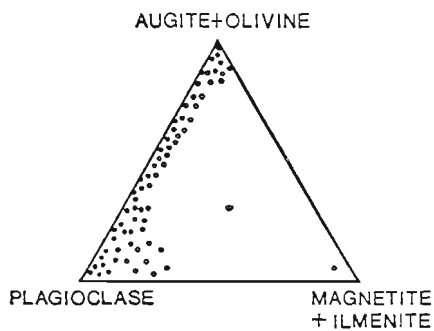
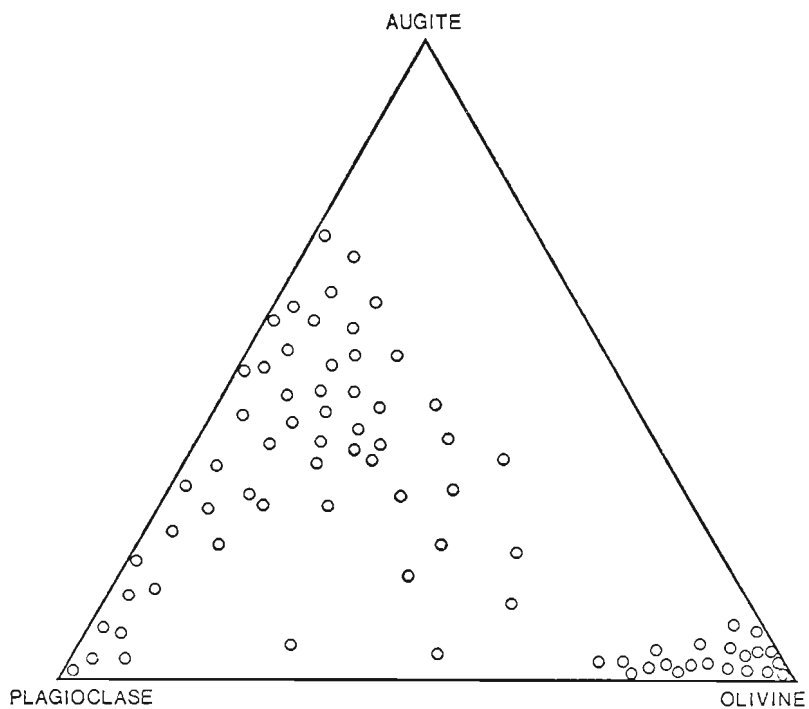


Fig. 4 — Mineralogy of Dark Slope xenoliths.

2) *Middleton's Ridge*

In places over 70 m of sediment of the Middleton's Facies are found. They contain the largest and most variable suite of coarse-grained blocks on Ascension. Of the three xenolith-rich horizons found, the lowest contains only granite, whereas the upper two contain both intermediate rocks and gabbros in approximately equal proportions.

The granites are very similar (if not identical) to the 5 Mile Post Granites described below. Vlasovite has been identified in one specimen. In the intermediate rock types, a typical assemblage is quartz (0-10 %), augite (5-20 %) and both sodic plagioclase and alkali feldspar. Many of the blocks are altered with the pyroxene replaced by amphibole and biotite, and the feldspar showing sieved rims.

The augite in some blocks contains up to 4 weight percent Na_2O .

In contrast to the Dark Slope gabbroic blocks, those on Middleton's Ridge are rather constant in mineralogy. Augite, olivine, and plagioclase are always present. Other differences in mineralogy include 1-10 % modal magnetite, more iron-rich ferromagnesian minerals and generally more sodic plagioclase. These suggest a slightly more evolved sequence.

The textures also differ conspicuously from those of the Dark Slope blocks. Preferred orientation is absent and nearly all specimens show a glassy mesostasis (up to 10 %), considered to represent interstitial liquid quenched during the sudden transfer of an incompletely crystallised rock mass to the surface (plate I).

3) *5 Mile Post (Green Mountain)*

The blocks here occur in a partially exposed horizon of poorly sorted sediment. The size of blocks ranges from 1 to 25 cm in diameter and most are rather friable and iron-stained.



Plate I — Middleton's gabbro showing euhedral plagioclase (B) and augite (C) projecting into glassy mesostasis (A) (X15 PPL).

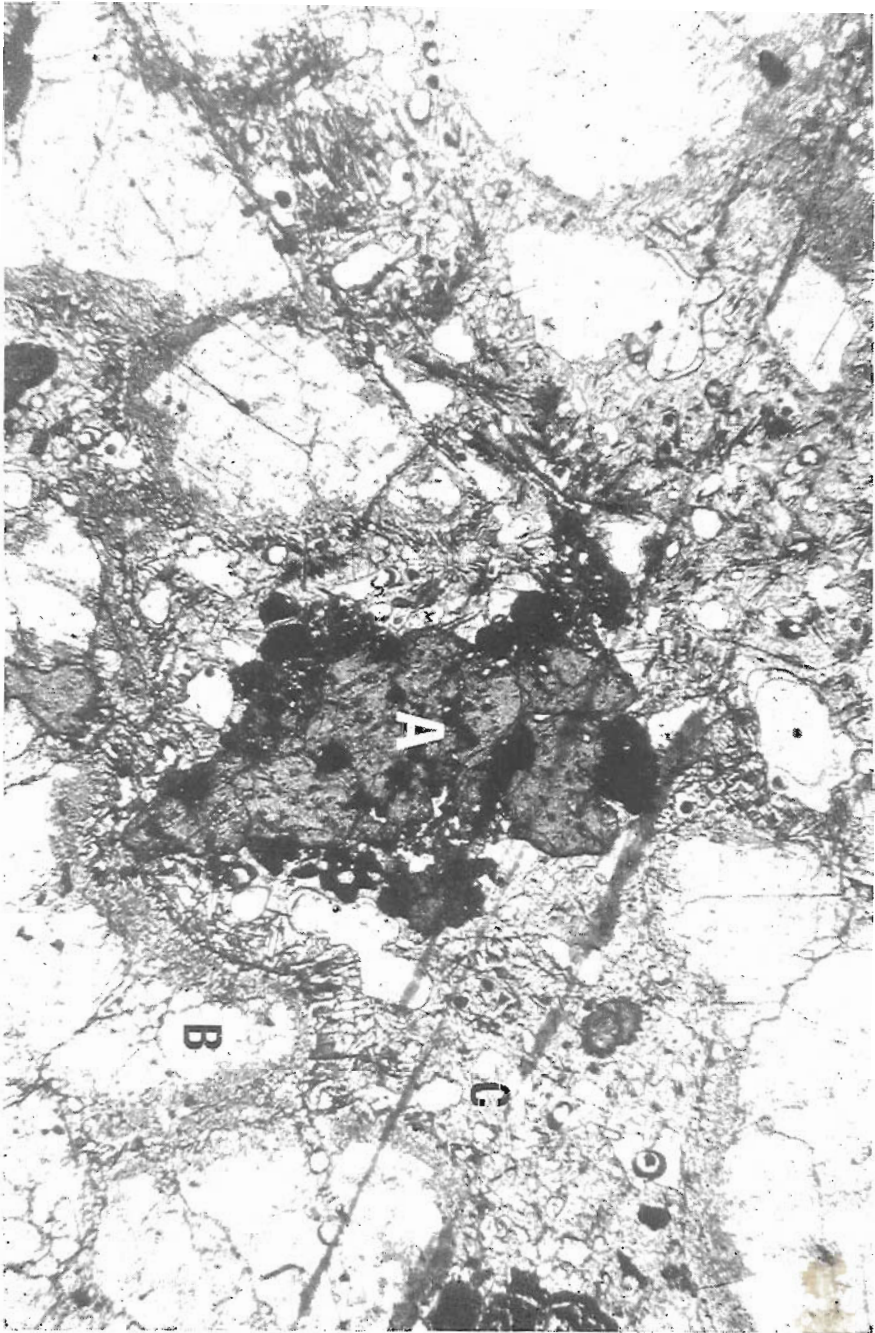


Plate II — Partially melted syenite from East Crater. A is augite containing small grains of an opaque mineral; B is anorthoclase with sieved rims adjacent to glass (C) which contains small quench crystals of feldspar (X15 (PPL)).

Three texturally similar types are evident (Roedder and Coombs, 1967) and appear to be intergradational. The rocks are all granites but with significant variations in mineralogy.

Hornblende-non-perthitic granites contain alkali feldspar which is rarely perthitic, accompanied by hornblende as the main mafic mineral together with some aegirine. This type is relatively rare.

Arfvedsonite/aegirine \pm oligoclase granites contain alkali feldspar which is generally non-perthitic, and occasional small oligoclase grains. The mafic minerals occur in irregular clots, sometimes with a calcic pyroxene surrounded by arfvedsonite and aegirine. Biotite is present in some of the clots, possibly as an alteration product, and magnetite is a not uncommon accessory.

Arfvedsonite/aegirine perthite granites \pm dalyite or vlasovite comprise about 70 % of the blocks collected at this locality. The feldspar and quartz often show a coarse granophyric texture. The «ferromagnesian» minerals are basically NaFe silicates and comprise 10-15 % of the rock. Rarer accessories are dalyite, vlasovite, aenigmatite, zircon and fayalite (in the cores of the mafic minerals). The blocks show prominent miarolitic cavities (distinguishing them from the other two types). Well-formed quartz and mafic minerals project into these cavities.

These blocks are remarkable for the presence of the zirconium silicates, dalyite and vlasovite, which are found in one and two other localities respectively (van Tassel, 1952; Cann, 1967; Fleet and Cann, 1967; Gittins et al., 1973; Tikhonenkova and Kazakova, 1961). Vlasovite ($\text{Na}_2\text{ZrSi}_4\text{O}_{11}$) may be interstitial or well formed and one good cleavage is visible in thin section. It is occasionally associated with zircon and sometimes rather altered. Dalyite ($\text{K}_2\text{ZrSi}_6\text{O}_{15}$) is unaltered, invariably interstitial and displays no cleavage, contrary to the description by van Tassel. It very closely resembles quartz in thin section. Vlasovite is much more common than dalyite but unaccountably was identified much later.

The two minerals have not, so far, been found in the same block. Dalyite blocks are slightly more miarolitic but otherwise they are identical. Differences between the whole rock chemistry of these two rock types are under investigation.

4) *East Crater*

At this locality, xenoliths occur in a trachyandesite emerging from a large cone, and range in size up to 30 cm in diameter. Many show a cleavage and thus occur in flat tablet form. The mineralogy of these blocks is remarkably uniform. Unaltered specimens contain 0-5 % quartz, 5-15 % augite with the rest of the rock composed of variably perthitic anorthoclase with some orthoclase. Magnetite and zircon are accessories. In altered blocks biotite and amphibole rim or replace the augite.

The distinctive feature of this group of blocks is the textural evidence of partial melting invariably exhibited (Plate II) (Cox et al., 1979). The partially melted material, which ranges from 1-30 % modally has been preserved as quenched glass. This is light brown to colourless and is found in quantity only along boundaries between grains of two different phases. In simple terms this must be due to a mutual lowering of melting point. Considerably more glass is seen along quartz-feldspar boundaries than between augite and feldspar. The glass adjacent to magnetite and pyroxene is often stained dark brown, due to the presence of 1-2 weight percent of iron oxide.

In the four specimens analysed the colourless glass contains between 72-77 weight percent SiO_2 whereas the whole rock has about 65 weight percent SiO_2 . Because quartz-feldspar contacts produce melts comparatively easily, partial melting of rocks such as these, with a small amount of modal quartz, produces liquids considerably richer in silica. Other features of partial melting include sieve textures in the rims of the feldspar and quench crystals which have formed along the grain boundaries of the feldspar on rapid cooling of the liquid.

OTHER LOCALITIES

These include other cones in which the blocks are all gabbroic but are smaller and finer grained than those of Dark Slope Crater ; the south coast lavas which contain small (rarely up to 10 cm) xenoliths in a «basalt» flow which is widespread along this coast. Most are gabbroic, some showing mesostasis or partial melting ; Green Mountain and Bears Back where the cinders contain small (< 3 cm) gabbroic xenoliths remarkably similar in mineralogy and texture to Middleton's Ridge gabbros ; The N.A.S.A. Road facies in which the blocks are variable but rather altered ; Devil's Riding School, where intermediate types such as fayalite-syenite, and granite and granophyric types are found, the latter being similar in mineralogy to, but finer grained than, the granites at Five Mile Post.

The last rocks to be described occur within the Cricket Valley lavas. Two types of coarse-grained rock are found here : small gabbroic xenoliths of the type found in the south coast lavas and a curious outcrop of coarse-grained rock unique on Ascension.

This outcrop is an irregularly shaped, 3 m by 1.5 m, coarse-grained mass in a 30 m basalt cliff (on the N.W. side of Cricket Valley). The rock consists of alkali feldspar and plagioclase (both usually zoned), augite (sometimes intergrown with the feldspar), a small amount of interstitial quartz, long needles of apatite, and about 10 % magnetite.

The delicate textures seen in this rock are undisturbed at the boundary with the basalt, so it would seem that the rock has crystallized *in situ*. Since the boundaries are unchilled, it is not intrusive into solid, cold basalt. A possible explanation of this is that a pocket of liquid separated from the existing magma at depth. A higher iron content (14.16 weight % FeO compared to 11.04 weight % FeO in the enclosing lava) would

confer a density greater than that of the remaining magma so that only small amounts of this liquid would be caught up in the subsequent eruption and transported to the surface. Once at the surface the higher iron content of the liquid would imply a lower solidus temperature for this material and crystallization would start essentially after the enclosing magma had solidified leading to the *in situ* formation of a coarse-grained facies, as the surrounding lava might be expected to cool slowly once *in situ*, acting as insulation.

This rock provides one of the few direct insights into possible mechanisms of formation of coarse-grained rocks within, and possibly below, the Ascension structure.

CONCLUSIONS

- 1) The compositional range of the coarse-grained rocks is that which might be expected from coarse-grained equivalents of the observed volcanic rocks.
- 2) It seems that one or more magma chambers existed under Ascension in which slow crystallization occurred, allowing coarse-grained rocks to form. No evidence can yet be presented as to the depth, size and shape of these chambers but a small pocket of coarse-grained material appears to have crystallized at a depth of only 50 m.
- 3) From the evidence of the only *in situ* coarse-grained rock on Ascension, it is suggested that a more evolved, but denser liquid separated from the existing magma below Ascension. This may have remained at depth long enough to crystallize some of the coarse-grained blocks now found on the surface.
- 4) Granitic liquids can be produced, at least in small quantities, from less salic coarse-grained rocks by partial melting.

ACKNOWLEDGEMENTS

We thank S. Baker, N. Charnley, G. Collins, C. Fagg, R. Holland, P. Jackson, K. Parrish and E. Wearing for advice and technical assistance. C. Harris is grateful to the N.E.R.C. for supporting this work financially and to The Queen's College, Oxford, for a travel grant to attend the Azores symposium.

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ON THE OCCURRENCE OF VITROPHYRES IN MACARONESIA

by

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ABSTRACT

Vitrophyres, defined as rocks in which more than 50 % of the groundmass is glass, irrespective of composition and whether porphyritic or not, occur in Macaronesia. In the literature, vitreous rocks are often referred to, but where chemical analyses are lacking and only inadequate petrographic descriptions are given, it is not always clear what proportion of such may actually be vitrophyres. On the other hand, references are given to vitrophyres in the region.

Vitrophyres certainly are present in the Azores, Canaries and Cape Verde archipelagoes, but are more doubtful in Madeira and the Selvagens. In Tenerife, these rocks are most voluminous, though more widespread in Gran Canaria. In the former, the Teide-Viejo volcano complex comprises essentially obsidian-type rocks.

It appears that the Macaronesian vitrophyres are of Quaternary/Sub-Recent age, though those of Gran Canaria and La Palma belong to Middle-Lower Miocene.

As not all islands have been given the same petrological attention, it is possible that further investigations would show vitrophyres to be more abundant than at present known.

(This paper was not read at the Symposium)

PLAGIOCLASE ACCUMULATION AND PHENOCRYST REACTION IN OCEANIC THOLEIITE: AN INDICATION OF SPREADING RATE

by

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ABSTRACT

A comparison of basalt lithology and chemistry for different mid-ocean ridge spreading axes indicates: (1) basalt generated at slow spreading axes (< 5 cm/yr, e.g. Mid-Atlantic Ridge) reflects widespread flotation of calcic plagioclase and phenocryst-liquid reaction; (2) basalt generated at fast-spreading axes (> 5 cm/yr, e.g., Juan de Fuca Ridge, Galapagos spreading Center, East Pacific Rise) is invariably aphyric or sparsely phyrlic, phenocrysts if present representing low pressure liquidus crystallization products. Interestingly, basalt generated at intermediate spreading rates (e.g., Costa Rica Rift, Gorda Rise, Gulf of California) shows incipient development of the «slow-spreading» petrographic tendencies. Recent experiments demonstrate a tendency for calcic plagioclase to float in basaltic melt at pressures greater than 6-7 Kbars, while

phenocryst-liquid reaction (often attributed to magma mixing) may be explained as due to re-equilibration of high pressure liquidus assemblages during low pressure storage of cogenetic magma. These effects can be plausibly ascribed to polybaric fractionation processes, with significant cooling and crystallization near the zone of initial melt segregation. Ridge-axis geotherm configurations, modelled as a function of spreading rate, and constrained by experimentally determined PT conditions for mantle-melt equilibration, imply transient polybaric fractionation systems at slow-spreading axes, but exclusively low pressure fractionation for fast-spreading axes. These qualitative predictions are confirmed by seismic evidence for near-surface magma reservoirs at the East Pacific Rise and their apparent absence from the Atlantic spreading axis. Petrographic and whole-rock chemical distinctions between fast and slow spreading axes thus appear to be sensitive to thermal and kinematic conditions at ocean ridges. Such discriminants may be applicable to obducted ocean crust of unknown provenance.

(This paper was not read at the Symposium)

GENESIS OF ULTRABASIC-BASIC ROCKS («OPHIOLITES») OF NORTH HUNGARY

by

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ABSTRACT

Most of the researchers consider the ultrabasic-basic magmatites of North Hungary (Bükk Mountains) to be an ophiolitic complex. Nevertheless, on the basis of the comparative analyses of the igneous formations with the typical (South-European, from Asia Minor, etc.) ophiolites, considerable petrological-petrogenetic difference can be established. The most characteristic difference is shown in the change of FeO^+/MgO as a function of silica. Dissimilarly of the typical ophiolites, the FeO^+/MgO ratio decreases parallel and unambiguously with the increase of silica. Its highest value is found within the given sequence in certain ultrabasites (3 to 4). The oxidation degree is also considerably lower than in the ophiolites cited. On the basis of this as well as of the crystallization sequence it can be stated without doubt, that the ultrabasic-basic complex of North Hungary was produced by an «inverse crystallization

differentiation», i.e. during crystallization and simultaneously with the increase of total iron in terms of FeO (but dissimilarly of the «fractionated crystallization» deduced by Fenner) the concentration of silica was gradually decreased. Thus, the sequence of rock formation is as follows: diabase ($\text{SiO}_2 = 47,7\%$) gabbro ($\text{SiO}_2 = 45,0\%$), ultrabasite ($\text{SiO}_2 = 41-30\%$). Since the gabbro forms considerable masses, the average SiO_2 content of the complex remains below 46 %. Under microscope it can be unambiguously established that first labradorite containing 56-52 % SiO_2 was formed from the melt of diabase and gabbro. This was followed by the precipitation of different mafic constituents (augite, diopside, amphibole). The quantity of opaque minerals is relatively small, which shows higher concentrations rather in the subsequent magmatites. In harmony with calculations this is due to the low oxidation degree being insufficient to the crystallization of magnetite. As a result of this process, during crystallization the silica and alumina contents of the melt gradually decreased, while the FeO and TiO_2 concentrations increased which considerably lowered the crystallization temperature and promoted the crystallization capacity. This process produced the formation of ultrabasic rock masses of high FeO-content in the final phase of crystallization.

Thus, the conclusion can be drawn that the material of mantle origin of the North-Hungarian (Bükk Mountains) ultrabasites-basites protruded in the near-surface level or to the surface along deep faults. The rapid magma formation proved to be favourable to the increase of total iron content, the relatively short time restricted the release of the more strongly bound MgO, and decreased the possibility of oxidation. This process might reach approximately the state of the Red Sea in our days.

SUBMARINE VOLCANOES EAST AND SOUTH OF IZU PENINSULA, CENTRAL JAPAN

by

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ABSTRACT

More than 50 volcanic centers are recognized as positive topography on the sea floor east and south of Izu Peninsula. Most of them are probably late Quaternary basaltic cones resting on the basement of Miocene submarine volcanic rocks. Recent dredge hauls have revealed that those submarine volcanoes located close to Izu Peninsula belong to the high-Al and/or high alkali basalts while those further south are either low alkali tholeiites or calc-alkali rhyolites associated with high-Al basalts. Submarine volcanoes close to Izu Peninsula are contemporaneous with a group of basaltic (and minor rhyolitic) monogenetic volcanic centers clustered in the central Izu Peninsula, which were active during the last 100,000 years.

The presence of active group of basaltic monogenetic centers along or very close to the volcanic front is not known elsewhere

in the Japanese islands. They are typically found in the back-arc region away from the front. No clearcut zonal pattern in alkali contents of the lavas is found throughout the area of this monogenetic volcano group, although they range more than 35 km perpendicular to the volcanic front. The geographic distribution of the monogenetic centers coincides with the area of hypocenters of the recent earthquake swarms occurring in and around Izu Peninsula. A model of leaking-out of a high-Al-alkali tholeiitic magma through fractures formed only within the area of active seismicity and crustal deformation seems in harmony with available data.

The southern group of the submarine volcanoes strongly suggests an echelon arrangement of island arc magmatism accompanied with large-scale warping of the crust. Chemical zoning parallel with the volcanic front is broken where calc-alkali rhyolite occurs on the front between Izu-Oshima and Miyake islands, both are of typical low-alkali tholeiite. These complications may be caused by temporal fluctuations of the subduction regime and mode of magma generation.

PETROLOGY AND GEOCHEMISTRY OF THE JUAN FERNANDEZ ISLANDS, SOUTH EAST PACIFIC

by

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AGE RELATIONS

The Juan Fernandez archipelago lies in the southeastern sector of the Nazca Plate some 700 km west of the Chilean port of Valparaiso (Fig. 1). It comprises the deeply dissected volcanic island of Robinson Crusoe (formerly Masatierra), its off-lying islet of Santa Clara and the younger shield volcano of Alexander Selkirk (formerly Masafuera) which lies 150 km to the west. The islands appear unrelated to any major structural features of the ocean floor and it is concluded that they are the products of isolated intra-plate volcanism.

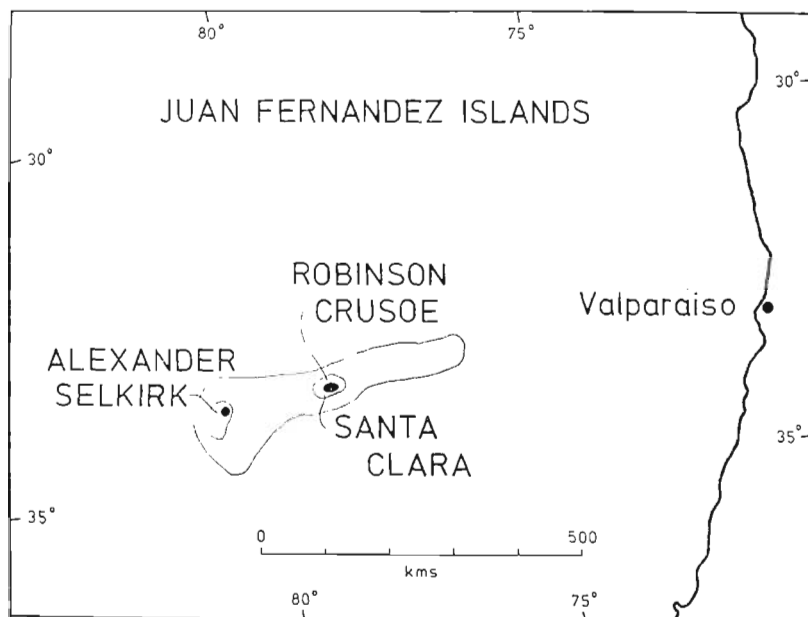


Fig. 1 — Location map of the Juan Fernandez archipelago.

A potassium-argon age determination on a dolerite from the north eastern part of Robinson Crusoe gave an age of approximately 5 Ma (personal communication D. C. Rex, Leeds University) and although no radiometric ages are available for Alexander Selkirk its general morphology would seem to suggest an age of less than 1 Ma. If this is so then the age relations between the two islands are consistent with easterly motion of the Nazca Plate over a fixed «hot spot» with a minimum motion of about 2 cm per year. On the same longitude but some 500 km north of here the age relationship and apparent plate motion finds a parallel in the twin islands of San Felix and San Ambrosio. These two islands are only 30 km apart suggesting a motion of the order of 10 cm per year. (GONZALEZ-FERRAN et al., 1979).

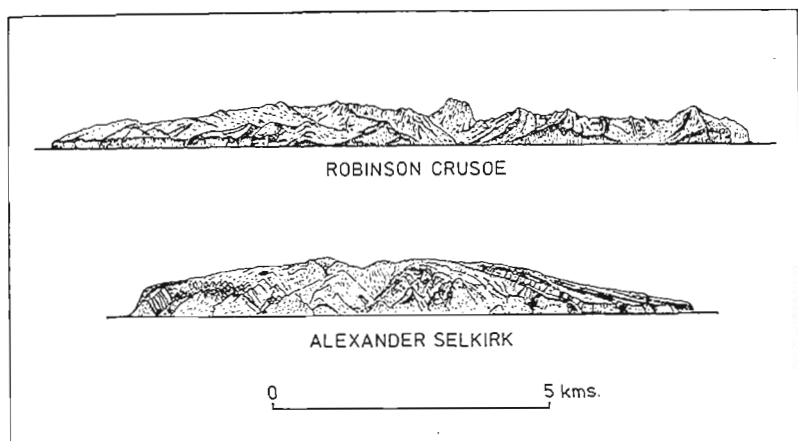


Fig. 2 — Sketches to illustrate contrasting morphologies of the two main islands of the Juan Fernandez archipelago. Robinson Crusoe viewed from the north-east and Alexander Selkirk from the east.

In spite of the general contrast in degree of erosion of the islands of Robinson Crusoe and Alexander Selkirk (Fig. 2) minor activity has apparently persisted to more recent times on the former, notably on the south-western peninsula. There are no records of any historic volcanic activity on either of the islands but there is a report of a submarine eruption off Robinson Crusoe in 1835 (SKOTTSBERG, 1956).

MORPHOLOGY

Robinson Crusoe (48 sq. km) is a forested island with sharp relief and a very irregularly embayed coastline. The main part of the island extends for about 12 km in a NW-SE direction and is about 3 km wide. Near the north-western end a ragged peninsula about 1 km wide reaches for some 6 km to

the south west. From their dips, the lavas and pyroclastics of the main part of Robinson Crusoe appear to have been derived from at least four separate volcanic centres which are now represented by the caldera structures forming the major indentations along the northern coastline. The north-westerly alignment of the four calderas is roughly parallel with the trend shown by numerous features in the South Pacific such as the Chile Rise, the Tuamotu Ridge and various fracture zones. The largest of these caldera structures forms a great amphitheatre around Bahia Cumberland and is overlooked by Cerro Yunque (922 m), the highest peak on the island. A number of tangential dykes, probably associated with the ring fracturing are exposed in places around the caldera rim. (Fig. 3).

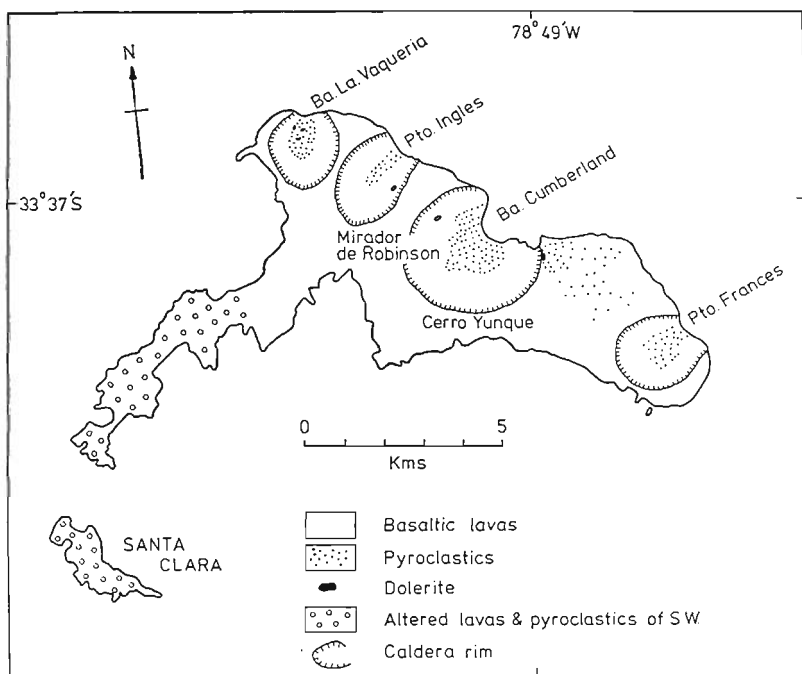


Fig. 3 — Simplified geological sketch map of Robinson Crusoe and Santa Clara.

Broad open valleys cut back into the other three volcanic centres of La Vaqueria, Puerto Ingles and Puerto Frances. At the northernmost point of the island vertical sea cliffs some 300 m high expose a section of lava flows and interbedded scoria with numerous cross-cutting dykes connected with the La Vaqueria centre. A series of rhythmically layered dolerite sills are exposed in the main valley running across the caldera floor.

The south-western peninsula of Robinson Crusoe contrasts sharply in relief with the main part of the island. The promontory lies only between 50 and 150 m above sea-level and there is scarcely any forest cover. From this gently undulating surface rise a number of small hills which are probably remnants of parasitic centres. The lavas and tuffs of this area have undergone extensive hydrothermal alteration unlike most of their counterparts to the north-east. The small island of Santa Clara (2 sq. km) can be regarded as an extension of the south-western peninsula of Robinson Crusoe, from which it is separated by a shallow channel about 2 km wide. It is deeply eroded and composed for the most of part rubbly decomposed lavas and tuffs cut by numerous dykes.

Alexander Selkirk (52 sq. km) reaches 1615 m above sea level and has a dome shaped form. It is roughly oval in plan and has a relatively smooth coastline lacking the embayments of its neighbours. It has the appearance of a relatively young shield volcano, with radiating valleys cutting into primary constructional surfaces.

PETROGRAPHY

Although dominantly basaltic, the lavas show a considerable compositional range from basanitoids, with more than 10 % normative nepheline to alkali basalts, olivine tholeiites, quartz tholeiites and hawaiites. Accumulative varieties, particularly picrite basalts are common but hawaiites (as defined by nor-

mative andesine) are the most abundant rock-type: more evolved types are rare but a single trachyte has been reported from Alexander Selkirk (Quensel 1912; McBirney and Williams, 1969). The basanitoids are all porphyritic rocks with phenocrysts of both olivine and clinopyroxene. The basalts are mostly porphyritic, mainly picrites, but aphyric varieties occur in the vicinity of Puerto Frances. Plagioclase phenocrysts occasionally predominate in some of the basalts at Puerto Ingles and at La Pina near Puerto Frances. On the whole the hawaiites are less porphyritic than the basaltic rocks and typically show a rather patchy or directive texture with flow banding. Plagioclase becomes a much more conspicuous component in these more differentiated rocks. Melting experiments (dry) carried out by N. Chapman at the Department of Earth Sciences, Leeds University, on picrite 17908 from Puerto Frances showed olivine as the liquidus phase over the 1-10 kb range and the temperature intervals 1300-1150°C. At pressures below 2 kb olivine was joined by plagioclase at 1150° but above 8 kb clinopyroxene precipitated before plagioclase.

Core compositions of olivines in the lavas reach Fo_{88} but the margins are invariably zoned eg. to around Fo_{60} . Clinopyroxenes usually have a pinkish-brown colour and a TiO_2 content of 2.75 % is recorded in one instance: their Al_2O_3 content is consistently around 5 %. The clinopyroxenes from the lavas are augites clustering around composition of $Ca_{46} Mg_{41} Fe_{13}$. Plagioclase is mostly zoned within the range An_{60} - An_{40} .

Small weathered ultramafic blocks are found at various localities within Cumberland caldera but they are most concentrated in a basanitoid flow in Queb Piedra Agujeriada. The blocks include lherzolites, harzburgites and dunites. The lherzolites contain olivine (Fo_{92}), enstatite, diopside, augite ($Ca_{42} Mg_{52} Fe_6$) and spinel. Exsolution features are common in the orthopyroxene.

GEOCHEMISTRY

Examples of the chemical composition of Juan Fernandez lavas are presented in Table 1. The more distinctive features of the Juan Fernandez suite are as follows:

- a) TiO_2 contents are high, reaching over 4 % in two of the quartz tholeiites (hawaiites) from Cumberland caldera. The values are, however, comparable with those in the lavas of Easter Island.
- b) There is marked variation in Fe/Mg ratios, with the most pronounced iron enrichment being evident in the quartz tholeiites. However, iron concentration does not attain the high values reached in either Easter Island (BAKER et al., 1974) or the Galapagos Islands (McBIRNEY and WILLIAMS, 1969).
- c) Enrichment in the incompatible elements Ba, Sr, Rb, Nb and Zr is especially marked in a group of alkalic lavas from Robinson Crusoe. However, these elements fail to discriminate between some of the undersaturated lavas and the tholeiites.
- d) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are almost entirely within the range 0.702-0.703, the lowest value being obtained on one of the more differentiated hawaiites from Alexander Selkirk.
- e) Chondrite-normalised rare earth element patterns show LREE enrichment. The basanitoids and alkali basalts show higher overall concentrations of REE and more pronounced enrichment in the lighter elements than the tholeiites.

- f) Apart from the trachyte, K_2O reaches its maximum value ($> 2\%$) in the basanitoids although even the tholeiites are more alkali rich than their Hawaiian counterparts.
- g) Although relatively few analyses are available from Alexander Selkirk and Santa Clara it would appear that tholeiitic varieties are more prevalent on these islands than on Robinson Crusoe.

A wide compositional spread such as that observed on Juan Fernandez seems to characterise isolated intraplate volcanoes and may be related to a rapidly changing geothermal gradient affecting both depth and degree of melting. Superimposed on this, polybaric fractionation would appear to be responsible for much of the compositional range observed in the archipelago. Variation in the more mafic lavas can be ascribed almost exclusively to fractionation of magnesian olivine. However, at higher pressures (above 8 kb) clinopyroxene which appears as phenocrysts in the basanitoids is also likely to have played a part. Separation of plagioclase may have exercised some influence on compositional relations in the more evolved rocks.

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TABLE 1

REPRESENTATIVE CHEMICAL ANALYSES WITH SELECTED
TRACE ELEMENTS AND PARTIAL CIPW NORMS OF LAVAS
FROM THE JUAN FERNANDEZ ISLANDS

		17910	17919	17908	17881	18001	17854
	SiO ₂	43.31	44.97	42.47	47.44	46.84	50.03
	TiO ₂	3.01	2.59	2.84	3.24	3.35	3.38
	Al ₂ O ₃	14.40	13.72	13.28	14.90	14.40	15.60
	Fe ₂ O ₃	2.85	2.77	3.50	3.54	7.06	3.02
	FeO	8.57	8.71	7.74	7.55	4.88	7.67
	MnO	0.20	0.22	0.19	0.15	0.14	0.13
	MgO	10.22	10.59	13.35	6.74	5.97	5.53
	CaO	10.40	9.29	11.20	11.28	10.27	8.94
	Na ₂ O	3.96	3.88	2.33	2.86	1.45	3.53
	K ₂ O	1.74	1.72	0.49	0.71	0.79	1.13
	H ₂ O+	0.68	0.66	1.81	0.47	2.42	0.49
	H ₂ O—	0.24	0.37	0.94	0.31	0.78	0.19
	P ₂ O ₅	0.75	0.83	0.58	0.45	0.49	0.60
	TOTAL	100.36	100.32	100.72	99.64	98.84	100.24
PPM	Ba	n.d.	750	450	n.d.	250	n.d.
	Nb	83	89	15	32	38	31
	Rb	41	53	3	7	14	20
	Sr	850	850	630	460	470	510
	Zr	330	360	240	210	230	300
PART NORM	Qz	—	—	—	—	9.59	0.30
	Ne	15.23	10.76	4.61	—	—	—
	Hy	—	—	—	6.31	8.63	13.37
	Ol	16.20	16.93	21.32	4.20	—	—

17910 : Alkali basalt, Puerto Frances, Robinson Crusoe.

17919 : Basanitoid, La Vaqueria, Robinson Crusoe.

17908 : Alkali basalt, Puerto Frances, Robinson Crusoe.

17881 : Olivine tholeiite, west side, Puerto Ingles, Robinson Crusoe.

18001 : Quartz tholeiite, north side of Bahia del Padre, Robinson Crusoe.

17854 : Hawaiite, south of settlement, Alexander Selkirk.