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

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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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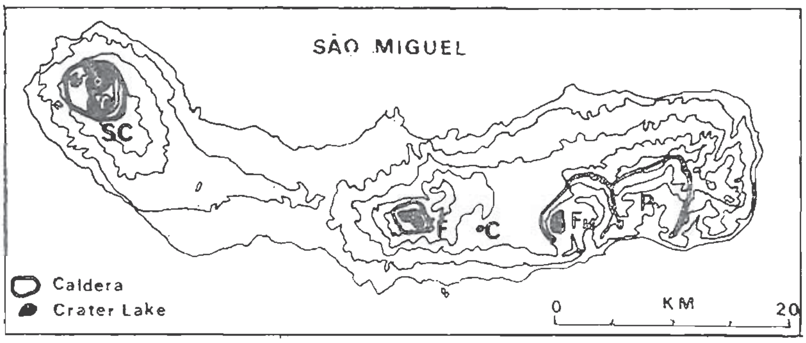

Fig. 1 — São Miguel Island. Symbols : SC = Sete Cidades, F = Furnas (Agua de Pau) C = Congra, Fu = Furnas, P = Povoação Vulcanoes.

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 Agua 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 $[An_{86}\ Ab_{13}\ Or_1 - An_{60}\ Ab_{38}\ Or_2]$, 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-

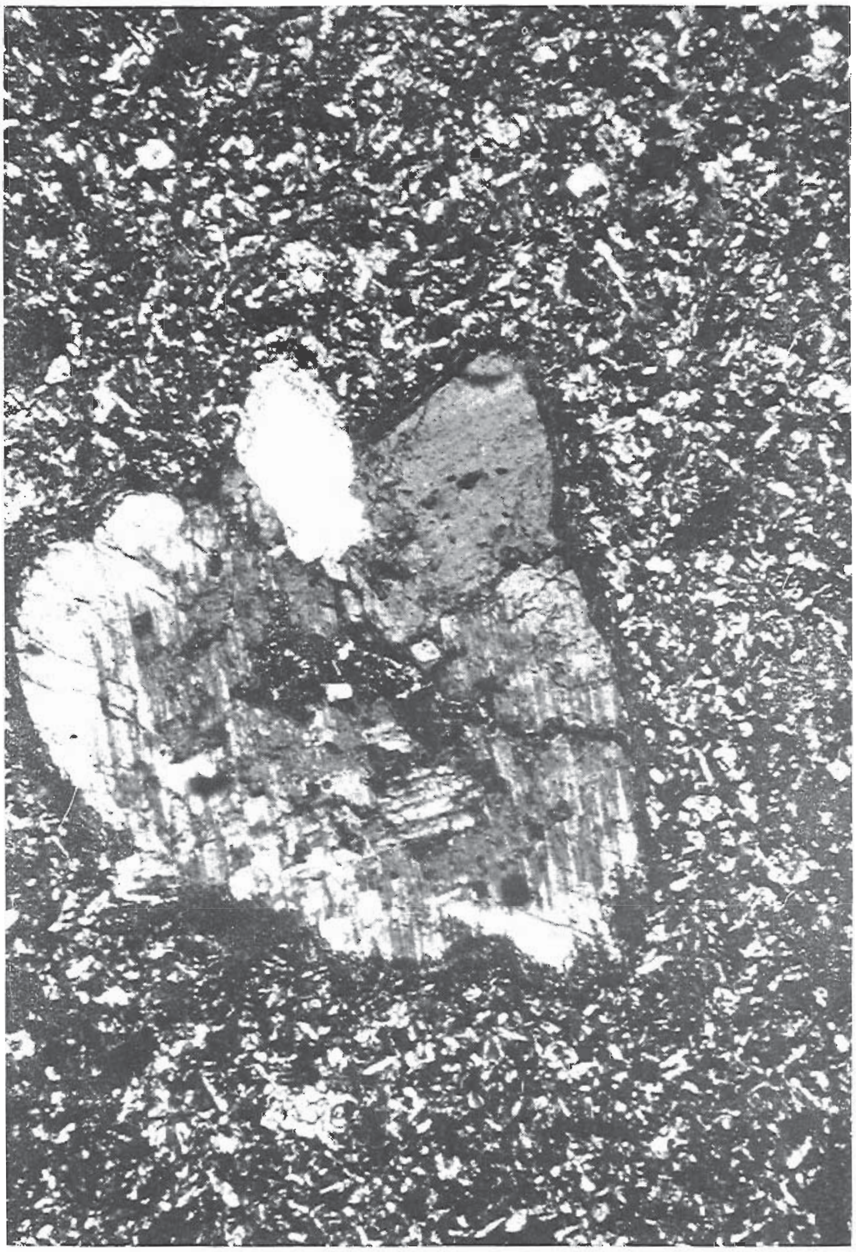

Plate 1 — Resorbed anorthoclase in hawaiite.

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 [$An_6 Ab_{39} Or_{55}$], 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 [$An_2 Ab_{61} Or_{36}$ -$An_6 Ab_{46} Or_{48}$] 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 (Fo_{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 $Na_2O + K_2O$ 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-

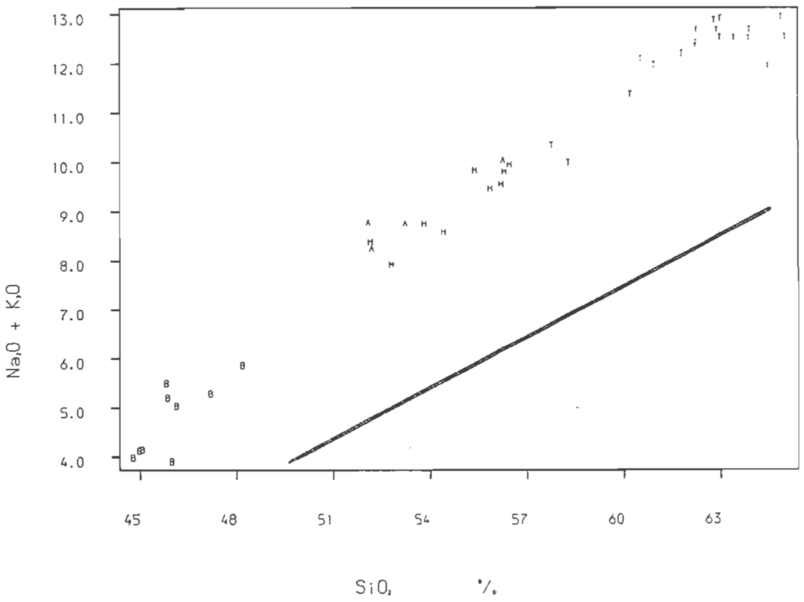

Fig. 2 — SiO_2 vs $Na_2O + K_2O$, Mac-Donald-Katsura plot. Symbols :T — trachytes, H — hawaiites, B — basalts, A — aphyric hawaiites.

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 ($< 50\ \%\ SiO_2$), the hawaiites (50-59 % SiO_2) an the trachytes ($> 59\ \%SiO_2$). 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 felspar 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.

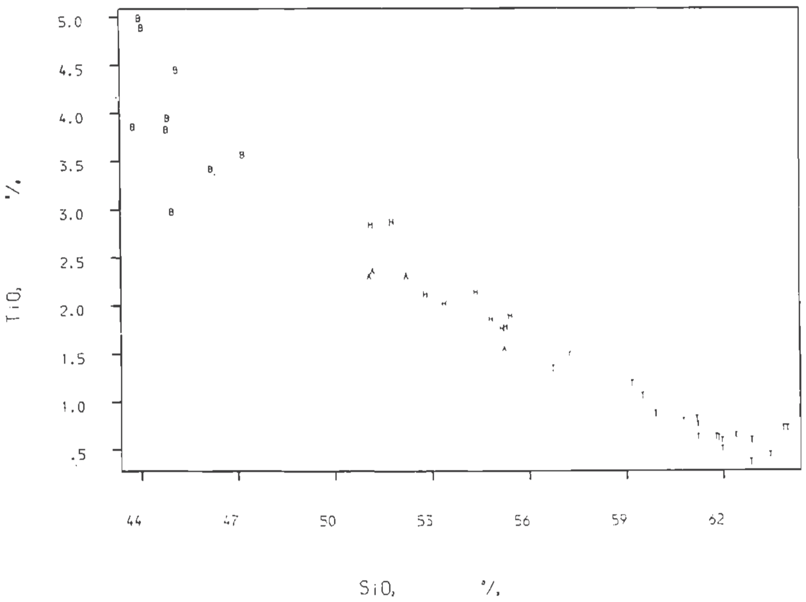

Fig. 3 — SiO_2 vs TiO_2 — symbols as for Figure 2.

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

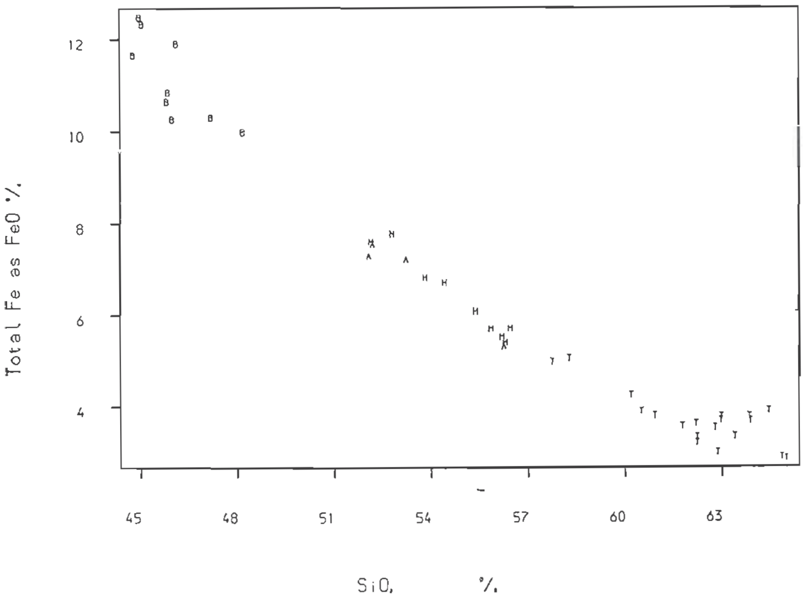

Fig. 4 — SiO_2 vs total iron as Fe_2O_3 — symbols as for Figure 2.

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 SiO_2, 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 K_2O and Al_2O_3 (Fig. 5), commencing at approximately 62 % SiO_2. This is consistent with the onset of fractional crystallisation of K feldspar from the trachytes.

Plots of SiO_2 vs MgO, Cr, Ni, P_2O_5 and the incompatible elements however do not follow the above simple patterns.

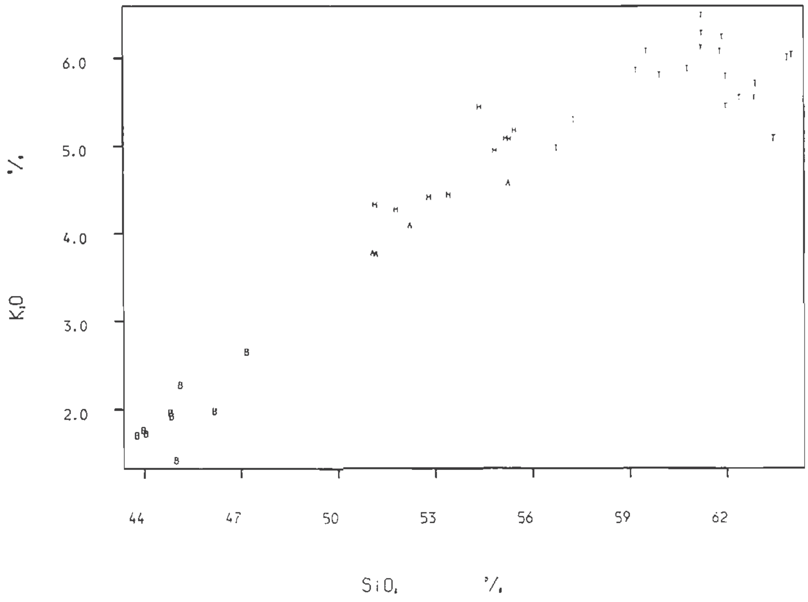

Fig. 5 — SiO_2 vs K_2O — symbols as for Figure 2.

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 silicae 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.

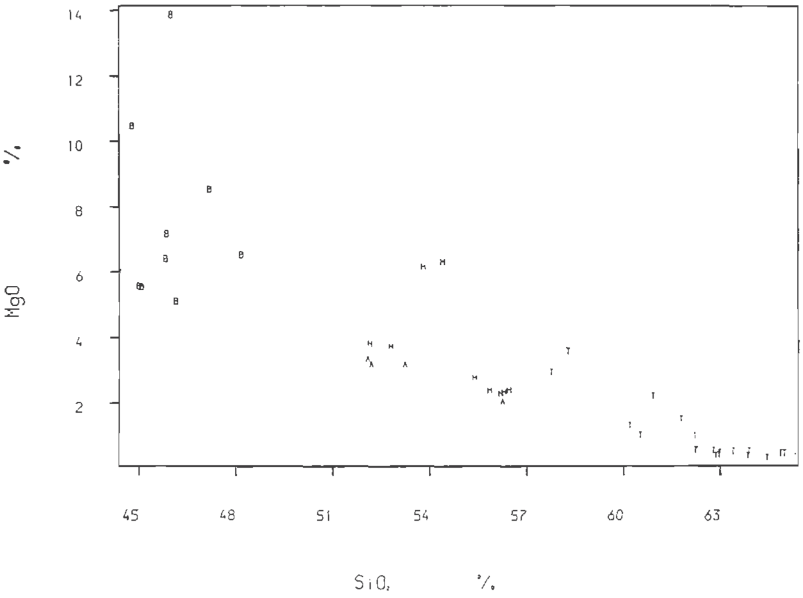

Fig. 6 — SiO_2 vs MgO — symbols as for Figure 2.

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 SiO_2 versus Zr, Rb, Nb and the REE. The main trends of the data form curved patterns with higher concentrations of incompatible elements with increasing SiO_2 (Fig. 7), but with little enrichment in the incompatible elements at SiO_2 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.

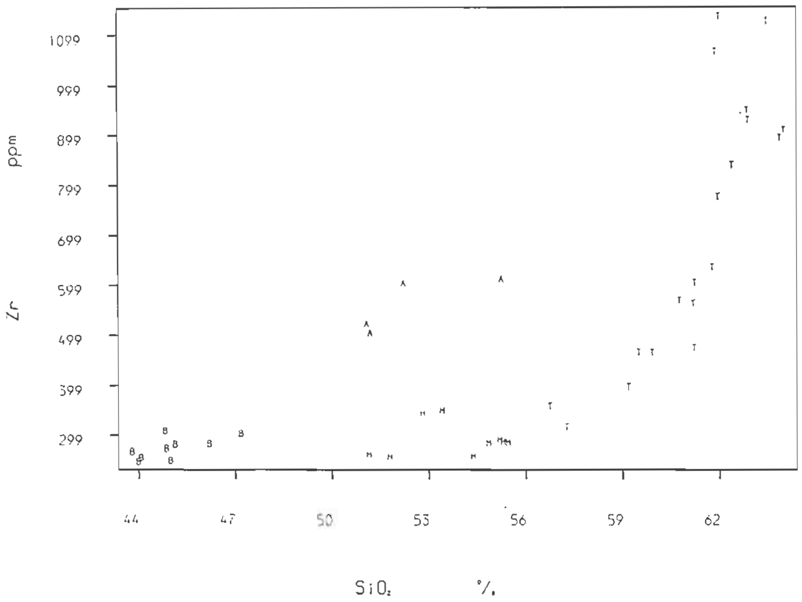

Fig. 7 — SiO_2 vs Zr — symbols as for Figure 2.

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 ($Eu/Eu^* \simeq 0.3$) 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 (Eu/Eu* ≃ 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.

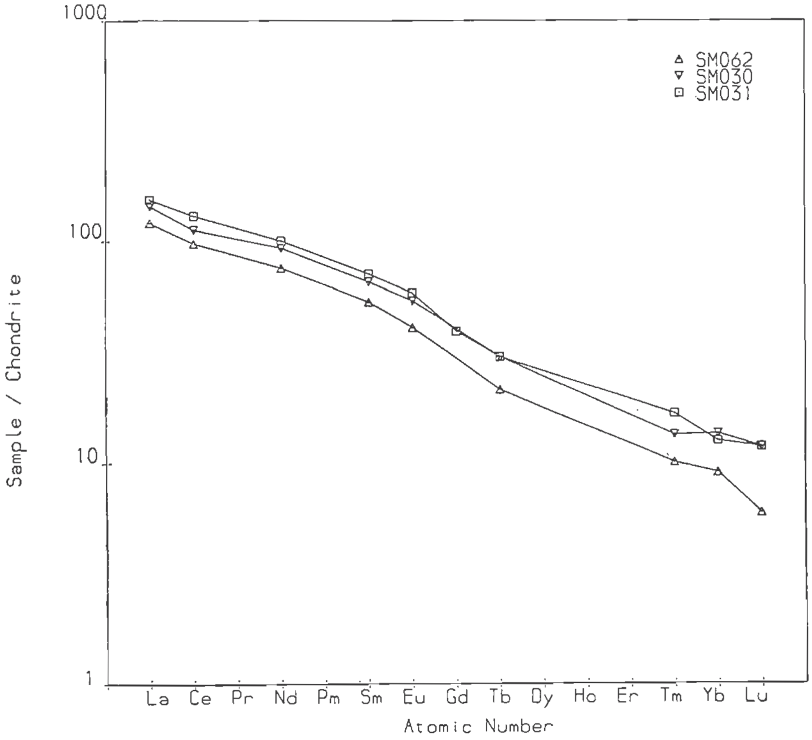

Fig. 8 — Chondrite normalised plot of REE for basalts.

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

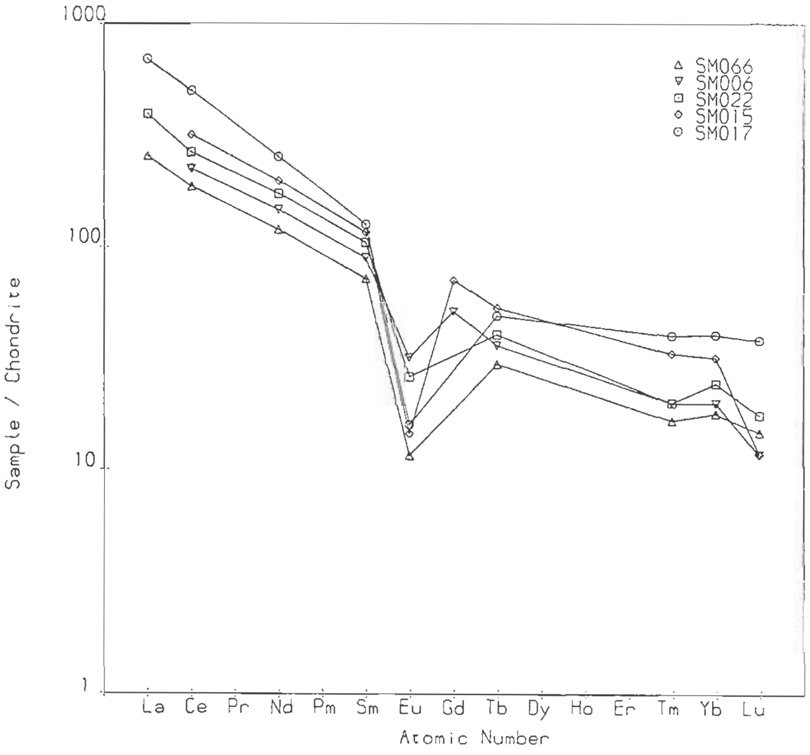

Fig. 9 — Chindrite normalised plot of REE for trachytes.

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.

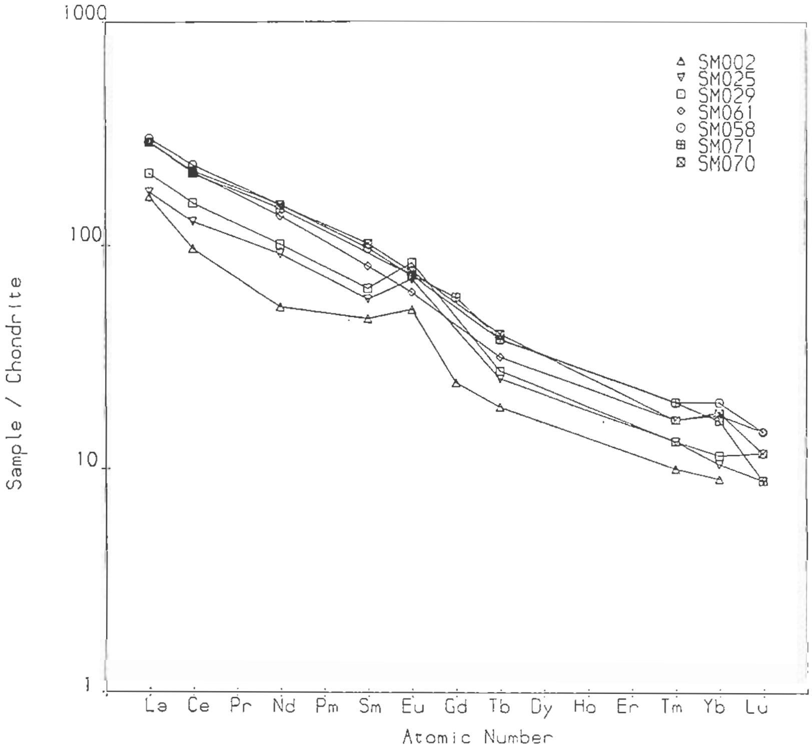

Fig. 10 — Chondrite normalised plot of REE for hawaiites :
SM002, SM025, SM029 = hawaiites
SM061, SM058, SM070,SM071 = aphyric hawaiites.

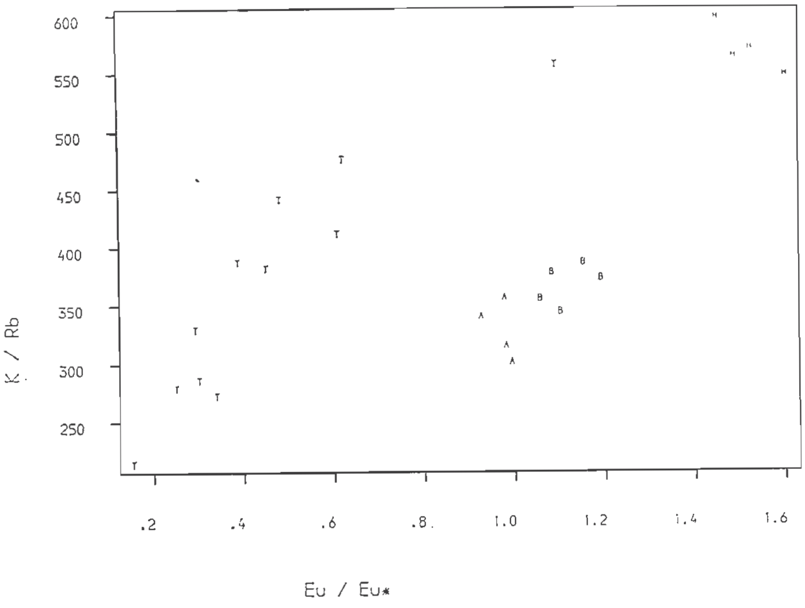

Fig. 11 — K/Rb plotted against Eu/Eu* symbols as for Figure 2.

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 swith positive Eu anomalies, dliuting 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 occurence of olivine /clinopyroxene and syenite xenoliths.

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