Stratigraphy, $^{40}Ar/^{39}Ar$ geochronology and geochemistry of flood volcanism in Yemen

J. Baker
M. Menzies
Department of Geology, Royal Holloway University of London, Egham, Surrey TW20 OEX, UK
L. Snee
Branch of Isotope Geology, USGS, MS 963, Denver, Colorado 80225, USA
M. Thirlwall
Department of Geology, Royal Holloway University of London, Egham, Surrey TW20 OEX, UK

Introduction

Flood volcanism in Yemen is part of a larger flood volcanic province extending into Eritrea and Ethiopia. Approximately 40,000 km^3 of bimodal basalt/rhyolite volcanism was erupted over an area of 20,000 km^2 in Yemen and constitute *c.* 10% of the entire volume of the volcanic province. There is a systematic change in the character of the volcanic pile from east to west and also north to south within Yemen. From east (rift shoulder) to west (rift margin) the volcanic pile thickens from *c.* 200 m to > 2000 m. The ratio of silicic to mafic magmatism increases markedly with increasing distance from the Red Sea rift margin and reflects the ability of explosive, silicic pyroclastic fall and flow units to travel further from their eruptive source regions. The silicic units were erupted from caldera centres represented by unroofed granite plutons in the Yemen rift mountains near the rift margin. From north to south the volcanic section thickens and becomes more basaltic in character. Field mapping and major and trace element geochemistry has allowed the lateral extent of some volcanic units to be identified, and requires individual basaltic flows and silicic pyroclastic units to have volumes in excess of 40 km^3 and 200 km^3 respectively.

Geochronology

Whole rock basalt samples from the volcanic pile in Yemen have complex $^{40}Ar/^{39}Ar$ age spectra despite being relatively young, and petrographically and geochemically unaltered. For example, samples often contain fresh olivine and may have negative LOI values. Age spectra display the combined effects of radiogenic Ar-loss from fine-grained groundmass, and inherited excess-^{40}Ar. Calculated total gas ages for the samples range from 21 to 54 Ma, similar to the range of published K–Ar dates for samples from the main flood volcanic phase in Yemen and Ethiopia, and have little or no age significance. No spectra define plateau ages *sensu stricto* but age minima in *simple* excess-Ar spectra or maxima in Ar-loss spectra produce a more tightly grouped range of age estimates from 26.9 to 31.5 Ma.

Amphibole and anorthoclase mineral separates from the base and near the top of the volcanic pile yielded precise plateau ages of 30.44 $\pm$ 0.18 (2sd; base) and 29.32 $\pm$ 0.1 (near top) and 28.260.1 Ma (top). The $^{40}Ar/^{39}Ar$ ages of the upper samples are concordant with Rb-Sr two-point isochron ages for whole rock - feldspar pairs from the same rhyolitic ignimbrite units which are: 29.1 $\pm$ 0.3 and 27.9 $\pm$ 0.7 Ma respectively. Thus, the main phase of flood volcanism may have been erupted in a period of < 3 Ma, and there is no marked time gap between the switch from predominantly mafic to silicic volcanism in western Yemen. Stratigraphic relationships allow comparison of the precise mineral ages with some of the age estimates inferred from the disturbed basaltic spectra. A significant number of the basalt age estimates are up to 3–4 Ma too young, even where the samples are clearly not intrusive sills, and suggest caution is required in interpreting $^{40}Ar/^{39}Ar$ spectra of whole rock basalt samples which do not yield plateau ages. As such the accuracy of published whole rock $^{40}Ar/^{39}Ar$ data for other flood basalt provinces,which commonly do not yield age plateaux, must be questioned.

If an eruptive duration of *c.* 3 Ma in Yemen is extrapolated to include the main phase of flood volcanism in Ethiopia/Eritrea, then flood volcanism was erupted at a rate of *c.* 0.15 km^3/yr similar to the Hawaiian archipelago and other examples of continental flood basalt provinces. This estimate is significantly lower than the likely emplacement rate, which includes estimates of underplated and intruded igneous material. Simple fractionation models, based on concentrations of incompatible trace elements in the volcanic rocks, suggests that most of the erupted basalts underwent 30–50% fractional crystallization and that the silicic units represent > 75% fractional crystallization from a basaltic parent. The amount of cumulate material required to account for the fractionated nature of

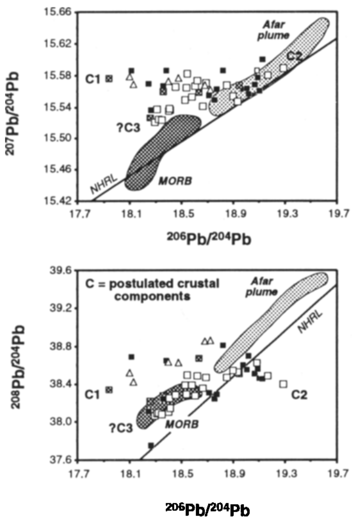

FIG. 1.

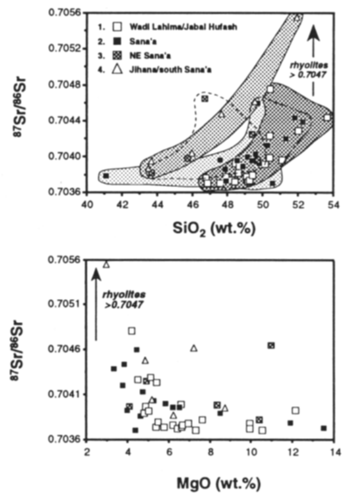

FIG. 2.

the eruptive products requires the emplacement rate to have been >0.3 km^3/yr, although this estimate does not include the total possible amount of intruded and underplated material.

Geochemistry

Sr–Nd–Pb isotopic data for basalts and rhyolites from the volcanic pile indicate that most of the volcanic units have compositions that lie outside the range of temporally and spatially appropriate mantle source compositions observed in this area (lithospheric mantle, MORB & Afar plume): $^{87}Sr/^{86}Sr$ = 0.7037–0.7062; $^{143}Nd/^{144}Nd$ = 0.51292–0.51248; $^{206}Pb/^{204}Pb$ = 17.8–19.2 (Fig. 1). Correlations between indices of fractionation and isotopic data requires crustal contamination to have modified the isotopic and incompatible trace element composition of most samples (Fig. 2). The crustal contaminants (C1, C2 & ?C3) are characterised by heterogeneous Pb isotopic compositions that produced complex mixing trends in the contaminated volcanics. One contaminant has low $^{206}Pb/^{204}Pb$ with high $\Delta^{207}Pb$ (C1) similar to the *enriched* lithospheric mantle component invoked by others to contribute to flood volcanism in Djibouti and Ethiopia. We contend that no such mantle component can be unequivocally demonstrated to contribute to volcanism in this region.

Primitive samples have radiogenic Pb coupled with low ratios of LILE to HFSE typical of HIMU OIB e.g., K/Nb = 150. Moreover, the isotopic and trace elemnt composition of these primitive samples approaches that of the Afar plume identified at the 46°E anomaly on the Gulf of Aden ridge and recent volcanics in Djibouti. However, HIMU mantle contributes to a variety of volcanic rocks in the Red Sea/Gulf of Aden region up to 3000 km from Afar, and in volcanic suites up to 200 Ma in age, including: intraplate volcanism in Israel, Saudi Arabia, Djibouti and Yemen; oceanic volcanism in the northern and southern Red Sea and the 46°E anomaly on the Gulf of Aden; flood volcanism in western Yemen and Djibouti.

Discussion

While isotope and trace element chemistry and the rapid eruption rate of the flood volcanics of Yemen, Djibouti and Ethiopia implies they are derived from the nearby Afar plume, this plume is unlikely to be responsible for the HIMU component found in volcanics located elsewhere. The model we prefer for the widespread occurrence of HIMU mantle in this region involves a protracted period (200 Ma) of plume upwelling from a deep seated HIMU reservoir trapping HIMU-like mantle in the asthenospheric or lithospheric mantle beneath the Afro-Arabian shield. Only when such plumes encounter thinned or extending lithosphere are voluminous flood basalts produced. Implicit in this hypothesis is that plumes, of similar scale and temperature to those in this region, are not the principal cause of rifts in such settings but rather they exploit rifts or at most influence the mechanics or location of rift formation.