U-Th-Ra isotope evidence for rates of fluid transport and magmatic processes beneath Santorini, Aegean Volcanic Arc, Greece

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The island of Santorini is situated in the Aegean and is part of the Hellenic Volcanic Arc, formed by the northward subduction of the African Plate under the Eurasian Plate. Santorini has been volcanically active since the middle Pleistocene. The two youngest (<200 ka) volcanic sequences are the second explosive cycle that terminated with the caldera forming Minoan eruption of ~1600 BC, and the Kameni island dacites, which comprise twelve historic lava eruptions from 46 AD to 1950. Selected rocks from these two sequences have been analysed for major and trace elements, for Sr and Nd isotopes, and for the short lived isotopes of U-Th-Ra by TIMS.

Second eruptive cycle

The compositions of the second eruptive cycle range from basaltic andesite to rhyolite, and samples are enriched in *LREE*, LILE, U and Th. Sr, Nd and Th isotopic compositions are also enriched relative to MORB, and they preserve good isotope-isotope correlations with $^{87}Sr/^{86}Sr$ = 0.7035–0.7052 and $^{143}Nd/^{144}Nd$ = 0.51285–0.51267 (Fig. 1), and $(^{230}Th/^{232}Th)$ = 0.97–0.90. The rocks tend to have similar $(^{230}Th/^{232}Th)$ and $(^{238}U/^{232}Th)$ activity ratios, and they are therefore in ^{230}Th-^{238}U equilibrium.

The within-suite trace element and Sr-Nd isotope trends can be modelled by AFC processes, indicating that variable assimilation of up to ~3% upper crustal material was responsible for the range in Sr, Nd and Th isotopes in the second eruptive cycle. The composition of the inferred pre-contamination magma reflects contributions from both sediment-derived melts (~0.3%) and hydrous fluids from the subducted slab. Relative to N-MORB, the enrichment in *LREE*, the high Th/Ta ratios and the low initial $^{143}Nd/^{144}Nd$ [~ 0.51285] and Th activity ratios [$(^{230}Th/^{232}Th)$ ~ 0.6] reflect modification of the mantle wedge by small degree melts of the subducted sediment. In contrast, the concentrations of fluid mobile trace elements [Rb, Sr, Ba, K, U and Pb] are significantly increased by introduction of slab-derived fluids. The data are consistent with a fluid Sr isotope ratio of ~0.7035, as inferred from studies of other island arcs (e. g. Turner *et al.*, 1997), and mass balance considerations indicate that fluid addition accounts for ~40% of the U budget. The

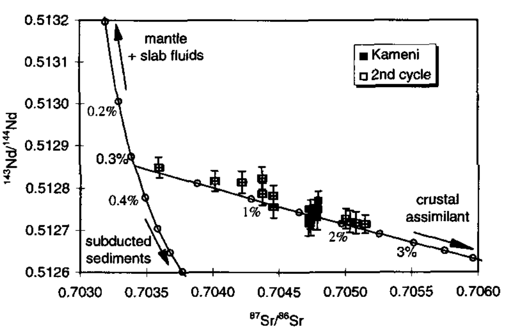

FIG. 1. Nd-Sr isotope correlation and petrogenetic interpretation.

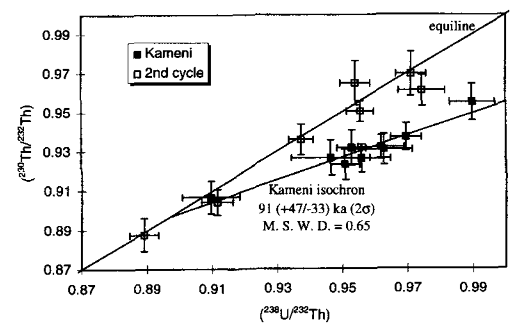

FIG. 2. U-Th equiline diagram for the second eruptive cycle and the Kameni dacites.

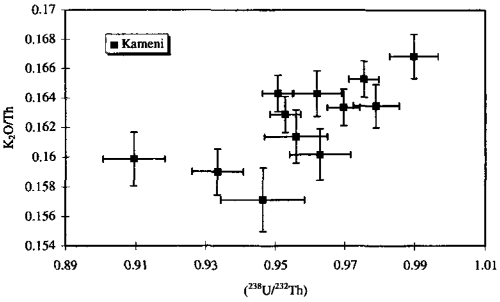

FIG. 3. Correlation of K_2O/Th ratios with ($^{238}U/^{232}Th$) activity ratios.

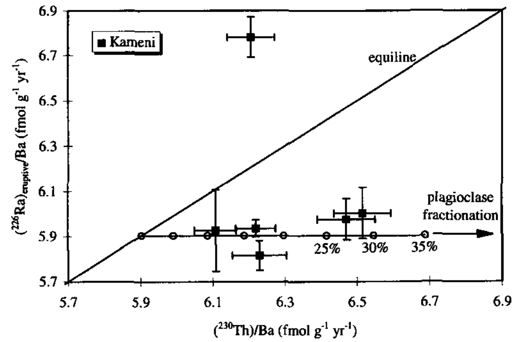

FIG. 4. Ra-Th equiline diagram showing the effect of plagioclase fractionation. (^{226}Ra)/Ba ratios are corrected to the time of eruption.

increase in U/Th ratios must have occurred at least 350 ka ago as all samples of the second eruptive cycle are in radioactive equilbrium (Fig. 2). This suggests that the combined transport and residence time beween hydration of the mantle wedge and volcanic eruption is close to or greater than 350 ka, which is much longer than that estimated from other arcs (30–90 ka, Heath *et al.*, submitted).

Kameni island dacites

The Kameni island dacites have a very restricted SiO_2 range of 65–68 wt.% and show little major and trace element variations (Barton and Huijsmans, 1994). They have constant Sr and Nd isotopic compositions of ~0.70475 and ~0.51274 and fall within the Sr-Nd isotope trend defined by the second explosive cycle (Fig. 1). However, their Th activity ratios range from 0.907 to 0.955 and are correlated with their ($^{238}U/^{232}Th$) activity ratios which show an even greater range from 0.909 to 0.990. A reasonable correlation is also observed between ($^{238}U/^{232}Th$) and K_2O/Th (Fig. 3). ^{226}Ra analyses of the Kameni island dacites give initial ($^{226}Ra/^{230}Th$) activity ratios ranging from 0.92 to 1.08, but most show ^{226}Ra depletion (Fig. 4).

Enriched Sr and Nd isotope ratios indicate that upper crustal assimilation processes have affected all the Kameni dacites. However, the constancy of their Sr and Nd isotopic composition implies that assimilation has affected all samples to the same degree.

On a U-Th equiline diagram, they yield a WR isochron of 91 ka (+47/−33 ka, 2σ M.S.W.D. = 0.65, Fig. 2). This is inferred to be the time between U-Th differentiation and eruption. Both U^{6+} and K are fluid mobile. The broadly positive correlation between ($^{238}U/^{232}Th$) activity ratios and K_2O/Th ratios indicates that U/Th differentiation was associated with a fluid phase, and we interpret the range in U/Th ratios to result from differential fluid addition from the subducting slab to the mantle wedge. Hence, for the Kameni dacites, ~60–135 ka have passed between hydration of the mantle wedge and volcanic eruption. This is a significantly shorter time than that for the second eruptive cycle.

The whole rock Ra analyses give ($^{226}Ra/^{230}Th$) < 1 for all but one Kameni dacites. This may be due to fractional crystallisation of a phase with $D_{Ra} > D_{Th}$, such as feldspar, within the last 8 ka. On a Ra-Th equiline diagram (Fig. 4.), age corrected samples have constant (^{226}Ra)/Ba ratios, but variable (^{230}Th)/Ba ratios. Accordingly, we suggest that each dacite has fractionated feldspar shortly prior to eruption.

Conclusion

At Santorini in the Aegean Volcanic Arc, transfer times are thus variable but much longer that those inferred for most other arcs (Marianas, Tonga-Kermadec, Lesser Antilles). We conclude that each arc has to be investigated separately when timescales of petrogenetic processes are considered.

References

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