Timescales of magma chamber processes from Th isotope systematics

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Introduction

Compositional heterogeneity observed within single flows, eruptive series, and suites of lavas represents the spectra of processes operating on magmas as they stall during ascent to the surface. Development of compositional heterogeneity within magma series probably occurs on geologic timescales sufficiently short for analysis by Th isotope systematics ($t_{1/2}$ ~75 ka). Here we examine the timescales and consequences of magma chamber processes for the production of four compositionally heterogeneous volcanic suites.

The volcanic flows described here are representative of a diversity of ages, chemical compositions, and evolutionary trends. They range in age from late Pleistocene to historic and collectively represent alkaline, calcalkaline, and tholeiitic compositions. Compositions range from basaltic (Pisgah, Great Rift) to dacitic (Great Rift); Paricutin lies wholly within the andesitic compositional range. Lavas of both Paricutin and Pisgah became increasingly differentiated over the course of eruption. Collectively, these lavas show consistent trends of Th isotope variation with increasing assimilation as well as high degrees of U/Th fractionation, including evidence for selective contamination.

Background and results

Great Rift, southern Idaho, USA. Holocene lavas of the Great Rift in the eastern Snake River Plain range from olivine tholeiites with >9% wt% MgO to silicic lavas with >64 wt% SiO_2 at Craters of the Moon lava field. Detailed field, petrologic, and geochemical studies (*e.g.* Leeman *et al.*, 1976; Kuntz *et al.*, 1986) show that while more evolved lavas assimilated crustal materials, the basalts are relatively free of crustal contamination and are derived from enriched mantle. Lava flows are typically zoned in composition and the compositional range of both xenocryst-bearing and xenocryst-free lavas increased in time towards the present. The most recent lavas (~2.1 ka) represent a compositional range of almost 20 wt% SiO_2.

$(^{230}Th)/(^{232}Th)$ ratios range from 0.87 to 1.11 and are enriched in (^{230}Th) with respect to (^{238}U) by up to 13%. If the U-Th isotope systematics of the lavas are dominated by crystal fractionation, the nearly equilibrated Th isotope signatures of the lavas require ~100 ka of *in-situ* decay since production of intermediate to silicic magma from their basic precursors but silicic samples closest to the equiline require several hundred ka. Simultaneous consideration of Th isotope and concentration data shows that ratios of assimilation to fractional crystallization <0.2 can account for the Th isotope signatures of these lavas, and therefore magma residence times of 100 ka are not required to explain the observed range in Th isotope ratios.

Paricutin, Mexico. Paricutin, an andesite cinder cone and associated lava flows in the western Trans Mexican Volcanic Belt, erupted continuously for 9 years beginning in 1943. Lavas became increasingly more differentiated with eruption progress and range in composition from 55-60 wt% SiO_2. Isotopic as well as chemical variations in the lavas require assimilation of rhyolitic crust in conjunction with fractional crystallization to explain the compositional variability.

U/Th ratios also decrease systematically in the Paricutin lavas with time for a total variation of ~16%. ^{230}Th enrichments increase sympathetically with this, such that the more differentiated lavas lie significantly above the equiline $(^{230}Th/^{238}U = 1.17)$. Consequently, in spite of the relatively small compositional variation overall, lavas of Paricutin exhibit a very large range in Th isotope characteristics. Xenoliths of granitic basement entrained in the lavas exhibit a significantly larger, almost 3-fold, variation in U/Th, largely as a result of hydrothermal alteration and U-enrichment in a subset of the xenoliths. Th isotopic compositions of these xenoliths lie near or significantly below the equiline.

Th isotope systematics in the Paricutin lavas define an array of age equivalent to >77 ka; the array defined by the xenolith data is equivalent to an age of 84 ka. The similarity in these isochron ages is provocative but a good fit of the trend in the lavas to assimilation of crust like that represented by the xenoliths suggests that this similarity is probably not diagnostic. In support of this, Ra-enrichments in the more evolved lavas (Reid, unpublished data) are not permissive of long magma residence times. A remarkable result of these data is that the divergence of the more evolved lavas from the equiline requires U/Th fractionation during assimilation, as might occur by partial melting of crust rather than bulk assimilatio: . Isotopic disequilibrium in the crustal xenoliths supports this interpretation.

Pisgah Crater, eastern California, USA. Pisgah Crater, a Pleistocene cinder cone located in the Mojave Desert region of California, is associated with a series of morphologically young, alkali basalt and hawaiite lavas flows which exhibit unusual geochemical and isotopic trends. Increasing differentiation in the Pisgah lavas is characterized by decreasing concentrations of many incompatible elements in spite of isotopic trends to more enriched compositions (Glazner *et al.*, 1991). This variation is attributed to the effect of progressive contamination of a depleted basaltic magma by mafic crust.

As for other incompatible elements, U and Th concentrations are nearly 3 times lower in the differentiated lavas of Pisgah compared to those of the more mafic lavas. Differential decrease in U with respect to Th results in a progressive increase in U/Th of > 34% with increasing differentiation. (^{230}Th)/ (^{232}Th) in both older and younger flows are similar ($\sim$1.03) and the most mafic lavas is enriched in ^{230}Th with respect to ^{238}U by over 20%.

The age of eruption of Pisgah is unknown but is inferred to be late Pleistocene (< 100 ka) based on underlying lake sediments. Age correction of the Th isotope systematics results in an array of negative slope on Th isochron diagram. Consequently, if compositional heterogeneity in the Pisgah lavas is the result of contamination, the assimilant must have a lower (^{230}Th)/ (^{232}Th) but higher U/Th ratio than that of the parental magma. ^{230}Th-enrichment in the most mafic Pisgah lava is extreme based on the range observed in most alkali olivine basalts (Williams and Gill, 1990). Allowing for still greater ^{230}Th-enrichment assuming an age for Pisgah of > 20 ka, it seems doubtful that magma residence times for the Pisgah lavas could have been significantly longer than this.

U/Th fractionation and timescales of magma chamber processes

Compositional variations in the lavas studied here are accompanied by a significant (> 15%) changes in U/Th. Partition coefficients for U and Th are similar for major mineral phases that precipitate over the range of compositions represented here. Accessory phases such as magnetite, apatite, and zircon are capable of changing U/Th but are likely to have affected only minor changes in U/Th in the lavas studied. Based on the correlation of changes in U/Th with other indices of crustal contamination, our data indicate that assimilation can have a significant effect on the U/Th characteristics of magma with important implications for the behavior of other incompatible elements. Importantly, trends in the data for Paricutin and Pisgah volcanoes show that the assimilant must lie off of the equiline and therefore, contamination must have been selective rather than by bulk assimilation.

In all instances, whole rock isochrons defined by the data for the various volcanoes require mean magma residence times of < 100 ka. To be rigorously valid, these ages apply only where magmas have evolved as closed systems. Isotopic considerations show that contamination has played a significant role in the volcanoes studied here. In all instances, Th isotope signatures decrease with increasing contamination as expected from Th/U in most crustal materials and in the xenoliths as well. Consequently, these ages provide extreme upper limits to the duration of magma residence in the crust. Considered in conjunction with other constraints on the evolution of these magma chambers, residence times of less than a few tens of thousands of years to less than a few thousands of years in most cases are likely.

References

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