Crustal assimilation no match for slab fluids beneath Volcán de Santa María, Guatemala

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ABSTRACT

New 238U-230Th and Sr isotope data from 40Ar/39Ar-dated mafic lavas of the composite cone, A.D. 1902 dacitic tephra, and 1922–present dacitic dome lavas from the Santa María–Santiaguito volcanic complex in northwestern Guatemala indicate that genesis of magma beneath the western end of the Central American volcanic arc requires sources much different than previously envisioned. Although U-series data from historical lavas along the Central American volcanic arc, including Guatemala, show variable but small degrees of either 230Th or 238U excess, 72–35 ka basalts and basaltic andesites from the Santa María cone have 15%–26% 238U excesses, among the largest measured in Central America. This implies that the mantle wedge beneath this sector of the arc was significantly modified by slab-derived fluids. A decrease in 87Sr/86Sr and (238U/232Th) ratios over the past 72 k.y. as basaltic andesite gave way to dacite is consistent with fractional crystallization coupled with progressive assimilation of crust that has relatively unradiogenic, mid-oceanic ridge basalt-like Sr isotope composition. Overall, our U-series data along with published 238U/230Th isotope results from Central America demonstrate that (1) slab-fluid flux can be high throughout Central America, including regions of relatively thick crust, and (2) the middle to lower crust beneath northwestern Guatemala may not be dominated by ancient metamorphic and granitic rocks.

INTRODUCTION

The geochemistry of arc lavas reflects contributions from the subducted slab, sediments on the slab, mantle, and subvolcanic crust; however, the mechanisms and extent by which these different components are incorporated into arc magmas remain enigmatic. The Central American arc is an ideal location to examine the role of subduction zone inputs and crustal contamination owing to prominent, well-documented, along-arc variations in lava geochemistry and crustal thickness (Carr et al., 1990). A consensus has developed that variations in erupted lava compositions (Ba/La, 10Be/9Be, U/Th) along the Central American arc reflect changes in the amount of subducted material from the Cocos plate involved in magma genesis (Fig. 1; Carr et al., 1990, 2003; Leeman et al., 1994; Patino et al., 2000; Rügpk et al., 2002; Eiler et al., 2005). It is generally accepted that the intensity of the slab signal peaks in west-central Nicaragua and decreases toward both ends of the arc. The crust is also thinnest beneath central Nicaragua (25 km) and becomes thicker (>40 km) toward the edges of the arc in northwestern Guatemala and central Costa Rica (Carr et al., 2003).

The 238U-230Th isotope system has been used widely, including in Central America, as a tracer of hydrous fluids released from the subducting oceanic crust and its overlying sediments (e.g., Reagan et al., 1994). It has been used recently to elucidate intracrustal processes in continental arcs (e.g., Jicha et al., 2009, Walker et al., 2007). This study combines new U-series and Sr isotope data from a suite of lavas erupted over the past 72 k.y. at the Santa María–Santiaguito volcanic complex, Guatemala, to explore the long-term evolution of this explosive volcano and compare the subduction zone input beneath this complex to other active Central American arc volcanoes.

*SANTA MARÍA–SANTIAGUITO VOLCANIC COMPLEX

Santa María–Santiaguito is one of 39 volcanic complexes that compose the Central American volcanic arc (Carr et al., 2003). It is located near the western end of the arc in the Guatemalan highlands and is built upon ~50-km-thick crust. On 24 October 1902, the second largest eruption
of the twentieth century commenced from a vent on the southwest flank of the Santa María composite volcano (Williams and Self, 1983). In 1922, the Santiaguito dome complex began to grow inside the crater formed during the 1902 eruption, and remains active, having erupted more than 1.2 km$^3$ of dacitic magma. Volcanism at Santa María–Santiaguito is bimodal in both composition and time, including roughly equal volumes of older basaltic-andesitic composite cone lavas (~8 km$^3$) and historic dacitic (~9 km$^3$) lava and tephra (Rose, 1987; Escobar-Wolf et al., 2010). Recent $^4$Ar/$^3$Ar and paleomagnetic results reveal that cone building occurred at Santa María in four phases from 103 to ca. 35 ka (Escobar-Wolf et al., 2010). In this study we focus on the evolution of the last three cone-building phases and the historic tephra and lava.

**LARGE FLUID FLUX IN GUATEMALA**

All 19 whole-rock samples from Santa María–Santiaguito are in $^{238}$U excess ($^{238}$U/$^{230}$Th) $> 1$ (see the GSA Data Repository$^1$ for methods), similar to the results of Walker et al. (2007), who analyzed two ca. 35 ka lavas from the Santa María composite cone. There are 12 mafic lavas from the Santa María cone, with the exception of a lava taken near the summit, that have $^{238}$U excesses ranging from 15% to 26%, among the highest measured in the Central American volcanic arc (Fig. 2). Lavas from western Nicaragua, where the slab signal is inferred to be at a maximum, have elevated ($^{230}$Th/$^{232}$Th) ratios, but relatively small $^{238}$U excesses (4%–10%) (Thomas et al., 2002). Only basalts from Cerro Negro in western Nicaragua, which have high water content in melt inclusions (Roggensack et al., 1997), have $^{238}$U excesses (14%–21%) comparable to those found in Santa María basalts and basaltic andesites (Fig. 2). Moreover, several basalts from Poás and Arenal volcanoes in central Costa Rica also have large $^{238}$U excesses (18%–26%) (Herrstrom et al., 1995; Allegre and Condomines, 1976) (Fig. 2).

Significant $^{238}$U excesses in continental arc lavas are relatively uncommon; most lavas with ($^{238}$U/$^{230}$Th) $>> 1$ are found in island arcs. Because experiments show that U is highly mobile in oxidizing aqueous fluids and Th is not (Brenan et al., 1995), the presence of large $^{238}$U excesses in arc lavas has been attributed to the addition of slab-derived fluids to the mantle wedge during magma genesis. Thus, U-series isotope data from Santa María lavas suggest that magmas were generated from a mantle wedge that was significantly modified by fluids released from the subducted slab. Eiler et al. (2005) analyzed oxygen isotope ratios of olivine and plagioclase phenocrysts in mafic Central American arc lavas and proposed that the slab-derived component beneath Guatemala was a water-poor partial melt of subducting sediment. Forward modeling of Cameron et al. (2003) also required a sediment melt component for volcanoes in southeastern Guatemala. However, Walker et al. (2007) suggested that sediment melt is not feasible in Guatemala because the subducting sediment has very high ($^{230}$Th/$^{232}$Th) ratios and Guatemalan lavas have some of the lowest ($^{230}$Th/$^{232}$Th) ratios in Central America. We concur with Walker et al. (2007) because U will not be significantly fractionated from Th during sediment melting, and thus a sediment melt is unlikely to be the dominant medium by which U is preferentially transported to the mantle beneath Santa María–Santiaguito.

**ASSIMILATION OF OCEANIC CRUST BENEATH SANTA MARÍA**

Unlike Santa María basalts and basaltic andesites, which have large $^{238}$U excesses, pumice and scoria from the 1902 eruption and dacitic lavas from Santiaguito have small $^{238}$U excesses (4%–10%) and $^{87}$Sr/$^{86}$Sr ratios that are generally less radiogenic than the older, mafic cone lavas (Fig. 3). Carr et al. (2003) proposed that the increase in $^{87}$Sr/$^{86}$Sr ratios in lavas from central to western Guatemala reflects enhanced assimilation of radiogenic, Paleozoic crust of the Chortis block, which underlies western Guatemala. In contrast, we propose that the decline in both ($^{238}$U/$^{230}$Th) and $^{87}$Sr/$^{86}$Sr ratios with time at Santa María–Santiaguito implies that dacites were produced from basaltic andesitic magma that underwent assimilation-fractional crystallization and incorporated ancient, low-$^{87}$Sr/$^{86}$Sr mafic crust. Alternatively, the trend toward more silica-rich magma with lower $^{87}$Sr/$^{86}$Sr ratios and smaller $^{238}$U excesses might reflect evolution of the mantle wedge and parental melts over the past 72 k.y. Because covariation of incompatible trace elements and their ratios are strikingly linear for the basaltic to dacitic compositions observed (Escobar-Wolf et al., 2010) and

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$^1$GSA Data Repository item 2010238, U-Th methods, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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![Figure 2. Percent $^{230}$Th and $^{238}$U excess versus distance along Central American volcanic front. Heavy gray line represents variation in crustal thickness along strike of the arc. (Sources of published U-Th isotope data as in Fig. 1.) Activity ratios determined by mass spectrometry (in Reagan et al., 1994) are preferred over those measured by alpha counting.](image)

![Figure 3. $^{87}$Sr/$^{86}$Sr versus ($^{238}$U/$^{230}$Th) for Santa María–Santiaguito lavas and tephras. Older mafic stratocone lavas have highest $^{87}$Sr/$^{86}$Sr ratios and largest U excesses, whereas 1902 dacite pumice and scoria and Santiaguito dacite dome lavas have lower $^{87}$Sr/$^{86}$Sr ratios and smaller $^{238}$U excesses. Youngest Santa María cone lava has lowest $^{87}$Sr/$^{86}$Sr and ($^{238}$U/$^{230}$Th) ratios.](image)
the range in \(^{230}\text{Th}/^{232}\text{Th}\) ratios is limited (Table DR1 in the Data Repository), we instead prefer a hypothesis that dacitic magmas are derived from earlier erupted basaltic andesitic magma via fractional crystallization coupled with assimilation of crustal melts. The crustal melts that contributed to the generation of Santa María–Santiaguito dacites probably dampened large \(^{230}\text{U}\) excesses that likely existed in the parent magmas. Potential crustal assimilants for Guatemalan lavas identified by Walker et al. (1995) from Chortis crust have \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios ranging from 0.70650 to 0.71427 (Walker et al., 1995), and therefore are not suitable assimilants for Santiaguito dacites. Wholesale melting of young precursor basalts that stalled in the crust, as suggested by Vogel et al. (2006), seems unlikely to have produced the dacites because gabbroic fragments ejected in the 1902 eruption and older mafic lavas from edifices surrounding Santa María have \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios higher than those of the dacites.

Hoernle et al. (2004) proposed that a belt of mafic igneous rocks extending from Costa Rica to Guatemala has been accreted to the Pacific margin of Central America. Although these rocks have relatively unradiogenic \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios (0.70306–0.70319), major and trace element geochemistry reflect an enriched intraplate origin (Hoernle et al., 2004). Energy-constrained recharge-assimilation-fractional crystallization (ERCFAFC) model calculations (i.e., Bohrson and Spera, 2007) indicate that the chemical and isotopic compositions of Santiaguito dacites can be produced from Santa María basalt that undergoes fractional crystallization coupled with assimilation of ~20% by mass of a partial melt of altered normal mid-oceanic ridge basalt (N-MORB)–like crust, and not ocean island basalt–like crust. Ophiolites that crop out along the south side of the Motagua fault in central Guatemala may compose a significant portion of the middle to lower crust beneath the active volcanic centers in northwestern Guatemala (Beccaluva et al., 1995; Alvarado et al., 2003). These rocks have a tholeiitic, N-MORB–like composition that could represent the potential crustal contaminant involved in Santa María–Santiaguito magma genesis. Assimilation of MORB-like crust is not unique to Guatemala; it has been inferred from the negative correlation between \(^{87}\text{Sr}/^{86}\text{Sr}\) and U-series isotopes in basalts at Lopevi volcano in the Vanuatu arc (Handley et al., 2008).

The uppermost lava flow in a package of ca. 35 ka lavas atop the Santa María cone has the smallest \(^{230}\text{U}\) excess (3%) and least radiogenic \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio of any of the Santa María lavas (Fig. 3). We interpret this to suggest that crustal melting and assimilation were ongoing well in advance of the 1902 eruption. Evidently, repeated injections of mantle-derived basalt during a >50 k.y. period (Escobar-Wolf et al., 2010) promoted crustal melting and long-term incubation of a hybrid dacitic magma that eventually erupted explosively in 1902.

IMPLICATIONS FOR ALONG-ARC TRENDS IN CENTRAL AMERICA

The slab signal in most arc lavas is likely composed of multiple components, including a partial melt of the sediment, fluid released from the downdropping plate, and overlying sediment pile, all of which transfer elements to the mantle wedge. Sediments atop the subducting Cocos plate are relatively uniform in composition along the strike of Central America and are composed of pelagic carbonates capped by hemipelagic oozes (Patino et al., 2000). The sediment column is characterized by unusually high Ba and U contents but relatively constant Ba/La and U/Th ratios (Plank and Langmuir, 1998; Patino et al., 2000). In western Nicaragua, Ba/La and U/Th ratios in the lavas reach a maximum, and this is where the slab signal is inferred to be the strongest, and it is commonly associated with slab-derived fluids. The popular model of Carr et al. (1990) for producing the elevated Ba/La and U/Th ratios in Nicaraguan lavas proposes that fluid flux from the subducted slab is nearly uniform along the arc but fluid addition to the mantle wedge varies with slab dip. In Nicaragua, where slab dip is steepest, fluids are focused to a narrow window in the mantle wedge, thereby leading to higher degrees of melting (e.g., lower La/Yb ratios). Less-focused fluids in other parts of the arc where dip is not as steep will result in smaller degrees of melting. There are two potential pitfalls of this focused versus defocused slab fluid–flux model. First, the correlation of slab signal with degree of melting in Central America is crude. La/Yb ratios from lavas spanning ~600 km of the arc from Pacaya in south-central Guatemala to Zapatera in eastern Nicaragua show limited variability (average La/Yb = 3.4 ± 1.7; 2 standard deviations) and no correlation along strike (\(r^2 = 0.07\)). Second, if \(^{230}\text{U}\) excesses truly reflect U-Th fractionation due to fluid transport of \(U^6\) to the mantle wedge, our new U-series data, along with published \(^{230}\text{U}/^{238}\text{U}\) isotope results, imply that fluid flux is highly variable along strike of the arc. This observation is consistent with water contents that range from 1 to 6 wt% in phenocryst-hosted melt inclusions in Central American volcanic arc lavas (Sadofsky et al., 2008, their figure 6). Moreover, olivine-hosted melt inclusions in the A.D. 1723 tephra erupted from Izalcuz volcano in Costa Rica contain high water concentrations (>3 wt%), and require significant recycling of water from hydrous sources in the subducting slab despite the fact that the melt inclusions have low Ba/La ratios (~16) (Benjamin et al., 2007). This apparent disconnect between measured \(H_2O\) contents in melt inclusions of historically erupted phenocrysts and trace element and isotope proxies for slab fluid in whole-rock samples poses a serious obstacle to understanding volatile transport in arcs. Further scrutiny of larger sets of combined U-series and melt inclusion data obtained from the same eruptive material will be needed to resolve this conundrum.

In contrast to models suggesting that lavas in western Nicaragua have maximum sediment and fluid signals, we propose that the elevated Ba/La ratios in western Nicaragua lavas only reflect a more pronounced sediment signature and are not related to fluid delivery to the mantle. This should not be surprising because Ba/La ratios correlate positively with \(^{10}\text{Be}/^{9}\text{Be}\) (Plank and Langmuir, 1998; Patino et al., 2000; Reagan et al., 1994). A diminished role of slab-derived fluids in Nicaragua challenges interpretations garnered from most studies of Central American arc magma genesis (e.g., Carr et al., 1990, 2007; Leeman et al., 1994; Herrstrom et al., 1995; Clark et al., 1998; Patino et al., 2000; Rüpke et al., 2002; Eiler et al., 2005; Sadofsky et al., 2008) and contradicts a recent tomographic study (Rychert et al., 2008).

CONCLUSIONS

Basalts and basaltic andesites from Santa María have \(^{230}\text{U}\) excesses among the largest measured in Central America, and are likely the result of significant fluid modification of the mantle wedge during magma genesis. We suggest that elevated Ba/La, U/Th, and \(^{10}\text{Be}/^{9}\text{Be}\) ratios in western Nicaraguan lavas simply reflect a pronounced sediment signature, most likely a partial melt of the sediment, not a large flux of slab-derived fluids. This contradicts previous interpretations that favor a maximum fluid signal in western Nicaragua. Production of dacite composing the 1902 Plinian fall deposit and Santiaguito dome complex requires assimilation of a MORB-like crustal component, which differs from ancient crustal rocks assumed to predominate in this region of Guatemala. Were we to have concentrated our investigation on only historical eruptions we to have concentrated our investigation on only historical eruptions of Santa María–Santiaguito, far different conclusions regarding magma genesis may have been reached, highlighting the fact that models based on along-arc geochemical observations will benefit by considering the magmatic history recorded by all products of long-lived volcanic centers, not just the most recent.

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