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Eruptive dynamics reflect crustal structure and mantle productivity beneath volcanoes

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ABSTRACT

Volcanoes exhibit a wide range of eruptive and geochemical behavior, which has significant implications for their associated risk. The suggested first-order drivers of intervolcanic diversity invoke a combination of crustal and mantle processes. To better constrain mantle-crustal-volcanic coupling, we used the well-studied Lesser Antilles island arc. Here, we show that melt flux from the mantle, identified by proxy in the form of boron isotopes in melt inclusions, correlates with the long-term volcanic productivity, the volcanic edifice height, and the geophysically defined along-arc crustal structure. These features are the consequence of a variable melt flux modulating the pressure-temperature-composition structure of the crust, which we inverted from xenolith mineral chemistry. Mafic to intermediate melts reside at relatively constant temperature (981 ± 52 °C; 2σ) in the middle crust (3.5–7.1 kbar), whereas chemically evolved (rhyolitic) melts are stored predominantly in the upper crust (<3.5 kbar) at maximum depths that vary geophysically along the arc (6–15 km). Our findings are applicable worldwide, where we see similar correlations among average magma geochemistry, eruptive magnitude, and rate of magma input.

INTRODUCTION

Volcanic island arcs, such as the Lesser Antilles arc (LAA), may show large along-strike variability in their eruptive frequency-magnitude relationships, crustal structure, geochemistry, seismicity, and isotopic signatures (Wadge, 1984; Hildreth and Moorbath, 1988; Schlaphorst et al., 2016; Melekhova et al., 2019; Cooper et al., 2020). The proposed mechanisms for such stark changes include different melt flux from the mantle ("melt flux"; Schlaphorst et al., 2018; Till et al., 2019; Cooper et al., 2020), chemically distinct mantellic melts (Pichavant et al., 2002), contrasting crustal differentiation mechanisms (Tamura et al., 2016), and shifts in wedge thermal structure (Turner et al., 2016). These processes can all modulate the thermal-chemical architecture of subvolcanic magma plumbing systems (Castruccio et al., 2017; Giordano and Caricchi, 2022), and subsequently the chemical and physical properties of magma via phase equilibria (Müntener and Ulmer, 2018). Presently, however, the connection between variegated crustal or mantle processes is less frequently extended to include the diverse chemistry, frequency, and magnitude of volcanic eruptions.

To explore the nested interplay among mantle, crustal, and volcanic processes, we turned to the well-studied LAA. We first recovered the generalized thermal-chemical structure of magma plumbing systems in the LAA and used this to contextualize variability in the regional geochemical, geophysical, isotopic, and volcanic record (see Supplemental Material[1] for compiled data sets, sources, and extended methods). In doing so, we highlighted a fundamental role for melt flux in controlling magma plumbing system architecture and, by extension, eruptive dynamics. Finally, we found that global data indicate that the first-order control of melt flux operates at volcanoes worldwide.

UNIQUE LAA VOLCANIC-PLUTONIC RECORD

The LAA, resulting from the westward subduction of the Atlantic plate beneath the Caribbean plate, hosts a well-studied geological and geochemical record. The 11 active volcanoes, spaced $\sim$50 km apart (4–122 km), express a range of magma compositions, eruptive styles, and magnitudes (Metcalfe et al., 2023). The LAA also fortuitously hosts a plutonic record via intrusive fragments ("xenoliths"; Melekhova et al., 2019). Their texture and geochemistry reflect separation of refractory cumulates during differentiation (cumulate intrusive fragments [CIFs]), mobilization of magmatic mush or solidified magma (plutonic intrusive fragments [PIFs]), and metamorphic overprinting (Stamper et al., 2014; Melekhova et al., 2017, 2022; Camejo-Harry et al., 2018; Brown et al., 2021). Their bulk chemistry (Table S1), mineralogy, and mineral chemistry (Table S2) dictate their origins under varied pressure–temperature–melt composition (*P*-*T*-*X*) conditions within the crust.

The limitations of using intrusive fragments from the LAA as a crustal archive are twofold. First, inversion of their *P*-*T*-*X* values via mineral chemistry cannot resolve subtle interisland differences in magma storage depths due to thermobarometer and chemometer uncertainty (Wieser et al., 2023). Second, mineral chemistry is absent for several islands and is weighted heavily toward CIFs. However, the data are sufficient to make general observations of crustal *P*-*T*-*X* structure in the LAA when combined with independent data sets. One such data set is the entrapment pressure from volatiles in melt inclusions (MIs) for the LAA (Balcone-Boissard et al., 2023). MI pressures have a smaller uncertainty compared to thermobarometry, yet

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[1]Supplemental Material. Published data tables and their sources used in this study as well as an extended methods description. Please visit https://doi.org/10.1130/GEOL.S.23802819 to access the supplemental material, and contact editing@geosociety.org with any questions.

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they have biases associated with MI selection, as well as issues of postentrapment reset and modification. Geophysics is another valuable along-arc data source (Melekhova et al., 2019), although resolution may tail off at depth. However, by integrating records from MIs, intrusive fragments, and geophysics, we can limit the resolution and uncertainty shortcomings of individual methods. Together, these data can contextualize the geochemical and eruptive variability between adjacent LAA volcanoes.

QUANTITATIVE WINDOW INTO SUBVOLCANIC SYSTEMS

Intrusive fragments from the LAA combine up to eight minerals, with most containing amphibole and/or clinopyroxene (Melekhova et al., 2019). Therefore, we applied the single-mineral amphibole and clinopyroxene thermobarometer and chemometer of Higgins et al. (2021a) to recover the pressure (*P*; kbar), temperature (*T*; °C), and major-element melt chemistry from which these minerals crystallized (*X*; SiO_2_liq; wt%; Table S2).

P-T-X data from intrusive fragments collectively highlighted noteworthy properties of LAA magma plumbing systems (Fig. 1A). *P-T* distributions overall were found to be subvertical between 3.5 and 7.1 kbar (∼10.5 to 21 km, where 1 kbar ≈ 3 km from the average xenolith density in Melekhova et al., 2019), a region dominated by CIFs (Fig. 1B). The temperature range was limited (981 ± 52 °C; ranges are 2σ), and SiO_2_liq values were basaltic-andesitic (56 ± 8 wt%). Amphibole was stabilized with decreasing temperature at the expense of clinopyroxene, agreeing with experiments (Melekhova et al., 2015) and intrusive fragment reaction textures (Melekhova et al., 2017). Thermal modeling results have implied that the lower to middle crust beneath active volcanoes is the thermal engine of a magmatic system (Annen et al., 2006; Karakas et al., 2017; Glazner, 2021). CIF data showed that this thermal engine runs at a rather constant temperature (981 ± 52 °C) in the LAA, maintaining a limited range of SiO_2_liq values throughout the middle crust (3.5–7.1 kbar). These features are indicative of buffering by a low-variance mineral assemblage (Blundy, 2022). At pressures between 1.2 and 3.5 kbar (3.6–10.5 km), PIFs and some CIFs (Fig. 1B) recorded a wider range of temperature (955 ± 136 °C) and SiO_2_liq (63 ± 15 wt%; Fig. 1A). The dominance of evolved melts in the upper crust is in good agreement with MIs, which record entrapment conditions in the uppermost LAA crust (∼2.5–0 kbar) with a tail to higher pressure (Fig. 1C). While rhyolitic melts are present throughout the crust, they preferentially reside in the upper crust (< 3.5 kbar). These general features concur with other compilations of LAA magma storage (Metcalfe et al., 2023).

Together, the *P-T-X* conditions of PIFs and CIFs from the LAA revealed a stratification, namely, a rather homogeneous thermochemical structure in the middle crust and a more thermochemically diverse upper crust (Figs. 1A and 1C). The middle crust (3.5–7.1 kbar) transfers heat and mass to the upper crust, where melts differentiate to SiO_2_liq values spanning to more evolved compositions (Metcalfe et al., 2023). Insights from intrusive fragments into the lowermost crust (>7.1 kbar) are lacking (Fig. 1A). However, they likely comprise olivine + clinopyroxene + spinel (Melekhova et al., 2017).

VARIABLE MELT FLUX DRIVES LINKED CRUSTAL-MAGMATIC-VOLCANIC SIGNATURES

Intrusive fragments and MIs indicated that the upper crust (<3.5 kbar) is the locus of rhyolitic melt storage in the LAA (Fig. 1). The mean upper-crustal thickness is ∼11 km (∼3.7 kbar), where the geophysical upper crust is defined as the distance (km) between layers 2 and 3 in Melekhova et al. (2019) (see also Supplemental Material). A depth of ∼11 km corresponds closely to the average depth at which the SiO_2_liq range increases (Fig. 1A), demonstrating good agreement between geophysical and geochemical data in the LAA. While unbalanced mineral chemistry data and thermobarometer uncertainty preclude a robust comparison of *P-T-X* values between islands, LAA receiver functions clearly show that the upper-crustal thickness varies along the strike of the arc (Melekhova et al., 2019).

The thickness of the upper crust could reasonably relate to the volume of evolved melt present, given that: (1) the upper crust is a factory for evolved melts (dacitic-rhyolitic; Fig. 1A), a common MI and matrix melt composition in LAA erupted products; and (2) evolved MIs overwhelmingly record entrapment pressures <2.5 kbar, and many indicate upper-crustal storage before eruption (Fig. 1C). To explore this hypothesis and assess if upper-crustal thickness correlates with frequency-magnitude-chemistry distributions of along-arc eruptions, we investigated the relationships between volcanic and crustal signatures in the LAA (Table S3). Indeed, we found a good correlation between the upper-crustal thickness beneath each island, the height of the volcanic edifice, and the erupted volume in the past 100 k.y. (Fig. 2A; Wadge, 1984; Melekhova et al., 2019). This assessment was limited to LAA stratovolcanoes to minimize the effect of fluctuations in dome height during the lifetime of a given volcano. While edifice shape data come with several caveats (see Supplemental Material), to a first order, the edifice height relates to the thickness of a magma column via the hydrostatic ("magmastatic") pressure equation ($P = \Delta\rho gh$). This fundamental relationship dictates that the volcanic edifice height increases with the vertical extent of a column of magma, with lower density than the crust and with interconnected melt (Castruccio et al., 2017).

Significant transcrustal connectivity in a magmatic system requires a sufficiently high melt fraction, which can only be sustained by heat input (i.e., injected high-*T* melt; Castruccio et al., 2017; Karakas et al., 2017). Thus, for comparable crustal thickness, volcanic edifice height should correlate with melt flux (Karakas et al., 2017; Weber and Sheldrake, 2022). Thermal modeling has independently shown that melt flux relates strongly to geochemical variance and eruptive magnitude (Caricchi et al., 2014; Karakas et al., 2017; Weber et al., 2020). However, melt flux is a highly elusive parameter, and so linking it to the diversity of magmatic systems and volcanoes beyond a conceptual model is problematic (Caricchi et al., 2014). Therefore, to assert that melt flux plays a central role in controlling geochemical and volcanological behavior in the LAA would require rare evidence of changing along-arc melt flux. Incidentally, recent geophysical and geochemical studies have revealed this may indeed be the

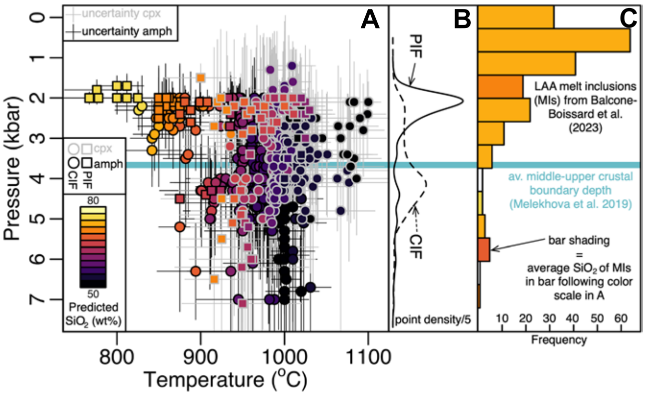

Figure 1. (A) Predicted temperature (*T*, °C) vs. pressure (*P*, kbar) from intrusive fragments using single-phase clinopyroxene (cpx, gray outlines) and amphibole (amph, black outlines) thermobarometer of Higgins et al. (2021a). Plutonic intrusive fragments (PIF, squares) and cumulate intrusive fragments (CIF, circles) are based on texture of intrusive fragments. Uncertainties (bars) are derived from method of Higgins et al. (2021a). Symbols are filled for SiO_2_liq in equilibrium with intrusive fragments calculated with chemometer of Higgins et al. (2021a). (B) Point density of PIF and CIF vs. *P* (kbar). (C) Melt inclusion (MI) entrapment *P* (kbar) from Balcone-Boissard et al. (2023). LAA—Lesser Antilles arc.

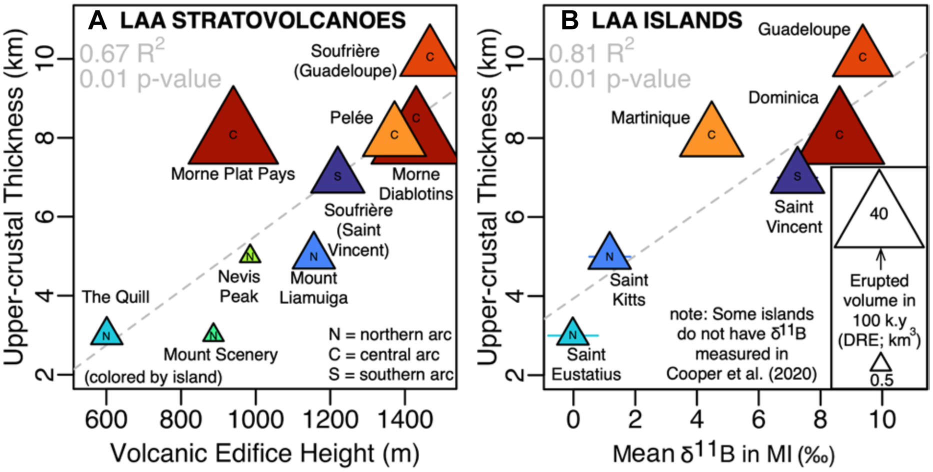

Figure 2. (A) Geophysical upper-crustal thickness from Melekhova et al. (2019) vs. volcanic edifice height for Lesser Antilles arc (LAA) volcanoes from Smithsonian Institution (2022). Symbol size is proportional to log of erupted dense rock equivalent volume (km^3) per 100 k.y. from Wadge (1984). (B) Upper-crustal thickness vs. mean δ^{11}B (‰) in melt inclusions (MIs) from Cooper et al. (2020). Horizontal bars (if bigger than symbol) are 1σ of δ^{11}B values for each island. North (N), central (C), and south (S) arc segment labels are according to Metcalfe et al. (2023).

case (Schlaphorst et al., 2016; Cooper et al., 2020).

In the LAA, slow subduction (2–4 cm/yr) creates lithospheric-scale fractures of the subducting slab, which expose the mantle to seawater. The ensuing serpentinization of the mantle leads to a heterogeneous water content in the subducting lithosphere. Higher water contents increase the degree of partial melting of the mantle, leading to a higher melt flux to the crust (Grove et al., 2012). Boron isotopes in melt inclusions express the relative contribution of these serpentine-derived fluids (Table S4; Cooper et al., 2020), with high δ^{11}B reflecting a serpentine-rich mantle source. Figure 2B shows that mean δ^{11}B (‰) in LAA MIs correlates with the upper-crustal thickness and the long-term volcanic output. These data suggest that higher water flux to the mantle, and by extension melt flux to the crust, thickens the upper crust. As the upper crust hosts mostly evolved melts (Fig. 1), higher melt fluxes appear to favor the growth of thicker, more chemically evolved upper-crustal magma reservoirs, underlying taller volcanic edifices. A similarly good relationship is observed between island area, a reasonable proxy for long-term productivity of volcanic systems built on oceanic crust, and both the upper-crustal thickness and mean δ^{11}B value (Supplemental Material).

Based on our observations (Fig. 2), LAA volcanoes atop a thicker upper crust are prone to generate more voluminous quantities of chemically evolved melts. Heat loss via hydrothermal circulation and advection in the upper crust is sustained by high rates of melt input, maintaining a thicker, active, upper-crustal magma reservoir (Glazner, 2021). Thermal modeling additionally shows that high melt fluxes lead to greater volumes of potentially eruptible upper-crustal mush (fig. 3b in Karakas et al., 2017). Upper-crustal melts do not necessarily erupt directly in the LAA; instead, evolved melts entrain various minerals to form hybridized andesitic-dacitic magmas (e.g., Dominica). In contrast, lower melt fluxes are associated with a thinner upper crust, promoting only the sporadic accumulation of potentially eruptible rhyolitic melts (e.g., Saint Kitts; Higgins et al., 2021b). In situ plagioclase Sr isotopes from intrusive fragments from Martinique further implicate the upper crust as a zone where melts are stored and blended prior to eruption (Brown et al., 2021). Our findings ratify previous studies (Cooper et al., 2020; Metcalfe et al., 2023) showing that volcanoes in the central LAA (Guadeloupe to Dominica) present the most significant modern-day risk in the region (Fig. 2A).

GLOBAL PROXY FOR MELT FLUX–CONTROLLED ERUPTIVE BEHAVIOR?

Melt flux modulation is demonstrably a viable method for controlling geochemical and eruptive behavior in the LAA (Fig. 2). To explore if our observations extend globally, we used the LaMEVE database of large-magnitude (volcanic explosivity index [VEI] >4; Table S5) explosive volcanic eruptions (Crosweller et al., 2012). It reports volcanic eruption parameters including magnitude, VEI, deposit volume, eruption age, and magma type. Principally, we wanted to gauge if we could scale up the relationship in the LAA (predominantly VEI <4; Metcalfe et al., 2023) between melt flux, volcanic output, and geochemistry (Fig. 2) to more productive systems worldwide. Giordano and Caricchi (2022) demonstrated that the average volumetric eruption rate (aVER; total erupted volume/volcano longevity) is proportional to the long-term rate of magma input into the crust (i.e., melt flux) despite deposit preservation biases. This is independent of the extrusive/intrusive ratio, which stabilizes in volcanoes that have been active for longer than a few hundred thousand years. Further, Giordano and Caricchi (2022) showed that the volume of the largest eruption from a volcano scales with aVER (Fig. 3). Larger eruptions are fed by magmatic systems with higher melt flux, agreeing with our observations from the LAA (Fig. 2). However, not only is there a proportionality between aVER and erupted volume, but also between aVER and the average erupted magma composition (color shading in Fig. 3). In other words, larger eruptions are systematically associated with volcanoes that erupt more chemically evolved (dacitic-rhyolitic) magmas (Mason et al., 2004).

Collectively, global data concur with our observations from the LAA indicating that higher melt flux conceivably drives geochemistry of magma reservoirs toward more evolved compositions, culminating in larger-volume eruptions on average (Figs. 2 and 3). In the LAA, this productivity manifests itself as a thicker geophysically defined upper crust (Fig. 2), representing the factory for evolved melt production (Fig. 1). We propose that the characteristic behavior of a volcanic system is strongly influenced by the mantle melt productivity and can be linked to a convolution of directly or indirectly measurable parameters such as the thickness of the upper crust, the active volcano height, and the geochemistry of melts in upper-crustal magma reservoirs (Figs. 1 and 2). Such first-order relationships may permit the rapid assessment of the potential for magmatic systems to feed large explosive eruptions, both at the regional and global scale, which is vital for appraising more remote and poorly monitored active volcanoes.

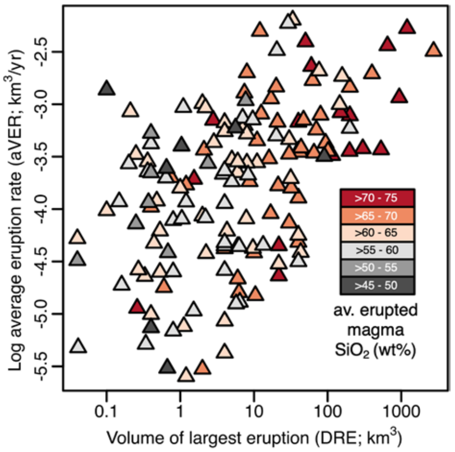

Figure 3. Log of average eruption rate (aVER; km^3/yr) vs. volume of largest eruption (km^3; dense rock equivalent [DRE]) for global volcanoes with sufficient data (volcanic explosivity index [VEI] >4; Table S5; Crosweller et al., 2012). Volcanoes are shaded by average erupted magma chemistry (see Supplemental Material [text footnote 1]).

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