Mantle heterogeneity controls on small-volume basaltic volcanism

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ABSTRACT

Eruptions of basaltic material in small-scale volcanic fields located in intraplate settings display a very diverse range in physical and chemical characteristics. Despite its relevance to the understanding of volcanic hazards, the relationship between physical properties of eruptions (explosivity, volume, location) and chemical composition of erupted products has, to date, not been investigated. Here we present a relationship between mantle heterogeneity and extents of partial melting, and both erupted volumes and eruptive style from the Auckland Volcanic Field (New Zealand), and we suggest that this provides a general model for small-scale "monogenetic" magmatic systems globally. Small volcanic centers consistently take the form of nephelinitic tuff rings and scoria cones, whereas larger centers are produced from effusive eruptions of less alkalic magmas. Nephelinitic melts are generated by melting of a deep, carbonated source, whereas less alkalic melts are the products of melting of a shallower, noncarbonated source. U-Th-Ra isotope data from eruptions closely paired in space and time show that mixing between magmas is extremely limited as a consequence of different ascent mechanisms due to differential segregation of melts from varying sources (early, carbonated melts ascending by higher porosity channels, and later, uncarbonated melts by a more diffusive regime). This suggests that extraction of melt is nearly instantaneous in these environments. Our results stress the importance of melting and magma dynamics in determining the size and style of eruptions in small volcanic fields, and suggest that mantle controls should be an important consideration in volcanic hazard assessment.

INTRODUCTION AND SETTING

Recent studies of small-scale basaltic volcanic systems have revealed that the chemical composition of erupted products varies both within single stratigraphic sequences and between individual centers in a contiguous volcanic field (e.g., Blondes et al., 2008; McGee et al., 2013; Strong and Wolff, 2003). These variations have been interpreted as the result of different degrees of crystallization (Luhr and Carmichael, 1985), crystal-melt interactions (e.g., Smith et al., 2008), multiple mantle source components (e.g., Cook et al., 2005; Haase and Renno, 2008), and variations in melting and ascent dynamics (e.g., McGee et al., 2011; Reiners, 1998). The study of primitive basalts in small-scale volcanic fields, which lack evidence for significant long-term magma storage processes, has proved extremely important in constraining possible source components and processes involved in the production of basaltic melts from the mantle. However, the link between what is observed at Earth's surface as a volcano and the source regions in the upper mantle that give rise to its magmas is a topic that has received little investigation to date.

The Auckland Volcanic Field (AVF) of northern New Zealand contains 50 small, young (younger than 250 ka) volcanic centers comprising basaltic tuff rings, maars, scoria cones, and lava flows. The volcanic field is intraplate, with a hot zone defined by lower S-wave velocities at a depth of 80 km (Horspool et al., 2006), the origin of which is not identified. Here we discuss three well-studied examples of paired eruptions from this field: Rangitoto (two eruptions in quick succession), the Mount Wellington–Purchas Hill pair, and Motukorea (with well-defined phreatomagmatic and magmatic phases) (see Table DR1 in the GSA Data Repository[1]). These centers encompass the entire spectrum of physical and compositional characteristics observed in the AVF, and thus provide the basis for an examination of deep magmatic and physical processes and the relationship between magma volume and chemical composition.

DISCUSSION

The most primitive samples from individual AVF centers display remarkable covariations between chemical composition and erupted volumes (Fig. 1). A primary observation is that the extremes of the trends are compositions from the most recent eruptions in the AVF (see Table DR1), showing that there is no progressive temporal link with eruptive volume or composition of the erupted basalts in the field.

Similarities in the correlation between eruption stage and magma chemistry are observed in the three AVF events discussed here. All begin with the eruption of a small-volume, nephelinitic to alkalic basanite composition that is relatively enriched in light rare earth elements (LREEs) and incompatible elements. In each case, this early stage is followed by a larger volume, alkalic basalt (subalkalic in the case of Rangitoto 2), which is less enriched in LREEs and incompatible elements (Fig. 2). McGee et al. (2013) identified three mantle sources: (1) fertile, garnet-bearing peridotite containing (2) a recycled component, and (3) a shallower, slightly depleted, spinel-bearing peridotite containing as much as 3% fluids. The proportion of melts from each source is modeled as increasing linearly with progressively larger initial degrees of melting. This effect can be clearly seen in a multielement plot (Fig. 2), where the prominent signatures, such as the trough at Zr-Hf and the negative K anomaly, are neutralized with increasing eruptive volume, while others (such as the positive Sr anomaly, which is thought to be caused by larger incorporation of melts of subduction-metasomatized lithosphere; McGee et al., 2013) appear with increasing eruptive volume. A similar correlation is seen in SiO_2 and CaO/Al_2O_3 with size for the Wudalianchi volcanic field of northeastern China, and in selected data from Hawaii (Fig. DR1 in the Data Repository). It is therefore suggested that this correlation may be valid globally, within a threshold small eruptive volume. However, due to the lack of comprehensive volume data (such as those for the AVF), detailed analyses cannot yet be undertaken on a global data set.

Preservation of Mantle Source Signatures

The fact that linear variations between various chemical indicators and eruptive volume (Fig. 1) are observed on the scale of the entire volcanic field is evidence of the preservation, and thus lack of homogenization of the individual melt batches (Stracke and Bourdon, 2009). The smallest center (Purchas Hill) of the AVF displays notably lower Mg# (57–64), extremely low SiO_2 (Fig. 1A), and much lower K/La (Fig. 1C) and Ti/Eu (Fig. 1D) compared to the next smallest center (Motukorea) and the rest of the

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[1]GSA Data Repository item 2015192, Table DR1 (physical and compositional characteristics of case study eruptions in the Auckland Volcanic Field [AVF]), Figure DR1 (comparison of AVF compositional data with that from the Wudalianchi volcanic field, and selected Hawaiian examples), and calculation of melting rate, including parameters and the correlation between modelled and measured (^{230}Th/^{238}U), for use in Figure 3B, is available online at www.geosociety.org/pubs /ft2015.htm, or on request from editing@geosociety .org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
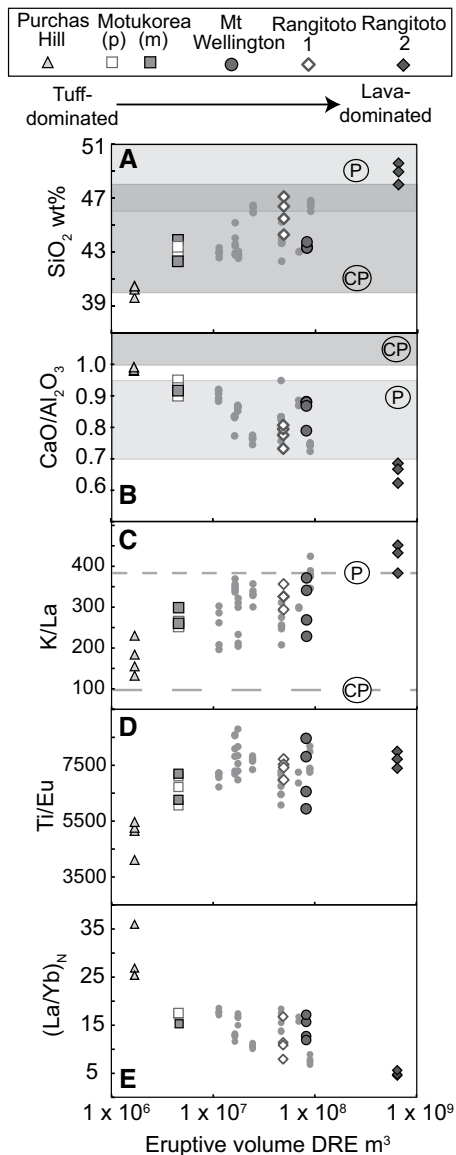
Figure 1. Element concentrations and element ratios plotted versus volume. Volumes are from Kereszturi et al. (2013); all Auckland Volcanic Field (AVF) geochemical data are from McGee et al. (2013). DRE—dense rock equivalent. Motukorea (p) and (m) refer to the phreatomagmatic and magmatic phases of this eruption (Table DR1; see footnote 1). Gray circles are from AVF volcanic centers not specifically discussed. Fields labeled CP and P in A and B are fields of compositions for experimental melts of carbonated and uncarbonated peridotite, respectively (from Gerbode and Dasgupta, 2010). Dashed lines in C are approximate compositions of 1%–3% garnet peridotite melt (P) and 1% carbonated peridotite melt (CP) (from Beier et al., 2013). La/Yb in E is normalized to primitive mantle after Sun and McDonough (1989).

AVF centers, as well as the most radiogenic Pb isotope composition. This suggests that it was produced almost entirely by melting of a distinct lithology, the signature of which is otherwise diluted in the rest of the volcanic centers. The
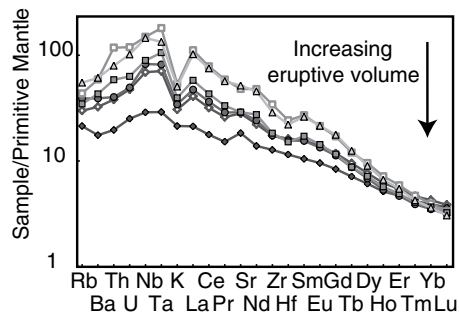

Figure 2. Multielement plots of the volcanic events discussed in the text. Averages of the five most primitive compositions from each event are plotted (data from McGee et al., 2013), normalized to primitive mantle (Sun and McDonough, 1989). Note the disappearance of anomalies at Nd, Zr, Hf, and K and the increase in Sr with decreasing elemental concentration and increasing edifice size. Legend as in Figure 1.

extreme geochemical compositions of Purchas Hill (Figs. 1 and 2) could be interpreted as the result of melting of a carbonated component (e.g., Beier et al., 2013; Marske et al., 2007) or melting of pyroxenite, as hypothesized in McGee et al. (2013) (e.g., Hirschmann et al., 2003; Kogiso et al., 2004; Stracke and Bourdon, 2009), or a combination of these.

Primitive samples from Purchas Hill and phreatomagmatic (early) Motukorea display chemical similarities (such as the pronounced trough at Nd-Hf; Fig. 2; e.g., Tappe et al., 2013) with deep, CO_2-rich melts which form kimberlites, as well as some intraplate basalts. Melting of a carbonated lithology may explain the highly silica-undersaturated, alkalic, nepheline-normative nature of the smallest centers (Fig. 1A; e.g., Kogiso et al., 2004; Pilet et al., 2011) as well as the elevated CaO/Al_2O_3 (Fig. 1B; e.g., Dasgupta et al., 2009; Gerbode and Dasgupta, 2010). Purchas Hill compositions plot within the fields determined experimentally for carbonated peridotite (from Gerbode and Dasgupta, 2010) and modeled by Beier et al. (2013) (Fig. 1). This is also indicated by the negative correlation of elemental ratios of K or Ti with melting degree-sensitive ratios (e.g., K/La or Ti/Eu versus La/Yb; after Beier et al., 2013; Scott et al., 2014), highlighting that this signature is only preserved at the end of the melting spectrum with the smallest degrees of melting. The relatively low Mg# of Purchas Hill samples could also reflect a pyroxenitic source lithology; a fusible mineralogy such as this would be more productive, and this would be expressed in a lower $(^{230}Th/^{232}Th)$ (e.g., Handley et al., 2011) due to the incompatibility of Th. Because the contrary is observed, we interpret the source of the small AVF magma batches to be carbonated garnet peridotite (Figs. 1A–1C).

Differences in Melting Dynamics Deduced from U-Series Isotopic Chemistry

By focusing on the three paired eruptions within the spectrum of volumes and compositions in the AVF (Fig. 1), the link between mantle sources, melting dynamics, and eruptive volume can be investigated in further detail. The use of U-series isotopes reveals the multiple aspects of a melting scenario when coupled with major and trace elements, such as relative depth of melting and melting rate (Fig. 3). Isotopes in the U-series decay chain are ideal for volcanic studies due to the unique aspect of radioactive decay of the daughter relative to its parent isotope that is often on the scale of magmatic processes (see Bourdon et al., 2003). Figure 3A shows the correlation of $(^{230}Th/^{238}U)$ and $(^{226}Ra/^{230}Th)$ with eruptive volume. Smaller centers display higher Th excess [i.e., $(^{230}Th/^{238}U)$ ratios > 1], which is further evidence that these smaller centers originate from greater depth. This high Th excess is overprinted with continued melting of the asthenospheric and lithospheric mantle sources (cf. Stracke and Bourdon, 2009). This
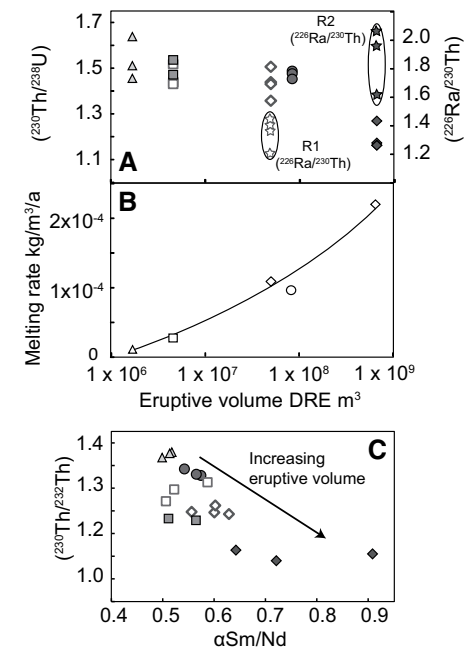

Figure 3. A: Correlation of $(^{230}Th/^{238}U)$ and $(^{226}Ra/^{230}Th)$ (stars) with eruptive volume. DRE—dense rock equivalent; R1, R2—Rangitoto eruptions. Parentheses denote activity ratios. B: Calculated melting rates for the case study centers, correlated with eruptive volume (see the Data Repository [see footnote 1] for parameters used and calculations); best-fit line shows the increase in melting rate with increasing volume. C: $(^{230}Th/^{232}Th)$ versus αSm/Nd (see text) in the Auckland Volcanic Field. Motukorea U-Th isotope data are from Huang et al. (1997). All U-series data are age corrected. The αSm/Nd was calculated after Sims et al. (1995). Volumes are from Kereszturi et al. (2013). Legend as in Figure 1.

is seen by the offset toward higher (^{238}U/^{232}Th) observed in Rangitoto 2 samples (not shown) and correlation with Sr* (see Fig. 2 for prominent Sr anomaly), which is thought to be due to the larger proportion of lithospheric melts (carrying fluids) involved in the petrogenesis of this center (McGee et al., 2013). This also corresponds with the lower (^{230}Th/^{232}Th) for Rangitoto 2 (Fig. 3C) reflecting shallower melting in the mantle (cf. Peate and Hawkesworth, 2005). In addition to the effect of localized source heterogeneity (e.g., Sims et al., 2013), variable degrees of melting can have significant effects on melt compositions that are amplified at the very low degrees of melting typical of intraplate basalts (i.e., <<6%; e.g., Williams and Gill, 1989). The variation in αSm/Nd (used as a proxy for fractionation related to the extent of partial melting, and calculated by using the Nd isotopic composition of the sample and time-integrated ^{147}Sm/^{144}Nd ratio of the source; see Sims et al., 1995; Fig. 3C) shows the clear difference between the larger and smaller centers in the AVF. Rangitoto 2 displays less fractionation of αSm/Nd (i.e. larger melting degrees) and Purchas Hill displays much greater fractionation (i.e., lower melting degrees). The correlation between (^{230}Th/^{232}Th) and αSm/Nd (Fig. 3C) thus provides evidence that the variable (^{230}Th/^{232}Th) in the AVF is in part due to variations in the degrees of melting in the garnet-bearing asthenosphere, in addition to differences in depth of melting and source. Modeled melting rates (kg/m^3/yr) of the AVF volcanoes using methods of Williams and Gill (1989) and parameters deduced from earlier work (see the Data Repository) show a positive correlation with eruptive volume (Fig. 3B). This indicates distinct segregation and ascent mechanisms for the melts from each mantle source.

Movement via Isolated Conduits Suggests Differential Segregation of Melts

The preservation of the unique chemical and isotopic signatures in the three case-study events along the size spectrum (Figs. 1–3) suggests the isolation of individual melting events, despite melting and eruption events occurring within a few hundred meters of each other and over small temporal ranges. It also indicates that magmas are extracted instantaneously after the inception of melting (e.g., Claude-Ivanaj et al., 1998). To further investigate the melt movement of the eruption pairs, the short-lived daughter isotope of ^{230}Th, ^{226}Ra, is used for the most recent AVF eruption (Rangitoto), as differences between ^{226}Ra excesses can be explained by radioactive decay from their initial disequilibrium as a function of varying depths and speeds en route to the surface (e.g., Jull et al., 2002).

A negative trend in (^{226}Ra/^{230}Th) versus (^{230}Th/^{238}U) for the two Rangitoto eruptions (McGee et al., 2011) is interpreted as the result

of differences in the way that melts ascend from the mantle (cf. Iwamori, 1994). In order to obtain high (^{230}Th/^{232}Th) but retain relatively low (^{226}Ra/^{230}Th), the initial melts must move from depth at high speed, requiring higher mantle porosity (i.e., movement in channels). Conversely, to develop relatively lower (^{230}Th/^{232}Th) but higher (^{226}Ra/^{230}Th), the second melt batch must have moved from shallower depths by a slower, more diffusive flow regime. Because modeled melting rates are slower for the smaller centers (Fig. 3B), it follows that the melts must be extracted nearly instantaneously in order to arrive at the surface.

A possible explanation as to why melts ascend differently between the first and second magma phases in an eruption sequence involves the heterogeneity of the asthenospheric mantle source of AVF magmas. The specific chemical signature of Purchas Hill hints that melting in this source initiates with the carbonated component while other components remain subsolidus. Melting of the most fertile component in a heterogeneous mantle cools the surrounding mantle and thus isolates channels that allow rapid ascent of the initial melts as well as shielding them from mixing (Rudge et al., 2013; Katz and Weatherley, 2012). Increase in temperature or further mantle upwelling will increase the melting rate (Fig. 3B) and partial melting degrees, and initiate melting of the uncarbonated lithologies; this latter signal will dominate and the previous signature will be lost or diluted (e.g., Prytulak and Elliott, 2009). As these lithologies likely dominate the volume of deep and shallow mantle under the AVF, their melting will not initiate formation of channels, thus forcing the later stage melts to ascend through a slow diffusive mechanism.

CONCLUSIONS AND CONNECTION WITH VOLCANIC STYLE

Using three well-constrained volcanic events in the AVF, we have quantified a correlation between mantle melting processes and the manifestation of a volcanic edifice. Small-volume eruptions producing silica-undersaturated magmas are more explosive and erupt to form maars and tuff rings. Larger magma volumes with less silica-undersaturated compositions erupt to form scoria cones and lava fields. We suggest that in small-volume basaltic volcanic fields, physical parameters such as eruptive volume and eruption style are inherently controlled by the melting of a heterogeneous mantle, which causes melts to behave independently despite their close spatial and temporal association due to their distinct segregation and ascent mechanisms. Rapid ascent of a carbonated magma batch created by small degrees of melting (≤1%) is far more likely to create phreatomagmatic eruptions for two reasons: (1) the addition of a hydrous component can aid in increasing

the explosivity of the magma on reaching the surface, and (2) smaller volumes of magma are more easily affected by the water-rich near-surface environment than larger volumes, which can overwhelm such effects, leading to more effusive eruptions (e.g., Németh et al., 2003).

The movement of melt in isolated conduits leads to the strikingly linear spectrum of volumes and compositions observed in the AVF, a feature preserved due to the lack of tectonic processes overprinting the signatures and the generally low magma flux in this volcanic field. Melting processes occurring beneath the AVF are likely to directly influence the physical manifestation of the eruptive event, and further work might reveal melting trends within individual eruptions that could shed light on likely future eruption scenarios. We suggest that studies of mantle dynamics should be included in hazard assessments in other analogous fields to test whether this mantle influence is true elsewhere, as we suspect it is in, for example, the Wudalianchi volcanic field of northeastern China (see Fig. DR1).

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Geology

Mantle heterogeneity controls on small-volume basaltic volcanism

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