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Temporal and compositional evolution of Jorullo volcano, Mexico: Implications for magmatic processes associated with a monogenetic eruption

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ABSTRACT

The 1759–1774 eruption of the Jorullo volcano in the Michoacán Guanajuato Volcanic Field (MGVF), Mexico, produced lavas that range in composition from basalt to basaltic andesite. We have conducted new major and trace element and isotopic studies (whole rock Sr–Nd–Pb–Hf–Os, and O isotopes in olivine separates) of the Jorullo lavas and tephras spanning the duration and compositional range of the eruption, to further constrain the potential roles of mantle source heterogeneity, subduction-related metasomatism, and crustal assimilation in the petrogenesis of the Jorullo magmas. This study presents the first Hf, high precision Pb and comprehensive oxygen isotope measurements for Jorullo volcanic rocks. All samples have arc-like trace element patterns with enrichments in large ion lithophile elements (e.g. Ba, Rb, and Pb) and depletions in fluid immobile elements (e.g. Nb, Ta). In addition, the samples show variations in $^{87}Sr/^{86}Sr$ (0.7038–0.7040), $^{143}Nd/^{144}Nd$ (0.51280–0.51285), $^{176}Hf/^{177}Hf$ (0.28297–0.28300), $^{206}Pb/^{204}Pb$ (18.62–18.66), $^{207}Pb/^{204}Pb$ (15.57–15.59) and $^{208}Pb/^{204}Pb$ (38.34–38.43). Osmium isotope signatures are, with one exception, more radiogenic than the depleted and primitive mantle ($^{187}Os/^{188}Os = 0.1231–0.1616$). Oxygen isotope ratios of olivine phenocrysts ($\delta^{18}.O_{SMOW} = 5.70–6.02‰$) show limited variation, but are isotopically heavier than normal mantle olivine. The samples define two geochemical groups: high-MgO samples with higher $^{87}Sr/^{86}Sr$, lower $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$, and a positive correlation of Sr and Pb isotopes; and low-MgO samples displaying lower $^{87}Sr/^{86}Sr$ but higher $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ than the former group, and a negative correlation of Sr and Pb isotopes. The high-MgO group comprises most of the early tephra and lavas, whereas the low-MgO group includes most of the late tephra and lavas. These compositional variations are inconsistent with shallow level contamination, but rather are interpreted to reflect mantle source heterogeneity. Trace element and isotopic signatures are consistent with North Mexican Extensional Province (NMEP) mantle metasomatised by subduction components composed of sediment- and oceanic crust-derived hydrous fluid. The temporal–compositional variations observed in Jorullo magmas are inferred to result from a combination of variable degrees of fractional crystallization of magmas produced by tapping a progressively less metasomatised mantle source that is vertically and/or laterally heterogeneous.

1. Introduction

Small-volume, mafic magmatic systems (<1 km^3) produced by single episodes of volcanic activity are referred to as monogenetic volcanic fields (Connor and Conway, 2000). They tend to occur as cinder cones, maars, tuff cones and lava domes. The duration of an individual eruption is typically shorter than that of composite volcanoes (e.g. stratovolcanoes), lasting from several days to years (Connor and Conway, 2000), but the volcanic field as a whole may span millions of years. Because of their small volume and mafic character, they are often considered to ascend very rapidly from their mantle source, and thus provide a key to understanding the magmatic processes that are often masked in larger magmatic systems. Nonetheless, they often show significant compositional variation within individual eruptions as well as among closely spaced eruptive centers. The origin of this compositional variation has been the source of considerable debate. Some studies suggest that the compositional variation reflects heterogeneity in the mantle source (e.g. Blondes et al., 2008; Reiners, 2002; Siebe et al., 2004), whereas others suggest that it is the result of assimilation

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of lithospheric mantle or crust during ascent (Chesley et al., 2002; Lassiter and Luhr, 2001; Siebe et al., 2004). Furthermore, questions remain about the origin of source heterogeneity including the role of subduction derived fluid and melts. Distinguishing subduction signatures from shallow level crustal assimilation poses a challenge, as both processes can produce similar chemical and isotopic signatures, and both processes may work in concert to produce compositional variations and temporal–compositional trends observed in some basaltic monogenetic eruptions and volcanic fields (Chesley et al., 2002; Siebe et al., 2004; Wallace and Carmichael, 1999). A related issue is the question of whether monogenetic systems develop sustained magma chambers, or whether magmas erupt more-or-less directly from their mantle sources.

The study of the petrogenesis of Jorullo volcano and its satellite cones provides a unique opportunity to evaluate the origin of compositional variation within individual monogenetic centers, as well as magmatic processes operating in subduction systems in general. Jorullo volcano is located within the Michoacán Guanajuato Volcanic Field (MGVF), which represents the volcanic front of the Trans-Mexican Volcanic Belt (TMVB). Previous workers have analyzed Jorullo samples for major and select trace elements (e.g. Lassiter and Luhr, 2001; Luhr and Carmichael, 1985), and Sr–Nd–Pb and Os isotopes (e.g. Chesley et al., 2002; Lassiter and Luhr, 2001; Verma and Hasenaka, 2004), and (for one sample only) oxygen isotopes (Johnson et al., 2009), but none covered the full duration or compositional range of the eruption. This study presents the first Hf isotope and high precision Pb isotope data for Jorullo samples, as well as an extensive new data set of Sr, Nd, Os and oxygen isotope analyses spanning the duration of the Jorullo eruption. We use the elemental and isotopic data for the Jorullo lavas and tephra to address the following aspects of their petrogenesis: 1) the influence of crustal assimilation; 2) the types and nature of the subduction components being added to the mantle wedge (sediment versus oceanic crust; fluid versus melt); and 3) the cause of the systematic compositional variations with time in the Jorullo eruption.

2. Tectonic setting

The TMVB is an active volcanic arc that trends in an E–W direction, and is approximately 200 km wide and 1000 km long. It contains more than 8000 eruptive vents including stratovolcanoes, calderas, domes, and monogenetic cinder cones. On the basis of available geochronological data, volcanic activity within the belt has occurred since the Miocene (Ferrari et al., 1999). Magmatism is generally accepted to be associated with the subduction of the oceanic Cocos and Rivera Plates beneath the continental North American Plate along the Middle America Trench (Fig. 1). The oblique orientation of the TMVB relative to the Middle American Trench is attributed to near-horizontal subduction of the Cocos plate beneath central Mexico between 100 and 250 km from the trench, and steep subduction of the Rivera plate to the west (e.g. Pardo and Suárez, 1995). Ferrari (2004) proposed that volcanism has migrated trenchward at a rate of ~10 km/Ma over the past 2 Ma, due to rollback of the subducted Cocos plate. Volcanism within the belt is compositionally diverse, as both calc-alkaline and intra-plate-type magmas have erupted across the volcanic belt, and in many places they are coeval. The calc-alkaline signatures are often considered to be derived from partial melting of the subarc mantle modified by slab melts or slab dehydration (e.g. Blatter and Hammersley, 2010; Cai et al., 2014; Petrone et al., 2003; Siebe et al., 2004; Straub et al., 2015). In contrast, the OIB-type magmas have been variously interpreted to represent melts of the unmodified subarc asthenospheric mantle (e.g. Luhr, 1997; Luhr et al., 2006; Siebe et al., 2004), melts of an enriched mantle (EM) source metasomatized by subduction fluid (Petrone et al., 2003), melts of pyroxenitic mantle produced by subduction fluid/melt infiltration (Straub et al., 2008, 2015), or a deep mantle plume (Márquez et al., 1999; Verma, 2000). Despite the controversy of the origin of the OIB-type magmas, clear subduction signatures are present in most samples and calc-alkaline magmas are volumetrically dominant compared to the OIB-type magmas.

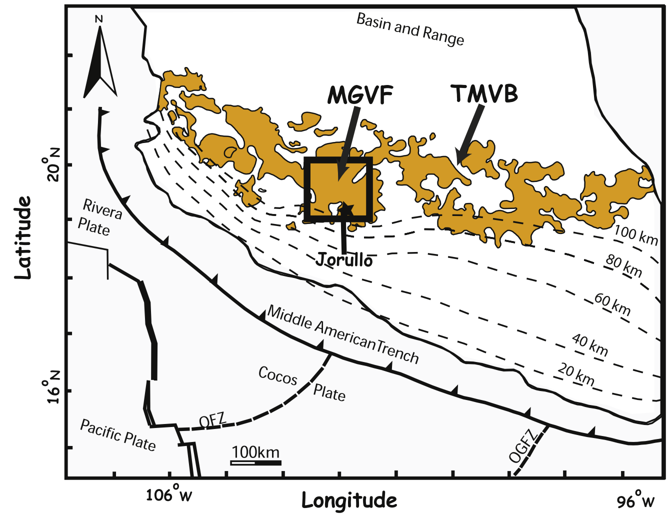

Fig. 1. Simplified regional tectonic map of the Trans-Mexican Volcanic Belt (yellow), modified after Siebe et al. (2004). The MGVF region and the location of Jorullo volcano are also indicated.

The MGVF represents one of several distinct monogenetic volcanic fields in the TMVB, and is thought to represent the volcanic front of the TMVB (Hasenaka and Carmichael, 1985). Based on hypocenter relocation of local earthquakes, the volcanic field is thought to lie ~80 km above the subducted Cocos plate (Pardo and Suárez, 1995), and as such, has been regarded as a key area to study the relationship between central Mexican volcanism and subduction of the Cocos plate (e.g. Verma, 2002). The MGVF contains more than 1000 eruptive centers, most of which are located about 200–300 km from the trench (Hasenaka and Carmichael, 1985). Two historic eruptions have occurred within the MGVF, including Jorullo (1759-1774 AD) and Parícutin (1943-1952 AD) volcanoes. The volcanic field consists mostly of monogenetic scoria cones, lava domes, shield volcanoes and maars. In addition, both alkaline and calc-alkaline compositions have erupted throughout the field (Luhr, 1997; Luhr et al., 2006). The origin of these compositionally distinct magmas has been the subject of extensive petrologic and geochemical studies. It has been suggested that the coexistence of calc-alkaline and intraplate alkaline volcanism in close proximity implies that they come from distinct domains in the mantle (Luhr, 1997) in which the intra-plate alkaline basalts are produced by partial melting of a convecting upper mantle uncontaminated by subduction components, whereas the calc-alkaline rocks are derived by melting of subarc mantle wedge that has been metasomatised by slab-derived materials (Luhr, 1997). Some studies have also invoked the involvement of crustal contamination during petrogenesis (Chesley et al., 2002; Lassiter and Luhr, 2001). Other studies (e.g. Verma and Hasenaka, 2004) have attributed the origin of the MGVF calc-alkaline rocks in general to partial melting of veined metasomatised mantle sources and suggested that the MGVF might not be related to the subduction of the Cocos plate, but rather to the ongoing rifting processes within the TMVB (e.g. Verma and Hasenaka, 2004). The origin of magmatism and the petrogenetic processes operating within the MGVF thus remain inconclusive, and are further evaluated in this study.

3. Jorullo eruption and samples

Jorullo volcano and its satellite cones (Volcán del Norte, an unnamed cone, Volcán de Enmedio, and Volcán del Sur) erupted over a fifteen-year period from 1759 to 1774, and produced pyroclastic deposits and lava flows totaling a volume of approximately 2 km^3 (Luhr and