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Origin of chemical and isotopic heterogeneity in a mafic, monogenetic volcanic field: A case study of the Lunar Crater Volcanic Field, Nevada

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ABSTRACT

Major and trace element geochemistry and Sr, Nd, Pb, Hf and Os isotope signatures of basaltic lavas and tephra from volcanic centers in the northern Lunar Crater Volcanic Field (LCVF), Nevada, provide insight into the nature of their mantle sources and the role of lithospheric contamination versus source-related enrichment in producing compositional variations in basaltic monogenetic volcanic fields. Three of the studied eruptive centers (Hi Desert and Mizpah, ~620–740 ka; and Giggle Springs, <80 ka) are located within ~500 m of each other; the Marcath volcano (~35–38 ka) and Easy Chair (140 ka), two of the youngest eruptive centers in the field, are located ~6 and 12 km southwest of these cones, respectively. Isotopic studies of the volcanic rocks show a limited range in $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$, but significant heterogeneity in $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$ and $^{187}Os/^{188}Os$. The older (>140 ka) Hi Desert, Mizpah, proto-Easy Chair and several unnamed flows exhibit Nb–Ta enrichment, Rb, Cs and K depletion, and high $^{206}Pb/^{204}Pb$ but low $^{87}Sr/^{86}Sr$. In contrast, the younger (≤140 ka) Giggle Springs, Easy Chair and Marcath lavas have high Ba, Rb and Cs and lower $^{206}Pb/^{204}Pb$ and higher $^{87}Sr/^{86}Sr$. The lavas produce a well-defined negative correlation between Sr and Pb isotopes, attributed to mixing of heterogeneous mantle sources. The geochemical and isotopic signatures of the older Hi Desert, Mizpah, proto-Easy Chair and unnamed lavas are consistent with derivation from a mantle source with a component of ancient recycled oceanic crust. In contrast, the relatively high Ba, Rb and Cs coupled with lower $^{206}Pb/^{204}Pb$ and higher $^{87}Sr/^{86}Sr$ of the younger Giggle Springs, Easy Chair and Marcath lavas are consistent with derivation from a similar, but fluid-enriched, mantle source. Mixing calculations indicate that incorporation of ~18% of 0.8 Ga recycled oceanic crust into depleted mantle can explain the trace element and isotopic signatures of the older group end member. Subsequent addition to this source of minor (<1%) hydrous fluid derived from subducted oceanic crust could account for the chemical and isotopic compositions of the younger group end member. Variable degrees of mixing between these two mantle end members can generate the full range of isotopic compositions observed in the northern LCVF sample suite, as well as within single eruptions. Our data indicate that the mantle source region in the LCVF is characterized by chemical and isotopic heterogeneity that manifests itself over a very small spatial scale (<500 m) and within the time frame of a single monogenetic eruption. Similar processes may explain the geochemical and isotopic heterogeneities observed in other mafic monogenetic volcanic fields, the evidence for which may be preferentially preserved where small degrees of melting and rapid source to surface transport prevail.

1. Introduction

Monogenetic volcanic fields consist of scattered small volcanoes that can occur as scoria cones, tuff cones or maars, depending on their eruptive style (Connor and Conway, 2000; Martin and Németh, 2006; Valentine et al., 2006; Valentine and Perry, 2007; Valentine and Gregg, 2008), and occur in a variety of tectonic settings, including extensional environments (e.g. Basin and Range) and subduction zones (e.g. Trans-Mexican Volcanic Belt). Such volcanic fields represent a common expression of continental volcanism, and can be active over periods of thousands to millions of years despite the fact that individual eruptions last only days to tens of years. Several studies have demonstrated that individual or closely spaced monogenetic eruptions can show significant compositional variation (e.g. Luhr and Carmichael, 1985; Reiners, 2002; Johnson et al., 2008). However, the origin of the chemical and isotopic heterogeneity remains controversial, and has been variously attributed to shallow level crustal assimilation (Lassiter and Luhr, 2001; Chesley et al., 2002; Righter et al., 2002), mantle source

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heterogeneity (Smith et al., 1999; Reiners, 2002; Siebe et al., 2004; Blondes et al., 2008), or some combination of these two processes (Borg et al., 2000). For example, studies of monogenetic volcanic fields including the Sierra Chichinautzin Volcanic Field (SCVF), Mexico and the Big Pine Volcanic Field (BPVF), California have attributed compositional variation to heterogeneous mantle sources (Siebe et al., 2004; Gazel et al., 2012). In contrast, Chesley et al. (2002) and Lassiter and Luhr (2001) concluded that the compositional variations observed in the Michoacán–Guanajuato Volcanic Field and the western Mexican Volcanic belt resulted from crustal assimilation. It also remains unclear whether monogenetic volcanoes develop prolonged magma storage zones in the crust, thus facilitating crustal contamination, or whether the magmas ascend more or less directly from their respective mantle source regions. A prior study of the Southwestern Nevada Volcanic Field (SNVF) suggested that monogenetic magmas ascended quickly through the crust (Valentine and Perry, 2007), but it is not clear if this is unique to that field. Furthermore, questions remain about the nature and scale of the potentially heterogeneous mantle source regions, and the role of pyroxenite veins in producing the heterogeneity. A number of studies have noted that the upper mantle may contain a large fraction of pyroxenite-rich veins (Mukasa et al., 1991; Pearson et al., 1993; Hirschmann and Stolper, 1996), which could play an important role in the origin of continental alkali-basalts (Zindler et al., 1984; Allègre and Turcotte, 1986; Prinzhofer et al., 1989; Leeman and Harry, 1993; Hirschmann and Stolper, 1996; Carlson and Nowell, 2001; Reiners, 2002).

In order to better understand the evolution of mafic monogenetic volcanic systems, it is important to perform detailed studies of both individual monogenetic centers as well as the encompassing volcanic fields, and to constrain the spatial and temporal extents of the compositional variations in addition to the nature of the chemical and isotopic signatures. This study focuses on the Lunar Crater Volcanic Field (LCVF) in central Nevada, one of the Quaternary monogenetic volcanic fields within the Basin and Range extensional setting, and is part of a larger collaborative project aimed at understanding the spatial and temporal scales of variations in magma source, evolution, ascent, and eruptive processes, and the links between these (e.g., Cortés et al., 2015). In the present study, the chemical and isotopic compositions (Sr–Nd–Pb–Hf–Os) of suites of volcanic rocks from individual eruptive centers (Marcath and Easy Chair), as well as samples from a closely-spaced cluster of volcanic centers are used to investigate the relative importance of (1) upper and/or lower crustal assimilation, (2) the role of mantle heterogeneity, including the potential role of crustal recycling in producing mantle heterogeneity, and (3) the spatial and temporal variability of the sources of magmatism in the monogenetic volcanic field.

2. Geologic setting of the Lunar Crater Volcanic Field

The Lunar Crater Volcanic Field, central Nevada, covers an area of ~1000 km^2 (Bergman 1982) and contains more than one hundred vents (Hintz and Valentine, 2012; Valentine and Cortés, 2013) that are distributed over two mountain ranges, the Reveille Range and Pancake Range (Fig. 1). Previous studies have shown that basaltic volcanism commenced in the Pliocene in the Reveille Range, and has generally shifted northward to the Pancake Range with time (Foland and Bergman, 1992). The early eruptions (~5.9 to 5 Ma) consist of alkali-basalt, followed by trachytic eruptions (~4.4 to 4.2 Ma) and lastly, basaltic eruptions (4.6 Ma to 38 ka; Naumann et al., 1991). The most recent activity occurred in the northern part of the volcanic field as recently as 35–38 ka ago (Shepard et al., 1995; Heizler, 2013) suggesting that the LCVF represents an active volcanic field.

The LCVF magmas were erupted through relatively thin crust (30–33 km), with a lithospheric thickness beneath the volcanic field estimated from elastic models and seismic anisotropy data to be 65–70 km (Jones and Phinney, 1998). The crust is composed of Proterozoic crystalline basement rocks overlain by a sequence of Paleozoic carbonate and clastic sediments (Menzies, 1989), which are in turn overlain by Oligocene and Miocene ash flow tuffs that range in composition from dacite to rhyolite (Ekren et al., 1972). The volcanic field is part of the Basin and Range province, which has been dominated by an extensional regime since the Oligocene (Zoback et al., 1981; Eaton, 1982; Glazner and Bartley, 1984; Christiansen and Yeats, 1992; Atwater and Stock, 1998). Pliocene through Quaternary volcanism in the Basin and Range occurs mostly along its margins; however, the LCVF is isolated in the central part of the basin. Previous studies have noted that the LCVF parallels the NNE-trending normal faults of the Basin and Range province, and have suggested that the volcanism may be associated with upwelling of asthenospheric mantle in response to Basin and Range lithospheric extension (Lum et al., 1989; Foland and Bergman, 1992). In detail, structural analysis indicates that feeder dikes for Quaternary volcanoes in the LCVF are aligned parallel to the maximum horizontal compressive stress that has been active during the Quaternary, as well as being parallel to Quaternary-age faults (Tadini et al., 2014). On a broader regional scale, the relationship between Basin and Range basaltic magmatism and extension remains unclear. Numerous studies have indicated that mafic volcanism progresses from lithospheric to asthenospheric sources with time, indicating that extension may play an important role in magma generation (Farmer et al., 1989; Kempton et al., 1991), but it is not clear why this mechanism should focus most of the volcanism around the margins, rather than throughout the interior of the Basin and Range. Other mechanisms, such as mantle upwelling due to lithospheric delamination (e.g. West et al., 2009), asthenospheric convection at a lithospheric keel edge (Stickney 2004) and shear-driven upwelling (Conrad et al., 2010) have also been proposed to generate the recent mafic volcanism in the Basin and Range.

3. Sample locations, ages and petrography

Companion papers by Valentine and Cortés (2013) and Cortés et al. (2015) discuss in detail the field geology, age and petrography of the northern LCVF. The present study focuses on the volcanic centers in the northern part of the volcanic field including three recently named volcanic centers that we refer to as the Hi Desert, Mizpah, and Giggle Springs volcanoes (Cortés et al., 2015), several yet unnamed lava flows, and Marcath and Easy Chair volcanoes. Hi Desert, Mizpah and Giggle Springs are located within ~500 m of each other, and were selected to test for compositional variability in closely spaced volcanoes that erupted over a span of time. The Marcath volcano, located ~6 km SW of these cones and representing the most recent eruption in the volcanic field, is extremely well preserved and allowed for detailed sampling to test for compositional variability within a single monogenetic event. Easy Chair, located ~6 km SE of Marcath, was subject to a similar detailed sampling campaign that demonstrated compositional variability throughout the duration of the eruption; furthermore, evidence was found for an older eruption at the same location, referred to as proto-Easy Chair (Valentine and Cortés, 2013; Cortés et al., 2015). Recent $^{40}Ar/^{39}Ar$ age determinations yield ages of 840 ± 3 ka for proto-Easy Chair, between 620 and 740 ka for Mizpah, 582 ± 6 ka for an unnamed lava flow, 140 ± 5 ka for Easy Chair, <81 ± 5 ka for Giggle Springs, and 35 ± 7 ka for Marcath (Heizler, 2013). Shepard et al. (1995) determined a ^{36}Cl and ^{10}Be age of 38.1 ± 9.7 ka for the Marcath lavas. Age data are not available for the Hi Desert basalts; however, Giggle Springs lavas were emplaced around and bank up against the Hi Desert cone remnants, thus Hi Desert is clearly older than Giggle Springs.

We collected 33 lava and tephra samples throughout the northern LCVF (Fig. 1). All of the lavas are porphyritic and contain 5 to 20% subhedral to euhedral phenocrysts that rarely exceed 3 mm in size (Cortés et al., 2015). Phenocryst phase assemblages are predominantly olivine + clinopyroxene + plagioclase in the Mizpah and Hi Desert samples, and olivine + clinopyroxene or olivine + plagioclase in the