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Notes

Mechanisms of low-flux intraplate volcanic fields—Basin and Range (North America) and northwest Pacific Ocean

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ABSTRACT

We compare two intraplate, Pliocene-Pleistocene volcanic fields in different tectonic settings—the central Basin and Range and the northwest Pacific Ocean. Both fields are characterized by widely scattered, small-volume, alkali basaltic volcanoes; within the fields, each volcano apparently originates from a separate, volatile-enriched parental melt from the upper mantle. There is no evidence at either field for locally anomalous heat flow or ongoing introduction of new fluids into the upper mantle such as might occur above a subducting slab. We conclude that the volcanic fields reflect deformation-driven collection of already existing partial melts in a heterogeneous upper mantle. Deformation-driven melt collection may be an important mechanism for other diffuse intraplate volcanic fields, and this is consistent with a tectonically controlled, low-flux end member for intraplate fields where magmatism is a passive response to regional deformation. Differences in the degree of fractionation and contamination between the two fields are inferred to be related to flexure-induced vertical variations in the orientation of principal stresses in the northwest Pacific Ocean, which cause stalling of ascending dikes in the lithosphere.

INTRODUCTION

Many volcanic fields occur in intraplate settings and sporadically produce scattered small, monogenetic volcanoes over millions of years with very low long-term eruptive volume fluxes. The underlying mechanisms of melt collection, ascent, and eruption at these volcanic fields are enigmatic. Here, we suggest that volcanism in two low-flux intraplate fields reflects deformation-driven collection of preexisting partial melts in a heterogeneous upper mantle, rather than generation of new melt. Low-flux fields have low dike injection rates that do not significantly alter the tectonic stresses and therefore provide an opportunity to explore the effects of stress environments on volcano characteristics. We suggest that some geochemical differences between the two fields are related to differences in lithospheric stresses that affect dike propagation in an extensional versus a flexural setting.

COMPARISON OF THE TWO INTRAPLATE FIELDS

Characteristics shared by the two volcanic fields are summarized in Table 1. The Southwest Nevada volcanic field (SNVF; Fig. 1A) is located in the central Basin and Range Province of the western United States. The field underwent rapid lithospheric extension and voluminous silicic eruptions between 10 and 13 Ma, but it has had relatively slow extension rates (<1% m.y.$^{-1}$) since then, along with waning alkali basaltic volcanism (total strains in the Crater Flat Basin, where many of the volcanoes reside, are on the order of ~50% to >100%; Fridrich et al., 1999). During the past 3 m.y., the Southwest Nevada volcanic field has produced a very low long-term eruptive flux of ~0.5 km^3 m.y.$^{-1}$ (Valentine and Perry, 2007). Geochemical and radiogenic isotopic data are consistent with magma sources in old, heterogeneous, subcontinental lithospheric (nonconvecting) mantle that is locally enriched in hydrous components, and with each volcano being fed by a separate parent magma (Valentine and Perry, 2007, and references therein). Heterogeneities or patches relatively enriched in hydrous phases have slightly depressed solidus temperatures and elevated degrees of partial melt under ambient conditions. Thermodynamic calculations suggest that the patches contained 5%–10% (by mass) partial melt of candidate fertile peridotite sources (with water contents of ~0.2 wt%), at temperatures between ~1120 and 1300 °C, and depths of ~50–70 km (Spera and Fowler, 2009).

Volcanoes of the northwest Pacific Ocean (NPO; Fig. 1B) are scattered over a broad area of the ocean floor and have similar volumes and compositions to those of the Southwest Nevada volcanic field (Table 1; Figs. 2A and 2B); they form where the Pacific plate is flexed (concave upward) as it moves into the Hokkaido Rise, prior to subduction beneath Japan. Hirano et al. (2006) and Machida et al. (2009) argued that the magmas were derived from low melt fractions in heterogeneous upper mantle with locally depressed solidus temperatures, and that each volcano had a separate parent magma. They concluded that the volcanoes formed because flexure-induced fracturing of the lithosphere provided pathways or conduits for magma ascent from source depths.

Consistency in the degree of deep fractionation (Fig. 2C) and lack of a crustal contamination signature in the isotopic compositions suggest that Southwest Nevada volcanic field dikes, once triggered at source depths, ascended rapidly through the crust with little or no storage in magma chambers; fractionation probably occurred during ascent and mainly at depths >30 km (Valentine and Perry, 2007; Spera and Fowler, 2009). In contrast, northwest Pacific Ocean magmas experienced variable degrees of fractionation and contamination as they ascended through the lithosphere (Fig. 2D; Hirano et al., 2004, 2006). A possible cause for these characteristics, which are different from the Southwest Nevada volcanic field, is discussed here.

DEFORMATION-DRIVEN MELT COLLECTION

There is no indication at either field of locally anomalous heat flow such as might be associated with upwelling mantle material, or of ongoing introduction of new fluids into the upper mantle such as might occur above a subducting slab. We suggest that regional tectonic deformation drives collection of partial melts that exist under ambient conditions in the upper mantle due to compositional heterogeneities as discussed already. Partial melt might feed tensional veins and dikes during deformation (Sleep, 1988); however, Rubin (1998) showed that this process is limited by the ability of melt to flow through its porous host matrix to feed a dike, compared to relatively rapid flow of magma in the dike itself. For the systems of interest to us, melt fractions are likely small, on the order of ~5%; movement of melt from the porous matrix into dikes that can ascend to the surface will be promoted if there is a mechanism by which the porosity can be increased.

Valentine and Perry (2007) suggested that as the Southwest Nevada volcanic field region extended, deformation of the lithospheric mantle was preferentially accommodated by the relatively weak partial melt patches, and, as they responded by shearing, melt was mechanically focused into bands of increasing melt fraction (Holtzman and Kohlstedt, 2007). Physical evidence (such as erupted volumes and dike lengths) suggests that length scales of partial melt patches that feed individual Southwest Nevada volcanic field volcanoes are on the order of several kilometers. These scales are similar to the vertical length scale (δ_c) of ~1 km for compaction of the partially molten rock with the appropriate range of melt

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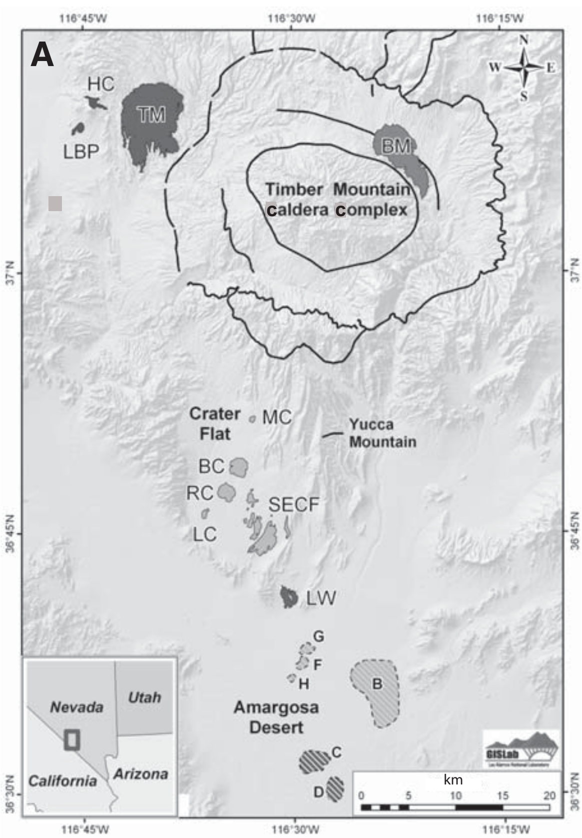
TABLE 1. SUMMARY AND INTERPRETATION OF SIMILAR CHARACTERISTICS OF TWO LOW-FLUX INTRAPLATE VOLCANIC FIELDS

Characteristic	Recent 5 Ma at Southwestern Nevada volcanic field*	Northwest Pacific Ocean†	Interpretation
Regional deformation	Slow extension (Basin and Range)	Plate flexure (concave up)	Extension in lower part of lithosphere
Major elements–total alkali-silica	Mainly trachybasalt to trachyandesite	Mainly trachybasalt to trachyandesite	Partial melts originated in lower lithosphere or asthenosphere
Isotopic composition	Nd and Sr isotopes vary but have characteristic of old (>1 Ga) lithospheric mantle*	Nd, Sr, and Pb isotopes characteristic of EM-1, with recycled fertile lithosphere components	Consistent with melt generation in heterogeneous upper mantle for northwest Pacific Ocean
Rare earth element pattern	Steep negative slope	Steep negative slope	Small degree of partial melting
Eruptive volume of individual volcanoes	≤ 1 km^3	≤ 1 km^3	Small volumes of generated melt
Volatile content indicators	Up to 4.6 wt% H_2O and 930 ppm CO_2 in melt inclusions and field evidence for highly explosive eruptions§	Up to 60 vol% vesicles at water depth of ~6 km	Presence of CO_2 and H_2O at magma source, resulting in depressed solidus temperatures
Longevity of individual volcanoes	Monogenetic, months to years	Monogenetic (inferred)	Each volcano fed by single pulse of magma from depth, rather than sustained influx of heat and mass
Relationships among volcanoes, faults, and shallow stress field	Volcanoes erupted along preexisting normal faults	Volcanoes elongated parallel to maximum principal stress (perpendicular to flexure axis), inferred to be due to fissure eruptions along preexisting seafloor fractures	Dikes captured by preexisting faults/fractures in shallow crust, dike injection rate less than tectonic strain rate (Southwest Nevada volcanic field)
Fissure length	Up to ~2.5 km	Up to ~3 km	Fissure length related to length scale of source region tapped for each volcano (Southwest Nevada volcanic field)
Spatial distribution of volcanoes	Small, long-lived clusters of volcanoes dispersed over wide area	Dispersed over wide area	Small localized melt sources
Temporal distribution of volcanoes	Episodes of closely timed formation of one to five monogenetic volcanoes in close proximity (cluster), repose period proportional to volume of prior episode (time predictable)	Episodic (inferred), but timing of episodes not determined	Threshold for dike injection related to regional tectonic stress relief at Southwest Nevada volcanic field
Duration of volcanic field	~11 Ma of basaltic volcanism	Several Ma (4.1 and 8.5 Ma volcanoes found in close proximity)	Magma sources present for long periods of time, despite small volumes

*Valentine and Perry (2007, and references therein).
†Hirano et al. (2006, 2008); Fujiwara et al. (2007); Machida et al. (2009).
§Nicholis and Rutherford (2004).



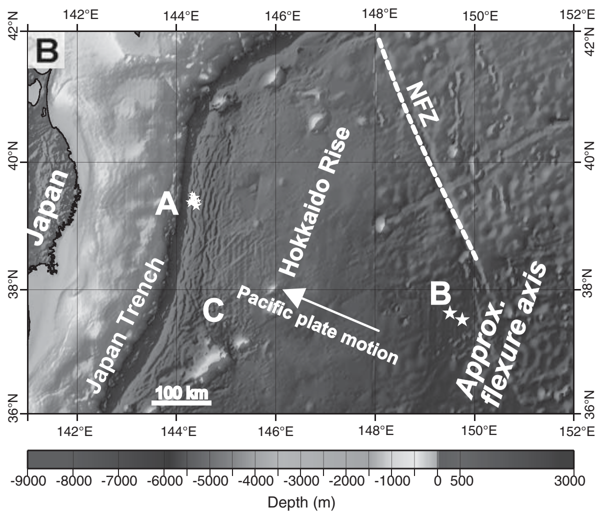


Figure 1. (A) Shaded relief map of Pliocene-Pleistocene part of Southwest Nevada volcanic field. Alkali basaltic volcanoes are shown in grayscale (areas with diagonal striping and dashed outlines are volcanoes buried beneath alluvium). Heavy lines show calderas of Timber Mountain caldera complex. Volcano labels: TM—Thirsty Mountain; SECF—Southeast Crater Flat basalts; BM—Buckboard Mesa; HC—Hidden Cone; LBP—Little Black Peak; MC—Makani Cone; BC—Black Cone; RC—Red Cone; LC—Little Cones; LW —Lathrop Wells volcano; B, C, D, F, G, and H are buried volcanoes of Pliocene age. Inset shows location with respect to southwestern United States. Figure was modified from Valentine and Perry (2007). (B) Shaded relief map of seafloor in northwest Pacific Ocean area, with study sites A, B, and C described in Hirano et al. (2006) and Fujiwara et al. (2007). Small-volume volcanoes form where Pacific plate flexes upward (approximate location of flexure axis is shown), such as at site B. At site A, volcanoes are faulted as Pacific plate bends downward into subduction zone (Japan Trench). Thin dashed line is approximate trace of Nosappu fracture zone (NFZ). Stars are locations of sampled volcanoes.

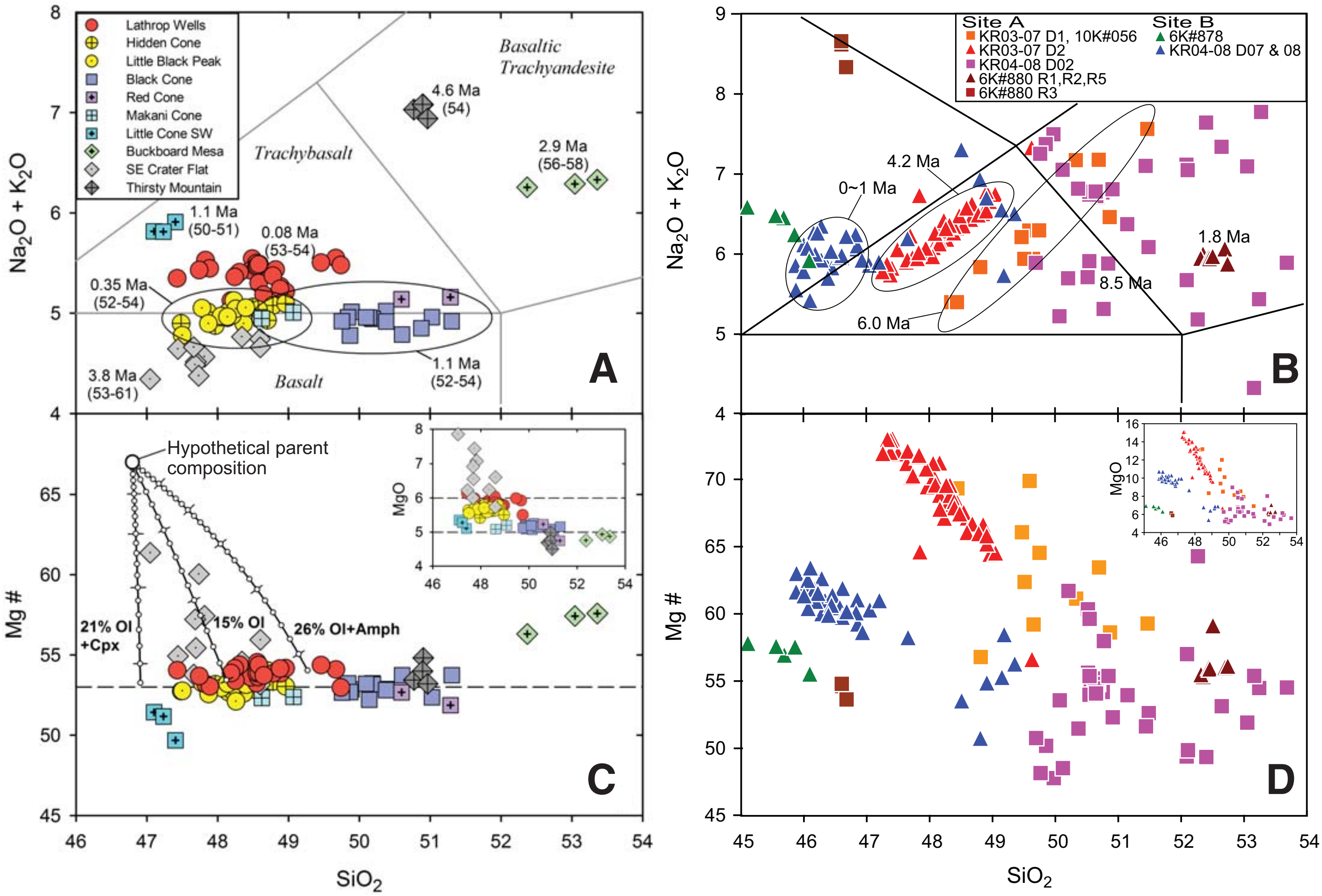


Figure 2. Total alkali-silica plots for (A) Pliocene-Pleistocene Southwest Nevada volcanic field (SNVF), and (B) northwest Pacific Ocean (NPO). Symbols correspond to individual volcanoes. (C) Mg number versus SiO_2 for Southwest Nevada volcanic field (modified from Valentine and Perry, 2007). Trajectories originating from a "hypothetical parent magma" show effects of fractionation of olivine plus clinopyroxene (Ol + Cpx), olivine (Ol), and olivine plus amphibole (Ol + Amph) assemblages, and percentages of fractionation of those assemblages needed to attain Mg numbers of ~53–55 (note that one volcano, southeast Crater Flat, shows evidence of shallow fractionation, while others show a consistent degree of fractionation that probably took place at depths >30 km). Data sources for Southwest Nevada volcanic field are Perry and Straub (1996) and Perry et al. (1998). (D) Mg number versus SiO_2 for northwest Pacific Ocean (data from Hirano et al., 2006). Linear trends for individual volcanoes record effects of fractionation (mainly olivine), while data sets with wide scatter likely represent a mix of fractionation and contamination by lithospheric rocks. Insets in C and D show MgO versus SiO_2 (note different scales on vertical axes). All compositional data are in wt%.

fractions (Rabinowicz et al., 2001). Holtzman and Kohlstedt (2007) used the compaction length as a scaling factor for the spacing between melt-rich shear bands ($\delta_{sp} \approx 2/5\ \delta_c$); the parameters here suggest spacing between shear bands on the order of a few hundred meters, and these would be inclined at an angle of ~20° from the shear plane. Shear bands would have well-connected porosity and vertical extents on the order of ~1 km, which in turn would produce fluid overpressures (p_f) of several MPa due to the buoyancy of the interconnected melt relative to the deformable matrix ($p_f \approx \Delta\rho g \delta_c$, where $\Delta\rho$, the density difference between melt and matrix, is ~200–500 kg/m^3). This is sufficient fluid pressure to initiate dike propagation in partially molten mantle rocks (Fowler, 1990), and shear focusing would promote the growth of the dikes as melt becomes more easily able to move through matrix of increasing porosity. As regional deformation progresses, patches with progressively smaller fractions of partial melt are tapped because they require more deformation to reach the necessary porosity to trigger dikes. It is likely that many small veins and dikes are triggered along shear bands, and these coalesce upward to feed one or a few major dikes (see Ito and Martel, 2002) that ascend into the upper lithosphere and potentially feed monogenetic events. This zone of dike and vein coalescence is likely where much of the deep fractionation recorded in the Southwest Nevada volcanic field takes place (Spera and Fowler, 2009). The relationship between melt collection/ascent and tectonic deformation (stress relief) results in a time-predictable relationship between eruption volume and repose time (Valentine and Perry, 2007).

We extend this model to northwest Pacific Ocean magmatism, wherein small fractions of partial melt that are present in upper-mantle heterogeneities are focused by the shear-banding mechanism as the Pacific plate passes through the flexure zone (note that geophysical data are ambiguous as to the location and nature of the asthenosphere around this region; Shimamura et al., 1983; Shinohara et al., 2008). This model does not require the presence of fracture-controlled pathways between the seafloor and the asthenosphere; rather, ascending dikes propagate their own fractures. On a related note, Kawakatsu et al. (2009) found seismic evidence for melt-enriched bands in the asthenosphere beneath the Philippine Sea plate, which they attributed to shear banding, consistent with our view of the potential importance of this process in intraplate settings. Future work should test whether flexure-related, low-flux volcanic fields develop in similar flexure settings outboard of trenches, and whether such systems exhibit time-predictable behavior.

DIFFERENT STRESS DISTRIBUTIONS CAUSE DIFFERENCES IN GEOCHEMICAL DIVERSITY BETWEEN THE TWO FIELDS

It is well known that dike orientation is primarily determined by the orientation of principal stresses in the surrounding rocks, such that the plane of a dike is approximately perpendicular to the least compressive principal stress (σ_3). In very high magma flux, magmatically controlled fields (Valentine and Perry, 2007), repeated dike injection can cause rotation of the principal stresses such that, for example, dikes begin to propagate horizontally as sills (see Parsons and Thompson, 1991). This in turn promotes the formation of crustal magma reservoirs and fractionation and contamination processes that are recorded in the erupted products.

In low-flux, tectonically controlled intraplate systems, on the other hand, dikes are widely separated in space and time and have little, if any, effect on the regional tectonic stresses on the scale of a given volcanic field. Ascending dikes at the extensional Southwest Nevada volcanic field likely experienced relatively little variation in the orientation of principal stresses as they transited the lithosphere, until they interacted with faults in the upper few hundred meters (Valentine and Krogh, 2006; Gaffney et al., 2007). As a result, most of the magmas ascended with little or no interruption, and this resulted in little fractionation or contamination above the lower lithosphere.

In contrast, the regional tectonics of flexure (concave upward) meant that dikes ascending in the northwest Pacific Ocean experienced a 90° rotation of σ_3 at midlithospheric depths; the base of the lithosphere is extended such that σ_3 is perpendicular to the flexure axis, while in the upper lithosphere, the least compressive horizontal stress is parallel to the flexure axis. We infer that this stress rotation caused many of the ascending northwest Pacific Ocean dikes to stall in the lithosphere. This process resulted in the observed variable degrees of fractionation of volcanic products and also promoted the entrainment of upper lithospheric xenoliths and xenocrysts because the temporary stalling allowed for thermal and chemical interaction between magmas and wall rocks. Dikes that propagated upward from these temporary reservoirs were oriented perpendicular to the least horizontal compressive stress in the upper lithosphere, i.e., perpendicular to the flexure axis. We suggest that geophysical surveys could search for the existence of stalled magma bodies in the midlithosphere in the northwest Pacific Ocean, although we anticipate that these are likely small and highly transient and might not be resolvable.

CONCLUSIONS

We propose that the Pliocene-Pleistocene Southwest Nevada volcanic field and northwest Pacific Ocean volcanic field are both the result of tectonic deformation-driven collection of preexisting partial melts in heterogeneous upper mantle, and that differences in their geochemistry are related primarily to the effects of different lithospheric stress fields on dike propagation. Such processes seem likely at other low-flux intraplate fields; a fruitful avenue of research will be to test these ideas at fields in a range of tectonic settings.

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