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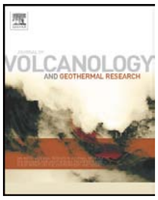

Thermal structure beneath the Snake River Plain: Implications for the Yellowstone hotspot

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ABSTRACT

Basaltic magmatism associated with the Yellowstone hotspot has been widely attributed to upwelling of a mantle plume, yet the temporal and spatial distribution of these magmas and their compositional characteristics are distinctive from oceanic hotspot magmatism. Fundamental questions concern the influence of continental cratonic lithosphere in producing the differences, and the extent to which upper plate processes contribute to magma production. To better understand scenarios of melt generation, *P*–*T* conditions are estimated for segregation of primitive Snake River Plain (SRP) basalts from the mantle. Combined with analysis of trace element and seismic constraints, we conclude from this that (1) melt production was concentrated at depths between roughly 70–100 km, (2) mantle temperature was only slightly higher than ambient conditions with a *maximum* potential temperature of 1450 °C, and (3) the mantle source was relatively fertile (Mg#<90). These results suggest that the seismically imaged plume below Yellowstone is significantly cooler than upwellings beneath Hawaii, Iceland and many other oceanic "hotspots". Our findings, in combination with other geochemical and geodynamic considerations, are permissive of magma generation within the ancient lithospheric mantle keel associated with the Wyoming craton. Plume contributions, while not excluded, involve physical and geochemical implications that suggest they are subordinate.

1. Introduction

The Snake River Plain-Yellowstone (SRPY) province is a region of diachronous bimodal rhyolite–basalt magmatism that has been attributed to migration of North America over the Yellowstone hotspot (e.g., Armstrong et al., 1975; Pierce and Morgan, 1992; Smith and Braile, 1994). A variety of other observations appear to support this hypothesis (Pierce et al., 2002). Perhaps the most compelling evidence comes from seismic tomography that defines a sub-vertical low-velocity pipe beneath Yellowstone that extends into the mantle to a depth of 500 km (Fee and Dueker, 2004; Yuan and Dueker, 2005; Waite et al., 2006). This feature connects to a low-velocity region between 60 and 120 km depth under the eastern Snake River Plain (Schutt and Humphreys, 2004; Yuan and Dueker, 2005; Waite et al., 2006; Schutt et al., 2008). Together, these images suggest that a plume of hot mantle is ascending from the transition zone to beneath Yellowstone Park, where it is swept to the SW by the North America Plate flow field as shown in Fig. 1.

The earliest volcanism directly associated with this phenomenon was manifest as eruptions of voluminous silicic ignimbrites and lavas in southwestern Idaho and adjacent areas of Oregon and Nevada around 16 Ma, shortly following onset of the Columbia River flood basalt activity (Camp and Ross, 2004). Silicic volcanism was associated with large eruptive centers, each active for 2–4 m.y., and it migrated northeastward to Yellowstone over time. Although it is inferred that this magmatism was fundamentally driven by injections of voluminous mafic magma into the crust (Hildreth et al., 1991; Bonnichsen et al., 2008), *eruptions* of basalt were delayed until waning stages of silicic activity, after which volcanism in any given area was dominantly basaltic. At Yellowstone, this transition has only just begun, whereas further west basaltic volcanism has persisted intermittently to Quaternary time across much of the SRP.

The pattern of SRPY volcanic activity differs conspicuously from that associated with oceanic island hotspots, for which magmatism is almost entirely basaltic and defines simpler time-transgressive patterns. The preponderance of silicic volcanism in southern Idaho is attributed to the fact that the region is underlain by cratonic crust, whereas roughly west of the Idaho border the basement comprises an amalgamation of accreted oceanic terranes with relatively juvenile crust (Fig. 1). This difference in basement type is clearly reflected in gravity and magnetic signatures for these areas as well as in the compositions of both basaltic and rhyolitic magmas, with those to the east having systematically higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$,

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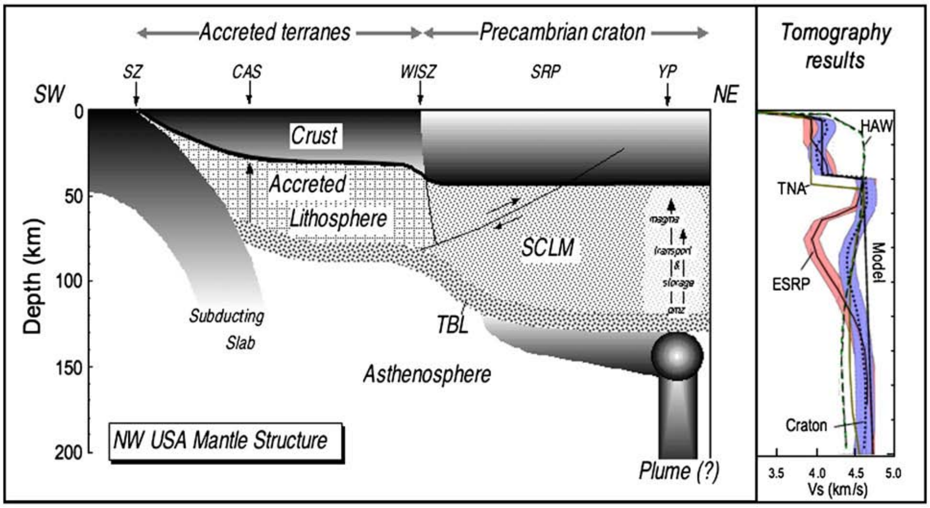

Fig. 1. Schematic lithospheric structure for NW U.S.A., with results of V_S tomography from the eastern Snake River Plain (SRP). Diagram portrays subcontinental lithospheric mantle (SCLM) beneath Precambrian cratonic North America, with locus of a postulated plume impinging beneath the Yellowstone Plateau (YP); an intervening thermal boundary layer (TBL) marks the base of the lithosphere (thickness is schematic). The Cascadia arc (CAS) and subduction zone (SZ) and Phanerozoic accreted terranes are juxtaposed outboard the Western Idaho Suture Zone (WISZ); mantle thrust fault signifies shortening related to a late Cretaceous accretionary 'event' (cf. Leeman et al., 1992). Beneath YP a thick zone of magma formation and storage coincides with anomalously low seismic velocities (reflected in V_S tomography and estimated magma segregation depths (~60 to 100 km; this paper). Profiles show mean V_S structure, derived from surface wave phase velocities (Schutt et al., 2008), for the hotspot track (red, ESRP) and the Wyoming Craton (blue; Craton). One sigma model error is shown by the width of the bands. Reference model is shown as a black line (Model). For comparison, velocity variations with depth are shown for Hawaii (HAW; Priestley and Tilmann, 1999) and Tectonic North America (TNA; Grand and Helmberger, 1984).

δ^{11}B, and B/Rb (Leeman et al., 1992; Savov et al., 2009-this volume). If SRP magmatism is plume-related, the presence of cratonic lithosphere appears to have profoundly influenced its surface expression. Alternatively, magmatism could be related to Basin and Range style extension, possibly enhanced by sub-lithospheric processes. To better constrain the origin of the basaltic magmas, we have evaluated the thermal structure of their mantle source and how this may relate to contrasting tectonic scenarios.

2. Tectonic processes

2.1. Lithospheric processes (extensional deformation)

The SRP is superimposed on the northern reaches of the Basin and Range province of western North America. Thus, it is relevant to review possible influences of the underlying extensional processes. Considerable evidence (cf. Snyder et al., 1976; Oldow et al., 1989; McQuarrie and Wernicke, 2005) indicates that extensional deformation began in the southwestern US and propagated northward over time following northward migration of the Mendocino triple junction. Extensional strain exceeds 100% (since early Oligocene time) at the latitude of Las Vegas and is on the order of at least 15–20% (since mid-Miocene time) at the latitude of the SRP (Rodgers et al., 2002). Moreover, associated magmatism was synchronous with or closely followed onset of extension as it propagated laterally (Gans et al., 1989; Armstrong and Ward, 1991; Axen et al., 1993). Initial mid-Tertiary magmatism was predominantly characterized by eruptions of voluminous silicic magmas, and in Neogene time evolved to bimodal basalt–rhyolite character. However, even the earliest silicic activity can be linked to inputs of mafic magmas into the crust (e.g., Feeley and Grunder, 1991).

Harry and Leeman (1995) considered the effects of extension on mantle melting and proposed that (for the southern and central Basin and Range province) early synextensional magmatism was driven by basalt production in the continental lithospheric mantle owing to decompression melting of entrained fertile (i.e., mafic) domains that were close to their solidus temperatures. This mechanism was suggested because depleted or refractory lithospheric mantle peridotite is unlikely to produce much magma and then only after significant lithospheric thinning (i.e., substantially later than inception of extension). Hydrated lower lithospheric mantle also could melt in rapid response to extension, but this process is less capable of sustaining the documented large magma production rates over time in the Basin and Range province (Best and Christiansen, 1991).

Available data (e.g., Fitton et al., 1988, 1991; Kempton et al., 1991; Daly and DePaolo, 1992; Bradshaw et al., 1993) suggest that the mafic magmas changed character over time, with the earliest having lithospheric affinity (e.g., higher ^{87}Sr/^{86}Sr, lower ^{143}Nd/^{144}Nd, and fractionated incompatible element signatures compared to younger basalts) whereas, once extension exceeded a critical magnitude (roughly 75–100%), younger mafic magmas tend to have asthenospheric affinity (OIB-like chemistry). This transition is attributed to the notion that, once lithosphere has been critically thinned by extension, magma generation may be dominated by melting of upwelling asthenospheric mantle — i.e., the binary source model of Leeman and Harry (1993). It appears that such a transition in sources for basaltic magmas occurred by early- to mid-Miocene time in southern California, but has only migrated as far as north-central Nevada at present (Lum et al., 1989). Thus, SRPY basalts could be derived from lithospheric mantle based on the fact that their Sr–Nd–Pb isotopic compositions are distinctive from most OIB or MORB (Leeman and Manton, 1971; Doe et al., 1982; Menzies et al., 1984; Hildreth et al., 1991).

2.2. Sub-lithospheric processes (hotspot influence)

Alternatively, evidence that a mantle plume underlies the Yellowstone area warrants consideration that SRP basaltic magmas may have been derived from such a source, but acquired their unusual isotopic compositions as a consequence of interaction with old lithospheric rocks (cf. Hanan et al., 2008). If the tomographically imaged anomaly beneath Yellowstone truly is a mantle plume, is it capable of producing SRPY basaltic magmas? To address this question we consider the following issues: (1) Under what circumstances can the mantle melt to produce basaltic magmas? (2) What is the cause of the tomographic anomaly and, specifically, what do the seismic data