STRUCTURAL CONTROL AND PLATE-TECTONIC ORIGIN OF THE YELLOWSTONE MELTING ANOMALY

Robert L. Christiansen, *U.S. Geological Survey*
and
David R. Lageson, *Montana State University*

Conventional models of lithospheric magmatism, its surficial volcanic expressions, and its tectonic contexts are commonly couched in dichotomies. The bulk of Earth's magmatism is seen as systematically related to plate boundaries, with the rest characterized somewhat vaguely as "intraplate". Certain magmatic compositions and rates of magma production at plate margins are taken as normal, in contrast to anomalous compositions and anomalously high production rates at "hotspots", typically expressed by linear chains of age-progressive volcanism. Deep-earth processes are categorized as active or passive, commonly inferring plate-margin magmatism to be a more or less passive response to plate-boundary tectonic processes and "hotspot" magmatism as representing chemical and thermal anomalies that originate deep in the mantle, perhaps even driving or modulating plate motions. The sources of diverse isotopic and trace-element compositions of primitive magmas are taken to represent partial melts of discrete mantle "reservoirs". An alternative, more unified view regards magma generation as a more or less pervasive upper-mantle process whose manifestations are controlled directly by lithospheric tectonics. In this vein, it is useful to follow Shaw and Jackson (1973), who deliberately avoided the term "hotspot" and its multiple connotations by using the term "melting anomaly" to describe a system of enhanced lithospheric magma production with compositions distinct from those of typical plate-boundary magmas.

This latter view is illustrated here in considering the origin of a linear system of volcanic features in the Northwestern United States that has commonly been viewed as defining a Yellowstone "hotspot" (Fig. 1).

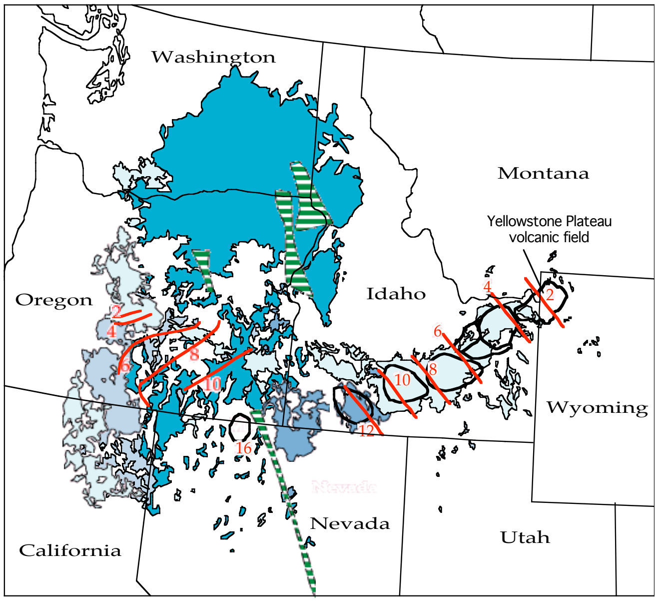

Figure 1. Map of the northwestern US showing basalts younger than ~17 Ma and age-progressive rhyolitic centers. Age groups of basalts indicated by blue colors: brightest for 17-12 Ma, dark for 12-8 Ma, medium for 8-4 Ma, and light for 4-0 Ma. Ages of rhyolites younger than ~12 Ma indicated by red contours.

In the Yellowstone Plateau volcanic field, ~6,500 km^3 of magma has erupted in the past $2.2x10^6$ years, ~95% rhyolite and ~5% tholeiitic basalt. Episodic activity typically erupts 10 to 10^3 km^3 of rhyolitic magma every 10^3 to 10^5 years; the intrusive/eruptive ratio is estimated to be about 10. Basalts generated in the upper mantle cause partial melting of the lower continental crust and thermally sustain rhyolitic upper-crustal magma chambers. Magma production since 2-3 Ma has been ~0.9 m^3/s for Yellowstone, comparable to ~3 m^3/s for Hawaii. The Yellowstone Plateau volcanic field represents the youngest segment of a system that has propagated nearly 600 km across a continental plate along the eastern Snake River Plain since at least ~13 Ma and probably has emplaced 10^4 km^3 of rhyolitic and basaltic magma within and onto the continental crust. The age-progressive magmatic system was preceded by the 17- to 14-Ma basaltic and bimodal magmatism of the Columbia River flood basalts and other basalts and rhyolites, probably aggregating ~10^5 km^3, in a backarc region adjacent to old, thick continental lithosphere that includes an Archean craton.

The widely espoused deep-mantle plume hypothesis for the Yellowstone melting anomaly seems deficient in several respects. Seismic studies fail to reveal any evidence for a deep-mantle plume and, in fact, point to the absence of any such feature beneath Yellowstone or the eastern Snake River Plain below ~200 km. The hypothesis also fails to address inherently the initiation of the melting anomaly in both spatial and temporal coincidence with a major mid-Miocene tectonic reorganization of a large region of the Western U.S., from localized extension along the Northern Nevada rift zone to accelerated uplift and regionally distributed extension of large magnitude. Similarly, the asymmetric distribution of flood basalts and related magmatism at the initiation of the Yellowstone melting anomaly, simultaneous NE propagation of the Yellowstone melting anomaly and NW propagation of the Newberry melting anomaly, and continued basaltic magmatism along both tracks all require *ad hoc* modifications of the plume hypothesis. We here interpret this system as an integrated product of regional tectonic interactions between the lithosphere and sublithospheric upper mantle, exploiting preexisting lithospheric structures

Major structural features, some cutting the entire lithosphere, were important controls on location and orientation of the track of the Yellowstone melting anomaly along the eastern Snake River Plain. The track parallels a pervasive NE-trending tectonic grain of Precambrian ancestry, including magnetic anomalies beneath the Great Plains of eastern Montana, and the Cheyenne Belt, Saint George trend, Colorado Mineral Belt, and Jemez trend to the south. More locally, numerous NE-trending tectonic features either straddle or align with the track of the Yellowstone melting anomaly, including: 1) the southwestern part of the pre-Tertiary Humboldt lineament, 2) an Early Proterozoic suture between the Archean Wyoming and Hearne Provinces, partly expressed by mylonite zones in the Beartooth Mountains, 3) the Proterozoic Great Falls tectonic zone, 4) a Late Cretaceous structural recess and consequent transverse sediment dispersal system in the Sevier orogenic belt, and 5) a conspicuous change in the orientations and expressions of Laramide foreland contractional structures.

We present a model for the Yellowstone melting anomaly that involves exploitation of preexisting tectonic features to accommodate oblique extensional strain across the Intermountain West since the mid-Miocene and strong contrasts in lithospheric architecture to initiate voluminous magmatism. In this model, lithospheric tectonic processes, including subduction, northward migration of the Mendocino triple junction, basin-range extension, and progressive outward concentration of basin-range extension toward the east and west margins in response to oblique extension and shear interact with sublithospheric upper mantle to produce the NW-propagating Newberry and NE-propagating Yellowstone melting anomalies. The volume of melting depends on source fertility, composition, focusing, prior history, the effects of horizontal temperature gradients, and thermal feedback on the dynamics of convection and melting in the upper mantle. Yellowstone and Newberry represent self-sustaining melting anomalies propagating along transform accommodation zones that bound a region of oblique large-magnitude extension. Exploitation of preexisting northeast-trending structural weaknesses along with basal shear melting of the southwest-moving North America plate and thermal feedback as magmas rise into the lithosphere and onto the surface may explain the exceptionally high magmatic productivity of the Yellowstone melting anomaly. Enhanced extension along the western margin of the Great Basin region produced crustal melting in the backarc of the Cascadian subduction system, propagating northwestward with extensional widening to produce the Newberry melting anomaly.

Thus, the lithosphere, asthenosphere, and deeper mantle interact as a dynamic feedback system that includes the generation and transport of fluid phases. Basaltic upper-mantle magmas may cause lower-crustal melting and can sustain long-lived upper-crustal magmatism. Lithospheric magmatism has long-term average rates that are coupled to tectonic displacement rates. Compositions reflect the physical state and composition of parent materials (including prior additions and subtractions by fluid phases), percentage of partial melting, rates of magma production and transport, and modification by phase separations during ascent and by thermal interactions with the lithosphere, including induced melting. All of these factors are influenced by stress distributions and ascent rates. Whereas oceanic magmas evolve in more or less transformed mantle peridotite and thin mafic crust; continental magmas evolve in mantle peridotite that may be ancient and in thick, heterogeneous but predominantly intermediate-composition crust. In such a view, plate-margin tectonic processes may simply act to focus more general upper-mantle magmatic processes also expressed in intraplate magmatism.