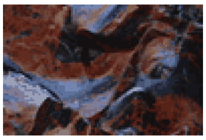

Quartz Mountain obsidian

The Oregon High Lava Plains: Proof against a plume origin for Yellowstone?

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Introduction

The High Lava Plains province (HLP) of central and southeastern Oregon is an enigmatic volcanic province characterized by bimodal volcanism with a west-younging progression in ages of silicic volcanic rocks. Were the age progression in a direction anywhere near the back-azimuth of plate motion it would be widely interpreted as the trace of a mantle plume. The age progression crudely mirrors the northeast-younging trend of the Yellowstone-Snake River Plain volcanic system (YSRP), with both trends originating in a common region in the axis of middle Miocene flood basalt volcanism of the Steens and Columbia River Basalts (Figure 1).

Given these relations, the HLP, YSRP, and middle Miocene flood basalts are commonly linked. The back-azimuth of the age progression of the YSRP is in the direction of North American plate motion, and therefore the YSRP has generally been interpreted as a manifestation of a hotspot (*Armstrong et al.*, 1975; and Yellowstone page), widely presumed to be a mantle plume (e.g. *Pearce & Morgan*, 1992; *Smith & Braile*, 1994). The middle Miocene flood basalts are commonly interpreted as representing the plume-head phase of this hypothesized mantle plume (*Brandon & Goles*, 1988; *Thompson & Gibson*, 1991; *Geist & Richards*, 1993; *Camp*, 1994; *Hooper*, 1997; *Camp et al.*, 2003; and Columbia River Basalts page). But how could the HLP possibly fit into a plume model? The existence of the HLP trend is one of the most frequently cited lines of evidence against the plume model for the YSRP, e.g.:

Hamilton (1989), “*Powerful evidence against the notion of a Yellowstone hot spot is provided by the presence in eastern Oregon of volcanic centers by which magmatism progresses 200 km northwestward during the past 10 m.y., a progression comparable in time to that of the supposed Yellowstone hot spot yet in an altogether different direction.*”

I have been a part of an Oregon State University research group, led by Anita Grunder, which has been studying the High Lava Plains since the early 1990s. Other researchers in this group include Martin Streck, Jenda Johnson, Jim MacLean, Al Deino (Berkeley Geochronology Center), Dave Graham, and Bob Duncan. In this review I discuss the geology of the HLP, tectonic interpretations of the HLP, and implications of these interpretations for the plume model for Yellowstone.

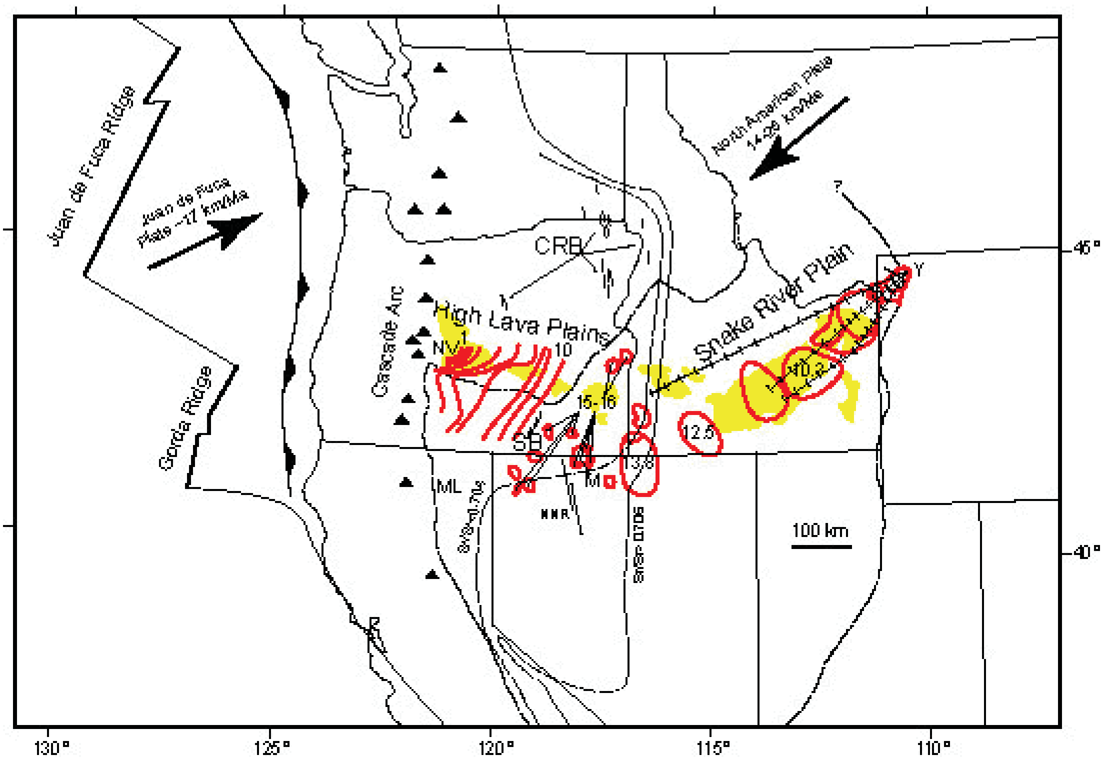

Figure 1

Geology and Petrology of the High Lava Plains

The HLP is a bimodal volcanic province, with only 8% of analyzed samples (n = 286 samples) being intermediate in composition (this figure probably over-representing the intermediate rocks because of focused sampling due to their petrologic significance). Basalts are mostly primitive, high-alumina, olivine tholeiites (distinct from arc basalts with high-alumina at low MgO). Trace element compositions of primitive HLP basalts are similar to N-MORB, but with highly elevated Ba, Sr, and Pb. Sr and Nd isotopic compositions. HLP basalts are more evolved than MORB with a minimum $^{87}Sr/^{86}Sr$ of 0.7032. $^{3}He/^{4}He$ ratios in HLP basalts range from 8.8 to 9.4 times the atmospheric ratio (*Jordan et al.*, 2000; *Graham et al.*, in prep).

Rhyolites were erupted in > 60 domes and dome complexes, three major ash flow tuffs (Prater Creek, Devine Canyon, and Rattlesnake), and several minor tuffs (Figure 2). Silicic rocks are mainly high-silica rhyolites (> 75 wt% SiO_2) and are metaluminous to mildly peralkaline. (*MacLean*,1994; *Streck & Grunder*, 1995; *Johnson & Grunder*, 2000). Some rhyolites are isotopically indistinguishable from associated basalts while others are more isotopically evolved.

A systematic age progression of rhyolites was recognized by *MacLeod et al.* (1975), and recent $^{40}Ar/^{39}Ar$ geochronology confirms this age progression (*Jordan et al.*, in prep). Ages of rhyolite domes and tuffs decrease westward from 10.5 Ma in the east to < 1 Ma in the west. The distribution of age-progressive rhyolites extends ~ 70 km south into the Basin and Range province, though the rhyolite belt in the HLP is more robust and continuous.

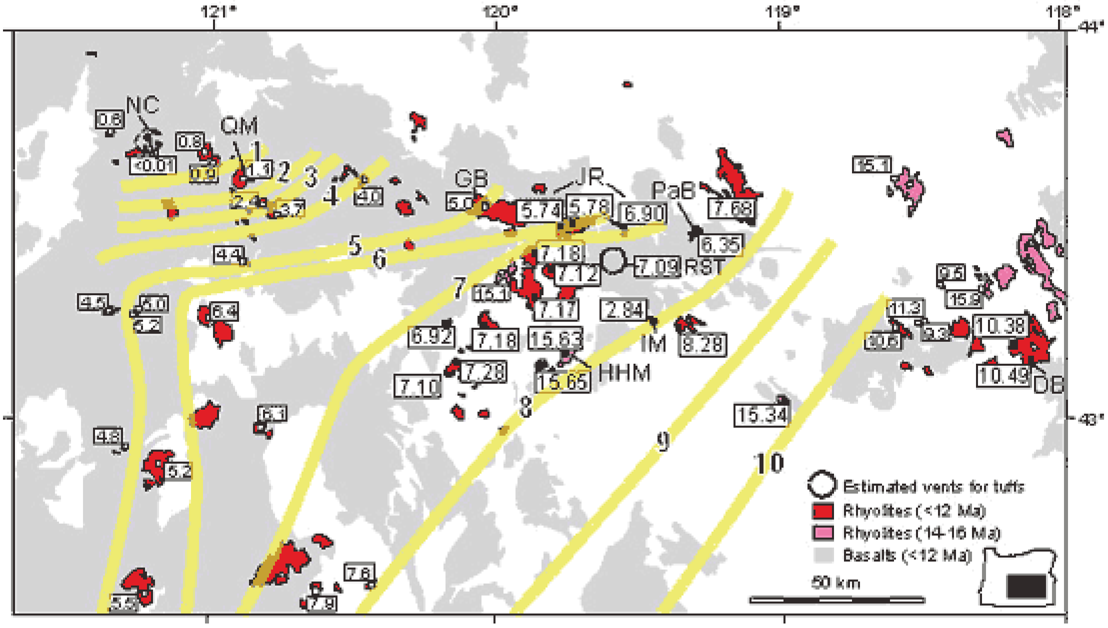

Figure 2

The age progression is commonly depicted as a series of isochrons (Figure 2). These isochrons are generally NE-trending. If propagation were perpendicular to the isochrons, this geometry suggests NW-migration. But from Duck Butte (DB in Figure 2) at 10.5 Ma in the east, the belt of silicic magmatism, which coincides with a belt of Pliocene and younger basaltic volcanism, trends N75°W to the Newberry area. This observation suggests that the NW-trend of the isochrons represents an initial condition and that magmatism has migrated westward as a “wave” rather than as a point. The western isochrons become progressively more closely spaced and E-trending. The spacing of the isochrons indicates propagation rates of 35 km/m.y. from 10 to 5 Ma and 15 km/m.y. since 5 Ma.

The present focus of this trend is commonly interpreted to be Newberry volcano, however Newberry is petrologically dissimilar to most HLP volcanic centers and may represent more complicated interactions between the HLP trend and the Cascade arc. We, therefore, discourage the growing use of the term “Newberry trend” or “Newberry hotspot” to describe the HLP age progression, preferring the antecedent “High Lava Plains trend”.

Migrating silicic volcanism of the HLP and northern Basin and Range is closely linked with the distribution of closely-spaced NW-trending normal faults of modest (< 100 m) offset, which includes the Brothers fault zone.

Interpreting the HLP: Implications for the plume model for Yellowstone

Several models have been put forth to explain the HLP, several of which also seek to explain the YSRP:

1. Propagating shear zones (*Christiansen*, 1993; part of *Christiansen et al.*, 2002)
2. Back-arc upwelling in response to changing subduction geometry (*Carlson & Hart*, 1987)
3. Entrainment of plume head material in a subduction-induced mantle flow cell

(*Draper*, 1991)

4. Upwelling around the residuum of middle Miocene flood basalt magmatism (*Humphreys et al.*, 2000)

I comment on each of these models in order below.

(1) Preliminary results of GIS analysis of the time space patterns of faulting across the HLP indicate that extension on faults of the Brothers fault zone has occurred at a rate of 0.2-0.5 %/m.y. across the province since at least 7.6 Ma, and that faulting did not propagate westward (ongoing research with Soren Klingsporn, Whitman College). Therefore, the propagating shear zones model is rejected for the HLP. These faults may have played a role in allowing magma to intrude and transit through the crust, but can not explain mantle magma genesis (low rate of extension, not adiabatic) or propagating crustal magmatism. There is no evidence for a shear zone coincident with the YSRP, and no need for one (extension north and south of the Plain are of similar magnitude), so this process doesn't work there either.

(2) There is no evidence of slab steepening in this time interval. Arc volcanism has occurred in the area of the modern Cascade Range since ~ 40 Ma. Also, this model envisioned high magnitudes of extension in the back arc during the late Tertiary, and this is clearly not the case (results described above).

(3) In explaining the origin of the HLP, the model of *Draper* (1991) invokes, rather than contradicts, the plume model for the origin of Yellowstone. A shortcoming of this model is that it is inconsistent with current models of plume head dynamics in which a plume head flattens as it approaches the lithosphere (*Griffiths & Campbell*, 1991) and can be emplaced across a region over 1,000 km across in less than a million years (*Duncan et al.*, 1997).

(4) The model of *Humphreys et al.* (2000) was created to demonstrate that a plume is not necessary to explain either the HLP or YSRP trends, though this model is consistent with the plume model as well (a question-marked plume is, in fact, shown in their cartoon). This model makes no attempt to explain initial melting (middle Miocene) to create the residue around which asthenosphere flows and wells up to generate the trends.

So models 1 and 2 are rejected and models 3 and 4 leave a plume origin permissible. To these I would add two other plume-related mechanisms that could explain west migrating silicic magmatism of the HLP:

(5) A plume head placed where global plate motion models suggest it should be, back tracking from Yellowstone) would have been emplaced east of the craton margin in southern Idaho (Figure 1). Flow of plume head and plume material on basal lithospheric topography (e.g. *Sleep*, 1996) would have driven a westward flow system. Additionally, this would explain the focusing of middle Miocene flood basalt vents at the craton margin!

(6) The plume head hypothesized in (5) would also have emplaced more and hotter material in the east (closer to the center) than the west. Therefore, the incubation time for driving a crustal magmatic system by advection and conduction would have been greater in the west (further from center).

These models are depicted in Figure 3. A combination of plume-lithosphere interaction and the model of *Humphreys et al.* (2000) can explain all of the deviations of the YSRP system from ideal mantle plume behavior. Some critics of the plume model consider any modification of the model from a vertical conduit arising from the base of the mantle creating magmatism directly above it to be *ad hoc*. I would argue that the modifications described above are not *ad hoc*, but based on physical processes that should be anticipated in consideration of any mantle plume in a similar setting (see *Sleep*, 2003 for well developed arguments on this point).

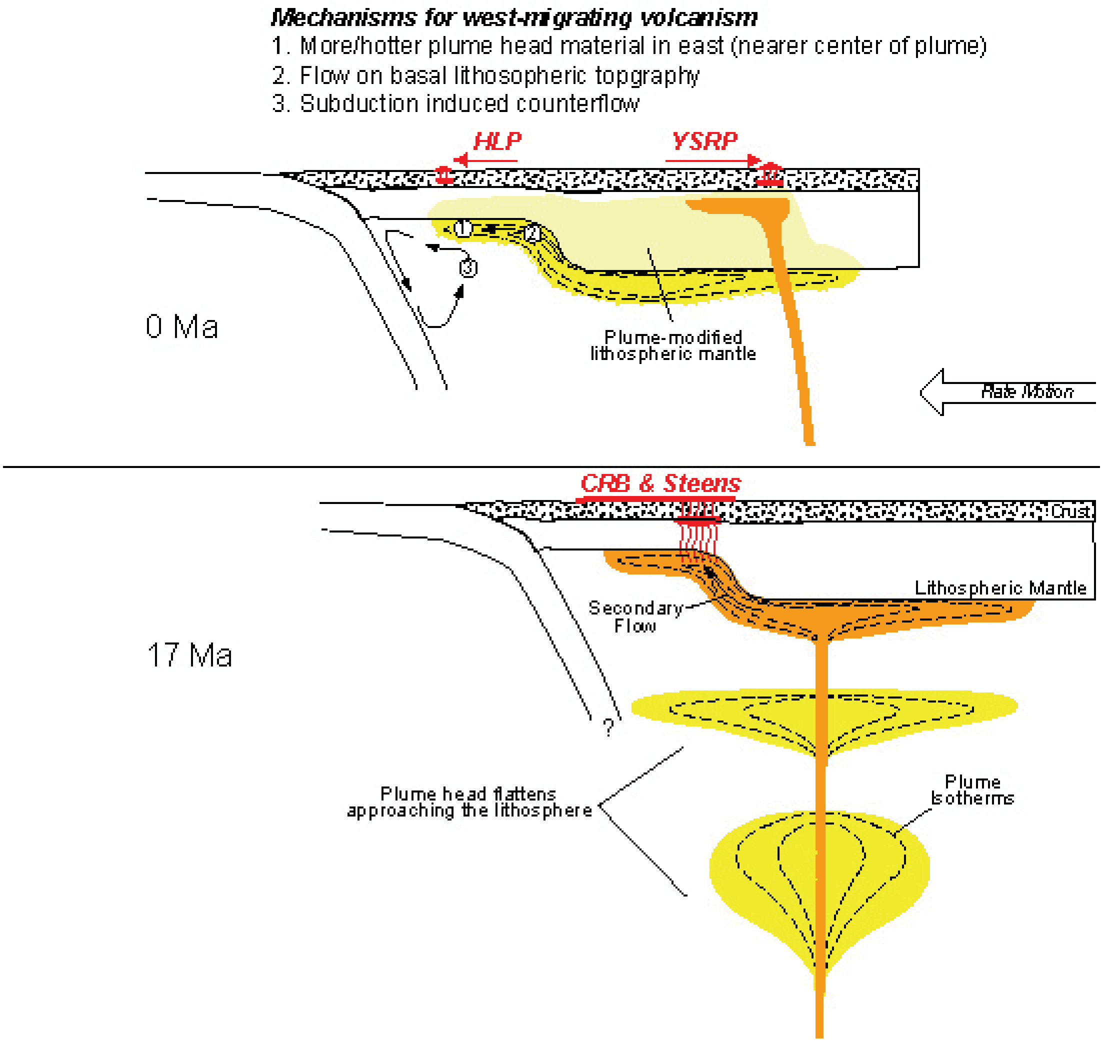

Figure 3

Are these models testable? A few ideas come to mind. Past sublithospheric flow of plume material might be detectible by appropriately aligned shear wave anisotropy at some depth. The area of greatest interest to me for this test would be the western Snake River Plain, which connects the location where the hypothesized plume should have been at 17 Ma (based on global plate motion models) to where most of the middle Miocene flood basalts erupted (NE Oregon, SW Washington). Sublithospheric flow with some thermo-mechanical erosion of the overlying lithosphere could be traced by the progressive introduction of a radiogenic cratonic mantle component under the accreted terranes to the west. Preliminary evidence in support of this has been reported by *Jordan et al.* (2002; and in prep.).

Conclusion

Temporal, spatial, and petrologic relations strongly suggest that the diverging age-progressive volcanic trends of the Yellowstone-Snake River Plain system, and the High Lava Plains province are linked. That they be linked does not require that they be generated by the exact same process as implied by those who argue against a plume origin imply (see quote from *Hamilton*, 1989 above). Rather, it suggests that the processes that formed them are probably linked.

The Yellowstone-Snake River Plain system is widely considered to be the result of plate motion over a mantle plume. Several reasonable physical mechanisms are described above that might explain how plume-related processes could also account for the High Lava Plains trend. ***This is not to say that the plume model has been proven, only that the existence of the HLP trend does not disprove it.***

Proof or disproof of the plume model for Yellowstone should come from:

1. high resolution tomographic studies of the Yellowstone area that consider all physically reasonable potential plume geometries; and

2. resolution of the debate regarding the significance of high ^{3}He/^{4}He ratios raised by *Anderson* (e.g. 2000; and Helium Fundamentals page). I am convinced that in order to satisfy both geophysicists (who widely question the significance of geochemical reasoning) and petrologists (who commonly doubt the resolution and interpretation of tomographic images) both issues must be resolved.

I, for one, will remain open to good ideas from both sides of the plume debate for Yellowstone and beyond.

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