Geochronology of Oregon High Lava Plains Volcanism: Mirror Image of the Yellowstone Hotspot?

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ABSTRACT

The High Lava Plains province (HLP) is a late Cenozoic bimodal volcanic field at the northern margin of the Basin and Range province in southeastern Oregon. The HLP is characterized by widespread basaltic volcanism and age-progressive rhyolitic volcanism. We present ⁴⁰Ar/³⁹Ar ages for 19 rhyolite domes, 5 rhyolite ash-flow tuffs, and 32 basaltic lavas from the HLP. The trend of westward migration of HLP rhyolites is confirmed. The rate of propagation is ~35 km/m.y. from 10 to 5 Ma, slowing to ~15 km/m.y. after 5 Ma. Three HLP dacite domes, part of a regional middle Miocene intermediate to silicic volcanic event, yielded ages of ~15.5 Ma. Basaltic volcanism was essentially continuous across the HLP since ~10 Ma. However, we identify several episodes of increased activity at approximately 7.5-7.8, 5.3-5.9, and 2-3 Ma, with the younger episode likely continuing into the Recent. The 7.5-7.8 Ma episode
was the most robust, and corresponds with the initiation of High Cascade volcanism suggesting that they are related to a regional tectonic event.

The trend of migrating silicic volcanism crudely mirrors the northeast propagation of the Yellowstone-Snake River Plain system, with both trends emerging from the axis of middle Miocene basaltic volcanism of the Columbia River and Steens basalts. Several lines of evidence support a link between the provinces, and we propose a model which explains both trends and the Miocene flood basalts as the consequences of interactions between a mantle plume and the structurally complex North American lithosphere and subsequent tectonic development.

INTRODUCTION

The High Lava Plains province (HLP) of central and southeastern Oregon is a Late Tertiary to Quaternary bimodal volcanic field. Silicic volcanic rocks of the HLP are progressively younger to the west (Walker, 1974; MacLeod et al, 1975; McKee et al, 1976; this study), generally mirroring the northeastward progression of silicic volcanic centers of the Snake River Plain to the Yellowstone Plateau (Armstrong et al, 1975). Migrating volcanism of the Yellowstone-Snake River Plain (YSRP) magmatic system is widely interpreted as the trace of a mantle plume now under Yellowstone (e.g. Pierce and Morgan, 1992; Smith and Braile, 1994). The existence of the antithetic HLP trend is often cited as evidence against this hypothesis (e.g. Christiansen and McKee, 1978; Hamilton, 1989; Christiansen et al, 2002). Proponents of the plume interpretation note differences between the trends and suggest that they are not linked (Pierce and Morgan, 1992), or that the HLP trend may not be a robust feature (Smith and Braile, 1994).
The HLP separates the Basin and Range extensional province from the less extended Blue Mountain province to the north; to the west the HLP impinges upon the Cascade Range (Fig. 1). Previous models relate the HLP trend to one or more of the processes active in the adjacent provinces. Christiansen and McKee (1978) and Christiansen et al (2002) propose that the HLP trend is the result of a propagating shear zone accommodating the northward termination of Basin and Range extension. Carlson and Hart (1987) relate middle Miocene magmatism and subsequent propagation of HLP silicic volcanism to the back arc setting, and a change in the geometry of subduction. Draper (1991) proposes that the HLP trend reflects the entrainment of plume head material in a subduction induced asthenospheric counter flow cell. Humphreys et al (2000) refine this model, proposing that both the HLP and YSRP trends could result from mantle flow around the buoyant residuum of middle Miocene magmatism (without speculating about the origin of this magmatism) in the shear fields created by plate motion and subduction counter-flow.

The problem of complex patterns of migrating volcanism posed by the HLP and YSRP trends has been recognized as one of the outstanding puzzles in understanding volcanism in the Pacific Northwest. We present new $^{40}$Ar/$^{39}$Ar incremental heating ages for rhyolites and basalts of the HLP and consider the bearing of these ages on the origin of the HLP trend and the potential relationship between the HLP and YSRP trends.

THE HIGH LAVA PLAINS

Volcanic Rocks

The HLP is underlain by widespread, thin lava flows of basalt intercalated with rhyolitic ash-flow tuffs and tuffaceous sediments and punctuated by rhyolite dome complexes. It is truly a
bimodal volcanic province with only 8% of a compilation of 286 analyzed samples being andesites or dacites; this figure probably over-representing intermediate compositions because of intensive sampling of these petrologically important units.

Basalts are mostly tholeiites (the high-alumina olivine tholeiites of Hart et al, 1984), though basaltic andesites, some of which are calc-alkaline, constitute approximately a quarter of analyzed mafic samples. HLP basalts are generally aphanitic to sparsely porphyritic with plagioclase (up to 1 cm) and olivine (up to 3 mm) being common phenocrysts. Clinopyroxene phenocrysts occur in some unusual basalts. Glomerophyric clusters, including two or three phenocryst phases are common in evolved basalts and basaltic andesites. Most HLP basalts have a diktytaxitic texture, although other groundmass textures include intergranular, subophitic, and ophitic.

Rhyolites were erupted in >60 domes and dome complexes, three major ash flow tuffs (Prater Creek, Devine Canyon, and Rattlesnake), and several minor tuffs (Fig. 3A). Silicic rocks are mainly high-silica rhyolites (>75 wt% SiO₂) and are metaluminous to mildly peralkaline. Rhyolite lavas and tuffs are aphanitic to moderately porphyritic, with varying combinations of plagioclase, quartz, sanidine or anorthoclase, biotite, hornblende, and clinopyroxene phenocrysts (MacLean, 1994; Streck and Grunder, 1995; Johnson and Grunder, 2000). Intermediate composition volcanic rocks are uncommon among rocks younger than 11 Ma, and are mainly simple mixtures of mafic and silicic compositions (Linneman and Meyers, 1990; MacLean, 1994; and Streck and Grunder, 1999).

Structure
The transition from the Basin and Range Province to the High Lava Plains is manifested by a northward decrease in relief on fault-bounded range fronts and a diffuse zone of closely spaced northwest-striking faults of modest (<100 m) normal offset (Fig. 2). The Brothers Fault Zone (Lawrence, 1976) is an apparent concentration of such northwest-striking faults that cuts obliquely the HLP (Fig. 2). Field relations indicate that both Basin and Range and Brothers Fault Zone faults were active in the eastern HLP by ~10 Ma (Johnson and Grunder, 2000), and that faults of both geometries have been active in the Quaternary (Pezzopane and Weldon, 1993).

**Previous Geochronology**

The west-migrating pattern of silicic volcanism of the HLP and northwestern Basin and Range was first recognized by the regional reconnaissance mapping and K-Ar geochronology of Walker (1974) and McKee et al (1976), and illustrated as a series of isochrons by MacLeod et al (1975) (c.f., Fig. 3A). No age progression was observed for basalts of the HLP. In a statewide compilation of K-Ar age determinations, Fiebelkorn et al (1983) reported other scattered published and unpublished ages for rhyolites and basalts and corrected previously reported ages for the currently accepted $^{40}$K decay constant (Steiger and Jäger, 1977). A few ages have been determined for rhyolites and basalts of the HLP and northwestern Basin and Range in the course of mapping and regional studies since the Fiebelkorn et al (1983) compilation as cited in the caption of figure 3.

**METHODS**

Samples were analyzed by the $^{40}$Ar/$^{39}$Ar technique in two labs. A suite of twenty-three samples consisting primarily of rhyolites was analyzed at the Berkeley Geochronology Center,
and thirty-five samples, primarily basalts, were analyzed in the College of Oceanic and
Atmospheric Sciences at Oregon State University. Sample preparation and analytical procedures
differed between the two labs and are therefore described separately below.

**Berkeley Geochronology Center**

Samples analyzed at the Berkeley Geochronology Center included 18 rhyolite and dacite
lavas, four rhyolitic tuffs, and one basalt. Lavas and tuffs were prepared as sanidine, biotite, and
plagioclase mineral separates or crushed obsidian except for one tuff which was prepared as a
separate of devitrified matrix material. The basalt was prepared as crushed whole rock. Samples
numbered HP-91-# were irradiated in the central thimble facility of the Omega West reactor of
the Los Alamos National Laboratory without the use of Cd shielding. All other samples were
irradiated in the Cd-shielded CLICIT facility of the Oregon State University TRIGA reactor.
Samples were regularly interspersed with monitor standards in wells drilled in a concentric
circular pattern on aluminum disks. Sanidine from the Fish Canyon Tuff, with reference age
28.02 Ma (Renne et al, 1998) was used as the neutron fluence monitor.

Seventeen samples were analyzed by the laser total fusion method using a focused Ar-ion
or Nd-YAG laser (Table 1). In these experiments, 6 to 15 single grains of sanidine, plagioclase,
or obsidian glass were analyzed per sample. Four samples were analyzed by incremental heating
using a defocused Ar-ion laser, all of which were run in duplicate (Table 2). Samples for laser
fusion or heating were loaded in to a copper sample holder and baked at 200 °C overnight. Two
samples were heated incrementally employing a double-vacuum resistance furnace (Table 2).
Isotopic measurements were made in a Mass Analyzer Products MAP-215/50 noble-gas mass
spectrometer.
Oregon State University

Samples analyzed at OSU (Table 3) were prepared as either whole-rock mini-cores (~100 mg), groundmass separates, or mineral separates (plagioclase). Samples and monitors (Fish Canyon Tuff biotite, FCT-3, with a reference age of 28.02 Ma; Renne and others, 1998) were stacked in quartz tubes and irradiated at the TRIGA reactor facility at OSU. Neutron flux was determined by analysis of monitors. Samples were degassed at 400 °C for 20 minutes then analyzed in a series of stepwise heating experiments with increments ranging from 50 to 200 °C to optimize instrumental operating parameters. Samples were heated in a low-blank tantalum resistance furnace with a programmable electronic control unit. Gases produced during heating were cleaned by sequential exposure to Zr-Al getters. Analyses were made with a Mass Analyzer Products MAP-215/50 mass spectrometer operating in peak-hopping mode (Duncan and Hogan, 1994; Duncan et al, 1997).

RESULTS

Of the 201 laser total-fusion analyses summarized in table 1, six fell more than two standard deviations beyond their weighted mean sample ages and were rejected from further analysis. Age probability spectra for the remaining laser total-fusion ages are near Gaussian for 18 samples, while one sample (HP-91-2) yielded a bimodal distribution (Figs. 4 and 5). Good correspondence in mean age was found between coexisting sanidine and non-hydrated obsidian (HP-91-10), and between sanidine and plagioclase (HP-91-14).

In all but one of the incremental heating experiments conducted at the Berkeley Geochronology Center (Table 2), incremental heating spectra yielded apparent age plateaus
using the definition of Fleck et al (1977) (three or more contiguous steps concordant at 2σ, and constituting greater than 50% of the 39Ar released in the incremental heating experiment). Data were also plotted on 36Ar /40Ar-39Ar /40Ar isochron diagrams ("inverse isochron"). Plateau ages are concordant with the isochron ages calculated from plateau steps, with isochrons meeting the statistical population criteria of MSWD (mean sum of weighted deviates) less than critical values defined by Mahon (1996). If the trapped argon component indicated by the isochron plot was within 2σ of the atmospheric composition (40Ar /36Ar = 295.5), the plateau age was accepted as the preferred age. The trapped component implied by the isochron plot for one analysis of HP-91-4 is beyond 2σ of the atmospheric ratio, so the isochron age is the preferred age for this sample. For samples which were run in duplicate, by either incremental heating or laser total-fusion, the weighted mean of both ages is reported and taken to be the best estimate of the age of the sample. Some of the ages determined at the Berkeley Geochronology Center have been previously reported (e.g. Streek and Grunder, 1995; Johnson and Grunder, 2000; Jordan et al, 2002a), but are here revised with reference to the most current age of the Fish Canyon Tuff standard (Renne et al, 1998).

Of the 39 incremental heating experiments conducted at Oregon State University (Table 3), 28 yielded plateaus with ages concordant (at 2σ) with isochron ages, with isochrons indicating a trapped argon component within 2σ of atmospheric composition (Fig. 6a). Four samples yielded plateau ages, which failed to overlap (at 2σ) with their isochron ages. The isochrons for these samples indicate excess argon, and the isochron age is preferred (Fig. 6b). One sample (2WHLP97) yielded overlapping plateau and isochron ages with a well developed isochron suggesting excess argon, and the isochron age is preferred for this sample. One sample (148CHLP98; Fig. 6c) did not yield a plateau but all data lie on an isochron indicating excess...
argon; it should be recognized that if the trapped component in a sample is non-atmospheric, it
can’t be expected to yield a plateau with ages generated assuming atmospheric composition for
the trapped component. One sample (145CHLP98) did not yield a three segment plateau, but two
precisely determined sequential releases that constitute 56% of the $^{39}$Ar released in this
experiment. We accept the two segment plateau age as the preferred age of this sample. The
remaining four experiments did not produce reliable crystallization ages. The integrated ages are
reported, but we do not consider these to be meaningful age estimates.

The dating results are consistent with stratigraphic relationships where they are known,
excepting three basalts from Egli Rim. Samples from two of the lowest lava flows in the section
(13WHLP98 and 15WHLP98) yielded ages of $5.58 \pm 0.11$ and $5.26 \pm 0.09$ Ma, and a sample
from the rim flow (24WHLP98) yielded an age of $5.89 \pm 0.12$ Ma. The youngest and oldest of
these ages are just beyond $2\sigma$ of one another. Hart et al (1984) analyzed rim and base samples at
Egli Rim by the K-Ar method, and also reported a younger age from the base of the section ($5.80$
Ma rim, $5.21$ Ma base). The lower flows are more likely to have been heated or altered, resulting
in some argon loss, so the rim flow age is considered the best estimate of the age of the
sequence.

Where the new ages for rhyolitic units are $^{40}$Ar/$^{39}$Ar analyses of units previously dated
by the K-Ar technique, the new data are typically ten times more precise and a little older. The
ages for the Devine Canyon ($9.74 \pm 0.02$ Ma), Prater Creek ($8.46 \pm 0.09$ Ma), and Rattlesnake
Tuffs ($7.093 \pm 0.015$ Ma) have been precisely determined and lie within error of the oldest ages
reported for these units; previous K-Ar ages ranged over more than two million years.
Morphologically youthful basalts yielded Quaternary ages. Three dacitic centers yielded 15.3-
15.7 Ma ages and expand the distribution of known silicic volcanism of middle Miocene age (Fig. 1).

One basalt from the lower portion of a section near French Glen yielded an age of 16.68 ± 0.13 Ma. This age coincides, at 1σ, with ages reported for the entire sequence of Steens Basalt exposed on Steens Mountain (16.58 ± 0.05 to 16.59 ± 0.02 Ma; Swisher et al, 1990), indicating that this is a Steens Basalt.

DISCUSSION OF AGES

Propagation of Rhyolitic Volcanism

New rhyolite ages confirm the contention of Walker (1974), MacLeod et al (1975), and McKee and others (1976) that silicic volcanism is progressively younger to the west along the High Lava Plains. The new ages require revisions to the isochrons of MacLeod et al (1975), but their general form remains the same (Fig. 3A). One new rhyolite dome age is not easily reconciled with a simple set of isochrons: Iron Mountain (2.84 ± 0.04 Ma), which had been previously recognized as much younger than the trend (Walker, 1974; MacLeod et al, 1975; McKee et al, 1976).

The pattern of isochrons in Figure 3A suggests migration of silicic volcanism along a front. Although the general trend of the isochrons is northeast, propagation of silicic volcanism was not perpendicular to the front but rather more westerly; the belt of maximum rhyolitic volcanism trends ~N75°W and coincides with the axis of Pliocene and younger basaltic volcanism. These observations suggest that the front of migrating silicic volcanism trended northeast initially, then migrated ~N75°W. Relatively young ages in the north-central and
western HLP require that the isochrons reorient to trend east-northeast, suggesting changes in the geometry of the propagating front (Fig. 3A).

Most of the data from 11 to 5 Ma fall in a field drawn to represent a two million year duration of silicic volcanism at any point along the trend. The slope of the axis of this field indicates a propagation rate of 35 km/m.y. Projecting this trend westward would be consistent with the occurrence of Quaternary silicic tuffs erupted from the Tumalo volcanic center (Sarna-Wojcicki et al, 1989) and Recent silicic domes and flows near South Sister (Fig. 7). That the current focus of the trend is near South Sister has been previously suggested by Hill and Taylor (1989). On the other hand, projecting the propagation of silicic magmatism westward based on the best fit of 11-5 Ma data makes Newberry volcano, as well as all of the silicic domes of the western HLP younger than the trend, unless the duration of volcanism at any locus is increased to 3.5 m.y. We prefer to interpret the ages in the western HLP to reflect a slowing of propagation rate to ~15 km/m.y. In this view Newberry volcano may be included in the trend but silicic volcanism at the South Sister is not related. We do not necessarily interpret Newberry volcano to simply be the Recent focus of the HLP trend, but rather interpret it as reflecting the interaction of processes responsible for HLP and Cascade magmatism. In general, silicic volcanism has been widespread in the western HLP and adjacent Cascades in the last million years. The Three Sisters area is the most productive segment of the Cascades in Quaternary time (Sherrod and Smith, 1990) supporting the notion of interaction between the provinces. Helium isotope data for Newberry flank lavas suggest an affinity with the Cascade Range (Jordan and others, 1999). We therefore offer that the term “High Lava Plains trend” is less ambiguous than “Newberry trend” of “Newberry hotspot” track.
**Middle Miocene Silicic Magmatism**

We report new ages for three dacite domes, Horsehead Mountain (15.63 ± 0.03 Ma), Little Juniper Mountain (15.65 ± 0.04 Ma), and Jackass Butte (15.34 ± 0.19). Previous workers have reported ages of 15-16 Ma for four other silicic domes in the HLP and adjacent northern Basin and Range (Fig. 3A; 16.0 ± 0.4 Ma Drum Hill Dome is just south of map area). The middle Miocene silicic domes are distinct from rhyolites of the HLP age progression in that they are predominantly dacite and rhyodacite-rhyolite, and only rarely high-silica rhyolite (MacLean, 1994). These ages coincide with ages of widespread ash-flow volcanism in southeastern Oregon and north-central Nevada (Fig. 1), including McDermitt Caldera (as summarized by Pierce and Morgan, 1992).

This episode of silicic volcanism follows the initial eruptions of the Columbia River basalts (CRB) and Steens Basalts, and coincides with the most voluminous phase of the CRB, the Grande Ronde Basalt. Many workers interpreted the Steens and CRB eruptions as the result of the head of the Yellowstone plume impinging upon the base of the lithosphere (e.g. Brandon and Goles, 1988; Thompson and Gibson, 1991; Geist and Richards, 1993; Camp, 1994; Hooper, 1997). Pierce and Morgan (1992) interpret widespread silicic volcanism at this time to also reflect the plume head phase of the Yellowstone plume. If this is the case, then the occurrence of middle Miocene silicic volcanic rocks spanning ~130 km, across more than half of the length of the HLP, indicates the minimum extent of this plume head (radius of ~400 km if plume centered in south-central Idaho as argued below).
Timing of Basaltic Volcanism

Basalt ages have no clear systematic spatial variation (Fig. 7), but several generalizations can be made. The oldest post-Steens basalts dated in the east are older than those in the west. This may simply reflect the lack of deep exposure in the west. In the northern Basin and Range there is a coarse westward progression in the age of cessation of basaltic volcanism, with no Pliocene basalts east of ~121 °W (in the map area). Quaternary basalts are limited to the axis of the HLP, and are sparse in the central HLP (Fig. 3). There is some indication of episodes of province-wide basaltic volcanism, with possible episodes of increased activity at 7.5-7.8, 5.3-5.9, and 2-3 Ma (Fig. 7). In the eastern HLP there seems to be a real hiatus in activity between 5 and 3 Ma, while in the western HLP basaltic volcanism is more continuous (Fig. 7).

The 7.5-7.8 Ma episode is the most robust of the suggested episodes. Seven of the $^{40}$Ar/$^{39}$Ar basalt ages reported in this paper overlap within 2σ with an average of 7.60 Ma (not including the relatively imprecise 8.21 Ma age of HP-33 which also overlaps with 7.60 Ma). These samples span nearly 200 km of the HLP, suggesting a major regional event, perhaps related to an early phase of activity on the Brothers Fault Zone. The timing of this event corresponds with the initiation of the ongoing High Cascades phase of Cascades volcanism and tectonism (estimated initiation age of ~7.4 Ma; Priest, 1990). These tectonomagmatic events in the HLP and Cascade Arc coincide with a change in the azimuth of motion of the Pacific plate to a more northerly direction (Atwater and Stock, 1998). This change would have caused a more northerly motion of the Juan de Fuca plate and therefore more oblique subduction.

We envision these events as related by the following scenario: at around 7.6 Ma there was a change in the relative plate motions at the continental margin; this change led to initiation of a new phase of Cascade volcanism and tectonism, and deformation along the Brothers Fault
Zone to the east. Activation of the Brothers Fault Zone allowed more mafic magma to intrude and traverse the crust leading to widespread basaltic volcanism.

We also note that the 7.6 Ma event preceded a widespread and relatively voluminous episode of silicic volcanism (~7.1 Ma; focused in the central HLP) by about half a million years. These events may be related; where the Brothers Fault Zone intersected the wave of westward propagating volcanism, the additional flux of mantle-derived magmas into the crust caused anomalously high rates of production of rhyolitic melts, peaking at 7.0-7.2 Ma.

The 5.3-5.9 Ma episode is suggested by ages for basalts mostly in the central HLP and northern Basin and Range, including samples at Egli and Burma Rims at the extreme northern margin of the Basin and Range. The 2-3 Ma episode is suggested by widely distributed ages along the axis of the High Lava Plains. Included in this 2-3 Ma episode are several compositionally anomalous volcanic units. The basalt flow underlying the Grassy Butte cinder cone in the western HLP (128WHLP98) is 2.92 ± 0.06 Ma. This basalt is distinctive in that it contains coarse olivine, plagioclase, and clinopyroxene phenocrysts and is characterized by a unique combination of high MgO (8.31 wt%) and high incompatible element abundances (K₂O=1.52 wt%, Ba=1185 ppm). Also in this period was the eruption of the basaltic trachyandesite of Paiute Butte in the central HLP (2.37 ± 0.04 Ma). This unit is characterized by high abundances of K₂O (2.10 wt%) and Ba (1552 ppm) and low MgO (2.15 wt%), and is interpreted to reflect extreme crystal fractionation and recharge (MacLean, 1994; Streck and Grunder, 1999). It is also notable that the silicic volcano falling most off of the HLP trend, Iron Mountain, also occurs in this time interval (2.82 ± 0.04 Ma).

Quaternary basalts occur along about 50% of the length of the HLP, mostly near the eastern and western ends of the province. Late Quaternary basalts are restricted to Newberry
volcano, the area immediately east of Newberry, and Diamond Craters in the eastern HLP. Quaternary volcanism of the HLP can be viewed as an episode, equivalent to the earlier proposed episodes and, indeed, a continuation of the province-wide volcanism initiated between 2 and 3 Ma.

**Other Ages of Interest**

**Crack-in-the-Ground**

An age was determined for the Green Mountain basalt in which the feature Crack-in-the-Ground is developed. Pezzopane and Weldon (1993) and Jordan et al (2002) interpret this feature as resulting from faulting after emplacement of the lava. Pezzopane and Weldon (1993) infer an age of ~100 ka to estimate the deformation rate of the fault. We report an age of 740 ± 59 ka (25WHLP97) for this unit, significantly reducing the *minimum* deformation rate (nominally, 0.013 mm/yr based on 10 m of offset).

**Dry River Gorge**

Samples from the Dry River Gorge, the best exposed sequence of older basalts in the western HLP, range from 7.75 to 3.98 Ma (Fig. 8). The lowest exposed basaltic andesite flow yielded an age of 7.75 ± 0.12 Ma (2WHLP97), which is equivalent to the 7.76 ± 0.13 Ma (74WHLP98) age from the highest lavas of West Butte, a basaltic andesite shield volcano 13 km ENE of the gorge which may have been the source of these lavas. The sequence of lavas and tuffaceous sediments exposed in the Dry River Gorge is generally conformable up through the 5.58 Ma basaltic andesites, but the 3.98 Ma basaltic lava (8WHLP97) apparently flowed down a west-facing paleotopographic surface and into a canyon near the current position of the Dry River Gorge. Interestingly, this unit is characterized by the same unusual compositional (high
K$_2$O and Ba at high MgO) and mineralogical (abundant clinopyroxene phenocrysts) characteristics as 128WHLP98 described earlier; a composition identified only in the northwestern HLP.

**REGIONAL RELATIONSHIPS**

**High Lava Plains Magmatism and Regional Structure**

Basaltic, and less commonly silicic, vent systems are aligned parallel to local fault geometries. An example is the link between the East and Four Craters lava fields in the western HLP. The four cinder cones of the Four Craters field are aligned on a northwest-trend which projects to the vent complex of the East lava field. Although not contiguous on the surface, identical distinctive compositions of the East and Four Craters lava fields indicate that these lava fields are probably linked by dikes in the shallow subsurface, and the northwest-trending vent alignment is parallel to local fault patterns. These relationships indicate structural/tectonic control of magma conduit systems in the upper crust.

The pattern of migrating silicic volcanism is most clearly expressed in the HLP but extends ~150 km south into the Basin and Range. The extent of migrating silicic volcanism approximately corresponds to the distribution of the family of northwest-trending faults that includes the Brothers Fault Zone. This relationship suggests a genetic link between these structures and silicic magmatism. Comparison of faulting of rocks of similar age in the western and eastern HLP allows a test of the hypothesis that the Brothers Fault Zone has propagated across the HLP, possibly driving age progressive magmatism. Qualitative examination of faults cutting 7-8 Ma rocks and 2-3 Ma rocks across the HLP reveals that the spacing and apparent displacement are not grossly different in the east and the west in units of similar age. This
suggests the Brothers Fault Zone has not propagated, but rather has been active across the entire HLP since at least ~8 Ma (Klingsporn and Jordan, 2003).

The northern limit of the northwest-trending fault pattern produces a clearly defined lineament (Fig. 2). This lineament is parallel to, and immediately north of, both the axis of Pliocene and younger basalts and the belt of silicic domes of the HLP (Fig. 3). This confirms the relationship between structure and magma genesis, for which there are three potential explanations: (1) extension on these structures has caused decompression melting in the mantle which drove the magmatic system; (2) magmatism is a manifestation of advective and conductive heating which weakened the lithosphere controlling the distribution of structures; and (3) preexisting lithospheric structure exerted control on both structural development and magma genesis. Model 1 is rejected because extension rates have been relatively low and the magmatic belt does not coincide with maximum extension. Models 2 and 3 seem feasible and may act in concert.

What preexisting structures might have played a role in HLP deformation and magma genesis? The HLP lies to the south and east of the Klamath-Blue Mountains lineament (Fig. 9) and west of the craton margin, as indicated by the $^{87}\text{Sr}/^{86}\text{Sr}$-discontinuity (Fig. 1), indicating that it is underlain by Paleozoic and Mesozoic terranes accreted during Mesozoic time (Vallier, 1995). The boundaries between terranes (Fig. 9) are somewhat irregular and not generally parallel to the lineament that marks the northern margin of the HLP. One major structure that is parallel to this lineament is created by the John Day and Mitchell faults (Fig. 9). Traced further east, this lineament aligns with the northern termination of north-trending faults observed in the NE portion of figure 2. The Mitchell fault experienced normal and right-lateral strike-slip offset around 30 Ma, and other east-west trending right-lateral strike-slip faults in the Mitchell area
have a pre-Eocene displacement history (E. Taylor, personal communication). A similar long-lived major structure may underlie the northern HLP. Reactivation of such a structure may have localized deformation allowing basaltic magmas to more readily intrude and transit through the crust.

The High Lava Plains, Yellowstone-Snake River Plain System, and Middle Miocene Magmatism

Spatial, temporal, and petrologic characteristics suggest a link between the HLP and YSRP trends, and middle Miocene flood basalt volcanism (Columbia River basalts, Steens Basalts, and Northern Nevada Rift). Both the HLP and YSRP trends emerge from the axis of middle Miocene flood basalt vents (Fig. 1). The area from which the trends emerge is also a broad region of middle Miocene dacitic-rhyolitic volcanism that was penecontemporaneous with the flood basalts. Both the HLP and YSRP trends became well-defined at about 10-12 Ma. Both trends are also characterized by bimodal volcanism. Pliocene and younger basalts are found along the lengths of both trends, and in the intervening Owyhee Plateau.

As has been described by Pierce and Morgan (1992) and Smith and Braile (1994) there are significant differences in the two trends, notably in types and volumes of silicic eruptive products (HLP mostly domes; YSRP mostly ignimbrites), and structural setting. Typical ignimbrite volumes of the HLP are 100’s of km$^3$ versus 1000’s of km$^3$ along the YSRP. However, given the extreme contrast in the age, thickness, and composition of the lithosphere on which the trends are developed, even if both trends were caused by the exact same tectonic process it might have been manifested differently in the two areas.
We consider the HLP and YSRP trends, and middle Miocene mafic and silicic volcanism to be linked. That they are linked does not require that the HLP and YSRP trends be generated by the exact same process, as implied by the arguments of Hamilton (1989), but does suggest that the processes responsible for these trends may be related.

TECTONIC MODELS

Evaluation of previous models for the High Lava Plains

Previously proposed models for the origin of the High Lava Plains have called upon processes active in the adjacent provinces, including: (1) extension of the Basin and Range (Christiansen and McKee, 1978; Christiansen et al, 2002); (2) subduction-related processes in back of the Cascade arc (Carlson and Hart, 1987); and (3) mantle plume processes of the YSRP and Columbia River basalts (Draper, 1991), or ,more generally, (4) the after-effects of emplacement of the middle Miocene large igneous province, regardless of its origin (Humphreys et al, 2000).

Christiansen et al (2002) attribute the westward propagation of silicic magmatism to enhanced extension at the northern margin of the Basin and Range that propagated with extensional widening of the province. Christiansen (1993) proposed that crustal melting may have been driven by basal lithospheric shear melting with dynamic feedback. We concur that faulting and tectonic stress have been important in the controlling the transmission of magma into and through the crust. However, Brothers Fault Zone and associated faults do not appear to have propagated in the interval over which rhyolitic volcanism has migrated. Also, there is no clear mechanism to initiate mantle melting that drove the HLP magmatic system. Deformation in
the HLP was probably less than 5% extension in 7-8 m.y., not enough to drive a magmatic system.

Carlson and Hart (1987) developed a model in which steepening of the subducted slab under the Cascade arc and considerable post-middle Miocene extension of southeast Oregon, as inferred from paleomagnetic results suggesting block rotation of the Oregon Coast Range (e.g. Magill and Cox, 1981), led to voluminous middle Miocene magmatism and west-migrating magmatism across the HLP. However, there is little evidence for sudden steepening of the slab in this time frame. Also, the southeastern Oregon Basin and Range is characterized by widely spaced and steep faults allowing for limited extension. Wells and Heller (1988) propose that paleomagnetic results may, in part, be accounted for by the rotation of blocks within the Coast Range, eliminating the need for the excessive extension. In any case, the model of Carlson and Hart (1987) does not account for the relationship with the YSRP trend which we find compelling.

The model of Draper (1991) attributes the HLP trend to entrainment of Yellowstone plume head material in subduction-induced counter flow. This is consistent with the similarity between propagation rate and the plate convergence rate. However, this model would predict propagation of basaltic volcanism across the HLP, which has clearly not occurred. The model is also at odds with current models of plume head dynamics in which plumes flatten as they approach the lithosphere (Griffiths and Campbell, 1991), and are emplaced across areas as large as 2,000 km diameter in periods of a few million years (Duncan et al, 1997).

The model of Humphreys et al (2000) makes no comment on the origin of middle Miocene magmatism but suggests that decompression resulting from spreading and shearing of the residuum of this magmatism caused HLP and YSRP volcanism. That the HLP propagation
rate is, at least prior to 5 Ma, similar to the convergence rate at the Cascadia subduction zone supports this model in a general way. However, neither the HLP trend nor the YSRP trend depart from the area that was the source of the bulk of the middle Miocene magmatism (northeast Oregon and southeast Washington).

The Plume Model for the Yellowstone-Snake River Plain System

Because we consider the evidence for a link between the HLP and YSRP to be strong, we next consider the validity and implications of the primary model for the origin of the YSRP, a mantle plume. The interpretation that the YSRP system is the result of a mantle plume, and that the Columbia River and Steens Basalts represent the initiation of this plume has been developed and supported by many workers (e.g. Brandon and Goles, 1988; Pierce and Morgan, 1992; Smith and Braile, 1994; Hooper, 1997). However, there are a number of differences between the YSRP and oceanic hotspot systems, and there is considerable debate as to the applicability of the plume model for the origin of the YSRP (e.g. Hamilton, 1989; Christiansen et al, 2002).

If the YSRP trend is considered the result of plate motion over a stationary hotspot, generally interpreted as a mantle plume, the propagation rates described above are in conflict with the motion of the North American plate estimated by global plate motion models (Fig. 1), especially prior to 10 Ma (Jordan, 2001). Smith and Braile (1994) suggest that this conflict can be reconciled by considering extension along the length of the trend. However, Rodgers et al (1994) estimated extension immediately south of the Snake River Plain to be ~20%, nowhere close to the 50-300% required to reconcile the length of trend, as generally presented, to the plate motion models.
Another potential explanation for this inconsistency is the relative motion of hotspots. However, when the model of Steinberger and O’Connell (2000), which successfully predicts the relative motion of Pacific hotspots, is applied, the prediction is for a trend that is not much longer with a considerably more easterly azimuth (Steinberger, 2000). If Columbia River/Steens magmatism is interpreted to reflect the initiation of the plume, then the model of Steinberger and O’Connell (2000) also predicts a shorter track as they suggest that the upper plume conduit would be dragged with the plate for the first five million years.

The link between the YSRP and middle Miocene flood basalts is complicated by the off-track position of most of the basalt vents, though several models have been proposed to explain this (Thompson and Gibson, 1991; Geist and Richards, 1993; Camp, 1995; and Takahahshi et al, 1998). Thompson and Gibson (1991) proposed that the off-track position Columbia River basalt vents could be explained by melting being focused at the point where plume material was emplaced at shallow depths, under accreted terranes. Both plume head and conduit material could have flowed westward on basal lithospheric topography (e.g. Sleep, 1996) from the thick craton to the accreted terranes focusing magmatism at the craton margin. We note that this model could also explain the track-length problem, with the plume not effectively driving a magmatic system in the Precambrian lithosphere until it was sufficiently far away from the craton margin, ~10 Ma (Jordan, 2001).

The emplacement of even a modest sized (diameter of ~1000 km) flattened plume head centered under southern Idaho would have resulted in plume material being emplaced under the entire HLP, which could have played a role in subsequent magmatism. Critically, it could help explain why there is such a robust magmatic system in an area of limited extension.
**Origin of High Lava Plains Magmatism**

To summarize the preceding discussion, in evaluating the origin of the HLP and YSRP trends we see evidence for the significance of several different processes:

1. Pre-existing lithospheric structure – belt of silicic volcanism and young basaltic volcanism of HLP parallel to northern termination of NW-trending faults, all of which may be related to preexisting structure; and middle Miocene flood basalt vents concentrated at craton margin.

2. Contemporaneous regional tectonics and structural development – migrating silicic volcanism of the HLP-trend coincides with distribution of NW-trending fault system; apparent structural control of near-surface vent alignments; coincidence in time of ~7.6 Ma basaltic event with change in relative plate motion and the Cascade arc.

3. A mantle plume – middle Miocene flood basalt province (plume head); age progression of YSRP rhyolites, younger than ~10 Ma (plume conduit); preconditioning mantle under the HLP for subsequent magmatism (plume head).

The question remains, can any of these processes account for the age progression of silicic volcanism of the HLP? We envision several ways in which the HLP trend may be an indirect consequence of plume processes (Fig. 10). If a plume head was emplaced under the region it would have emplaced more, and hotter, plume head material under the eastern HLP (closer to the center) than the western HLP. Therefore the lag time to initiate crustal magmatism by advective and conductive heat transfer would have been greater in the west. This process might be limited to the HLP and northwestern Basin and Range because this is the only area where plume head material was emplaced under thin accreted lithosphere that also underwent subsequent extension.
Westward flow of plume material from under the craton could have driven a westward flow system that extended under the HLP and perhaps slowed with time (as suggested by the change in propagation rate of HLP magmatism). While we make the case above that subduction-induced counter-flow (Draper, 1991; Humphreys et al, 2000) was probably not the sole cause of HLP magmatism it could provide another mechanism for westward flow. Changes in the isotopic composition of primitive basalts of the HLP through time (Jordan et al, 2002b) may be evidence in support of westward flow of sublithospheric mantle.

CONCLUSIONS

Our new $^{40}\text{Ar}/^{39}\text{Ar}$ ages (laser total fusion, laser incremental heating, and furnace incremental heating) for 23 rhyolitic units of the High Lava Plains of central and southeastern Oregon confirm the previous interpretation that ages of silicic volcanism are progressively younger to the west. The rate of propagation of silicic volcanism was $\sim$35 km/m.y. from 10 to 5 Ma, and slowed to $\sim$15 km/m.y. from 5 Ma to Recent. The volumetric output of silicic volcanism also declined with time. The distribution of age-progressive silicic volcanism corresponds with the distribution of northwest-trending normal faults including the Brothers Fault Zone, but extending south to the Oregon-California border area. Our new $^{40}\text{Ar}/^{39}\text{Ar}$ ages for 32 basaltic units show that basaltic volcanism has occurred across the province since the middle-late Miocene with possible province-wide events at 7.5-7.8, 5.3-5.9, and 2-3 Ma, the latter event possibly continuing to the Recent. Pliocene and younger basalts form a N75°W-trending belt across the HLP coinciding with the most intense silicic volcanism, and immediately south of the northern terminus of northwest-trending faults.
The HLP trend crudely mirrors the northeast progression of silicic volcanism of the Snake River Plain to the Yellowstone Plateau. We consider these trends related because they co-originate from the axis of middle Miocene flood basalt volcanism and a region of diffuse silicic volcanism, both trends become organized between 12 and 10 Ma, both are bimodal, and there is a band of Pliocene and younger basaltic volcanism continuous across both trends. We recognize roles for preexisting lithospheric structure, contemporaneous structural development, and mantle plume processes in the origin of HLP magmatism. Therefore an important conclusion of this work is that rather than viewing the HLP trend as contradicting the mantle plume model for the YSRP trend and middle Miocene flood basalts, we suggest that the HLP trend is itself best understood as an indirect consequence of plume processes in which a plume head preconditions the lithosphere and subsequent tectonic events related to the Basin and Range and Cascade arc superimpose structural controls on the distribution of volcanism.

ACKNOWLEDGMENTS

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to Grunder, EAR-9218879 to Deino, and EAR-9725166 to Grunder, Duncan, and Dave Graham) and by a student research grant from the Geological Society of America to Jordan.

REFERENCES CITED


Figure 1. Map showing the tectonic setting of the Oregon High Lava Plains and Snake River Plain. Y=Yellowstone, M=McDermitt Caldera, NV=Newberry volcano, ML = Medicine Lake volcano. Pliocene and younger basalts of the HLP and YSRP are shaded gray. The bold dash-dot line shows the limit of Basin and Range extension. Curved lines cutting across the HLP and northwestern Basin and Range are isochrons of silicic volcanism, 10 Ma and 1 Ma are labeled. Encircled areas are caldera complexes of the YSRP and Owyhee region (after Pierce and Morgan, 1992); ages are given for some calderas to indicate age progression. Also shown are dike complexes which fed middle Miocene flood basalts; CRB, Columbia River basalt dikes; SB, Steens Basalt dikes; NNR, Northern Nevada Rift. Ticked lines across the YSRP are back-projected from Yellowstone to show the lengths of hotspot tracks predicted by global plate motion models plus extension (the northern line is based on Gripp and Gordon, 2002, extrapolated beyond the 6 Ma period of the model; middle is Müller et al, 1993 the southern is Duncan and Richards, 1991). The light dashed lines indicate approximate positions of the Sr-isotope discontinuities (after synthesis of Ernst, 1988); the 0.706 line is thought to broadly delineate the craton margin.

Figure 2 Map of faults of the High Lava Plains and northwestern Basin and Range after Walker and MacLeod (1991).

Figure 3. Maps of the High Lava Plains showing the distribution of (A) rhyolites and (B) basalts. Both maps show the locations of $^{40}\text{Ar}/^{39}\text{Ar}$ ages presented in this paper, as well as previous age determinations, where not superseded by new ages, from the summary of Fiebelkorn et al (1983), Hart et al (1984), Diggins et al (1990), Pickthorn and Sherrod (1990), and Johnson (1998). The 15.9 Ma age is weighted mean of two ages reported by Fiebelkorn et al (1983) for a rhyolite dome near Venator. Isochrons on the rhyolite age map are in 1 Ma increments, and are in part constrained by points off the map to the south. Abbreviations are: NC=Newberry Caldera, GB=Glass Butte, JR=Juniper Ridge, HM=Horeshed Mountain, IM=Iron Mountain, PaB=Palomino Butte, DB=Duck Butte, DRG=Dry River Gorge, WB=West Butte, PH=Pot Holes lava, DG=Devil's Garden lava, ER=Eglio Rim, EL=East lava, FC=Four Craters lava, BR=Burma Rim, AR=Abert Rim, PiB=Plute Butte, PJ=Poker Jim Ridge, WP=Wright's Point, DC=Diamond Craters.


Figure 5. Age probability diagrams for auxiliary plots of $^{40}\text{Ar}/^{39}\text{Ar}$ analytical data (moles $^{39}\text{Ar}$, percent radiogenic $^{40}\text{Ar}$ ($^{40}\text{Ar}^*$), Ca/K ratio, and a display of individual analyses) for laser total-fusion dating of coexisting obsidian glass and sanidine from sample HP-91-10 collected from Horse Mountain. The mode of each spectra is shown near the peak of the curves.
Error bars near the bottom represent the standard error of the weighted mean, both with (outer ticks) and without (inner ticks) error in J, the neutron fluence parameter.

Figure 6. Representative plateau and inverse isochron plots for incremental heating analyses performed at Oregon State University. Segments on plateau plots are shown with 2σ uncertainty. On isochron plots, shaded squares are data used to determine isochrons; < indicates atmospheric ratio (1/295.5); and gray range indicates 1σ uncertainty on the $^{36}$Ar /$^{40}$Ar -intercept. Figures show: (A) a well developed plateau and a concordant isochron with intercept within 2σ of atmospheric value, plateau age is accepted age; (B) plateau and isochron with $^{36}$Ar /$^{40}$Ar – intercept beyond 2σ of atmospheric ratio, isochron age accepted; (C) no plateau developed, but a good isochron indicates excess $^{40}$Ar, isochron age is accepted.

Figure 7. Plot of previous and new rhyolite and basalt ages versus distance along the HLP trend. Data are projected N15°E or S15°W to the axis of the N75°W-trending belt of Quaternary HLP basalts. Error bars indicate 1σ error. RST is the Rattlesnake Tuff. Sources of previous ages are those cited in Figure 3 plus ages for silicic tuffs erupted from the Tumalo volcanic center (TVC) from Sarna-Wojicki et al (1989). Also shown are Quaternary silicic lavas erupted at Newberry Volcano (NV) and South Sister (SS). Dashed line represents the eastern border of the Cascade Range. The yellow field indicates the silicic age progression as interpreted here: 35 km/m.y. from 10.5-5 to 5 Ma and 15 km/m.y. from 5 Ma to Recent, with a 2 m.y. duration of rhyolitic volcanism at any given point along the trend. The diagonally-ruled fields depict the episodes of province-wide enhanced basaltic volcanic events including the mapped distribution of Quaternary basalts.

Figure 8. Photo looking north and northeast across the older volcanic succession exposed in the Dry River Gorge in the northwestern HLP. Ages shown are discussed in text.

Figure 9. Map showing boundaries between accreted terranes in southwestern (Irwin, 1985) and northeastern (Vallier, 1995) Oregon; D=Dothan, WJ=Western Jurassic, PT=Western Paleozoic and Triassic, GR=Grindstone, IZ=Izee, BA=Baker, WA=Wallowa. Also shown is the Klamath-Blue Mountains lineament of (Riddihough et al, 1986), which is interpreted to mark the western margin of pre-Tertiary lithosphere. Distribution of pre-Tertiary rocks from Walker and MacLeod (1991).

Figure 10. Cartoon depicting the scenario envisioned to explain the distribution of middle Miocene basaltic vents, and trends of migrating silicic volcanism of the HLP and YSRP. Many map features shown are as explained in figure 1.
Figure 1.
Figure 2.
Figure 4.
Figure 5.
Figure 6.
Figure 7.
Figure 8.
Figure 9.
Figure 10.
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**NOTES:** bold, preferred age. *AFT, ash-flow tuff; R, rhyolite; B, basalt. † Bl, biotite; WR, whole rock. § L, laser; F, furnace.
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**NOTES:** bold, preferred age. * AFT, ash-flow tuff; R, rhyolite; RD, rhyodacite. † S, sanidine; P, plagioclase; O, obsidian. § age of HP-91-2 is uncertain due to bimodal nature of probability-age spectrum.
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NOTES: bold, preferred age. * B, basalt; AFT, ash-flow tuff; D, dacite. †WR, whole rock; GM, groundmass; P, plagioclase. § isochron MSWD exceeds critical value. ! Plateau based on selected steps, isochron based on all steps. ¥ two step plateau. # 40/36-intercept beyond atmospheric ratio, but poorly constrained by low 39/40-Ar.