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Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest

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[1] The Columbia Plateau, Oregon Plateau, Snake River Plain, and Northern Nevada Rift compose a single magmatic system containing all the essential characteristics ascribed to a mantle plume genesis. A mobile mantle is delineated by volcanic migrations, divisible into two types: (1) Rapid, radial migrations (~10–100 cm/yr) are associated with impingement and spreading of the Yellowstone plume head along the Chief Joseph, Steens Mountain–Picture Gorge, and Northern Nevada Rift magmatic trends from ~16.6 to 15.0 Ma. (2) Subsequent (post-15.0 Ma), slower migrations (1–5 cm/yr) are associated with shearing off of the plume head, generating the Snake River Plain hot spot track above the plume tail, and with westward asthenospheric drag of the plume head beneath the Oregon Plateau. The plume head provided a melt component to Imnaha and Grande Ronde Basalts. Depleted mantle lithosphere lying above the plume head provided a melt component to Steens Basalt and Picture Gorge Basalt and to younger eruptions of high-alumina olivine tholeiite. The plume head currently resides beneath a broad lithospheric swell, marked by young volcanism, high heat flow, and slow P wave travel times. The periphery of the plume head is delineated by the cratonic margin to the east, a gravity discontinuity and a set of wrinkle ridges to the north, and a prominent belt of young high-alumina olivine tholeiites and active volcanoes adjacent to the Cascade volcanic arc to the west. *INDEX TERMS:* 8121 Tectonophysics: Dynamics, convection currents and mantle plumes; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8499 Volcanology: General or miscellaneous; 3699 Mineralogy and Petrology: General or miscellaneous; 1214 Geodesy and Gravity: Geopotential theory and determination; *KEYWORDS:* mantle plume, Columbia River Basalt, Oregon

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1. Introduction

[2] The vast geological and geochemical database for volcanic rocks composing the Columbia Plateau, the Oregon Plateau, the Snake River Plain and the Northern Nevada Rift has led to the development of numerous tectonomagmatic models for each. Although distinct in character, we believe that each of these provinces is an inherent part of a single magmatic system. As such, genetic models developed for any one province should be constrained in part by their ability to interpret the geology of adjacent provinces. Understandably, however, the characteristic features of each have often led workers to prefer one model over those advocated by others for adjacent provinces.

[3] Most workers on the Columbia Plateau, for example, have embraced a mantle plume origin to account for the voluminous main phase of flood basalt eruption and its short duration, generating ~220,000 km^3 in ~1.5 Myr [e.g., *Brandon and Goles*, 1988; *Hooper and Hawkesworth*, 1993; *Takahahshi et al.*, 1998; *Hooper et al.*, 2002; *Camp et al.*, 2003]. In contrast, many workers on the Oregon Plateau have preferred a model of back arc extension, based on the association of crustal stretching and basaltic volcanism in the northern Basin and Range Province [e.g., *Eaton*, 1984; *Hart and Carlson*, 1987; *Carlson and Hart*, 1988]. Although several workers have advocated a mantle plume origin for the Snake River Plain [e.g., *Duncan*, 1982; *Draper*, 1991; *Pierce and Morgan*, 1992], such a model has recently been questioned by *Humphreys et al.* [2000] and *Christiansen et al.* [2002], based on the apparent control of both volcanism and rifting along preexisting structures, and on the lack of geophysical evidence for a plume-like structure beneath Yellowstone National Park. They suggest instead a shallow mantle origin for the hot spot track, which implies that the initial flood basalt eruptions in eastern Oregon may have also been generated in the upper mantle. Such an origin is advocated by *King and Anderson* [1995, 1998], who attribute the eruption of flood basalts to upper mantle

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convection along the boundary of two lithospheric plates of contrasting thickness. Left unresolved by a shallow mantle genesis, however, are the high $^3He/^4He$ ratios for basaltic rocks from both the Columbia Plateau and the Snake River Plain [*Dodson et al.*, 1997; D. Graham, personal communication, 2003] which have been used as robust indicators of a deep mantle source.

[4] This lack of consensus has divided workers into two primary camps: those supporting a mantle plume genesis, and those supporting nonplume interpretations. Individually, the magmatic provinces considered here have geologic features consistent with more than one interpretation. To apply separate models to each, however, is at odds with the geologic evidence that they are contemporaneous and genetically related. The application of nonplume interpretations becomes less convincing when applied to the system as a whole. Although the back arc spreading model, for example, is an attractive explanation for the Oregon Plateau, it is a less attractive model for the Columbia Plateau, where there is a lack of evidence for significant crustal extension, and for the Snake River Plain, which occurs well inland from the back arc area. As a group, however, this magmatic system appears to contain all the essential geologic features ascribed to a mantle plume origin in other terrestrial hot spots. We intend to illustrate these similarities and to develop a unifying model for the Columbia Plateau–Oregon Plateau–Snake River Plain–Northern Nevada Rift magmatic system based on field, petrochemical, and paleomagnetic data, and on the recognition of temporal and spatial magmatic trends in the eruption sequence.

2. Extending the Columbia River Flood Basalt Province Into Southeastern Oregon

[5] The Imnaha and overlying Grande Ronde Basalts represent the main phase (>90%) of flood basalt eruption on the Columbia Plateau, from ~16.1 to 15.0 Ma [*Hooper et al.*, 2002]. Recent mapping, combined with new XRF analyses and Ar-Ar dates, demonstrate that these lavas extend into southeastern Oregon [*Ferns et al.*, 1993a, 1993b; *Lees*, 1994; *Binger*, 1997; *Hooper et al.*, 2002; *Camp et al.*, 2003], where they thin and pinch out against Steens basalts on the Oregon Plateau.

[6] In contrast, the main phase of flood basalt eruption on the Oregon Plateau is slightly older, between ~16.6 and ~15.3 Ma [*Swisher et al.*, 1990; *Hooper et al.*, 2002]. The oldest of these lavas are well exposed at Steens Mountain, where *Johnson et al.* [1998] have subdivided the 900-m Steens basalt-type section into primitive lower flows which are chemically distinct from more evolved upper flows.

2.1. Distribution of Flood Basalt Units

[7] The approximate distribution of Steens, Imnaha, Grande Ronde Basalts, and coeval tholeiite lavas on the Oregon Plateau is illustrated in Figure 1. The southern and western extent of the flood basalt succession is similar to that of *Mankinen et al.* [1987] for Steens basalt, but the northeastern extent is expanded to include the recently mapped Imnaha and Grande Ronde Basalts. *Hooper et al.* [2002] showed that Imnaha Basalt north of Steens Mountain overlies the chemically distinct lowermost flows of Steens

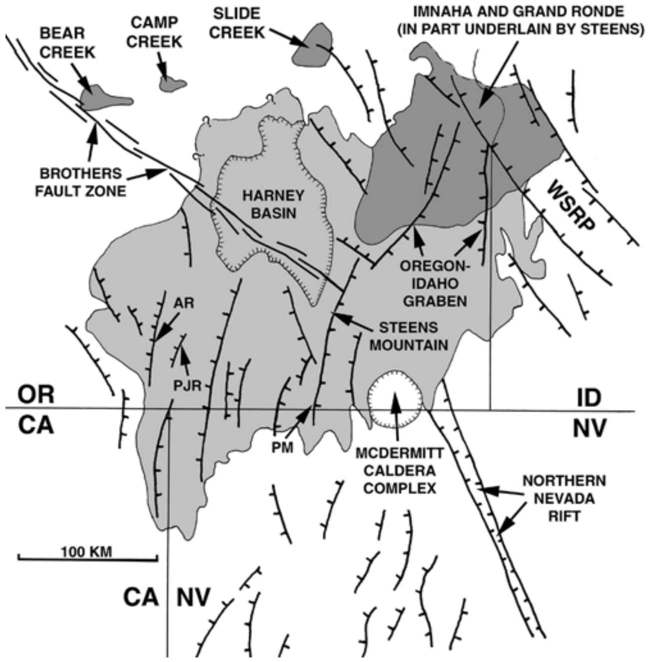

Figure 1. Approximate distribution of Miocene flood basalts in southeastern Oregon (~16.6–15.3 Ma). AR, Abert Rim; PJR, Poker Jim Ridge; PM, Pueblo Mountains, WSRP, Western Snake River Plain. See color version of this figure in the HTML.

basalt. *Camp et al.* [2003] suggested that these lavas may also be partly interbedded with the more evolved uppermost flows of Steens basalt.

[8] Nearly 650 m of Steens basalt is exposed at Poker Jim Ridge and Abert Rim, southwest of the Harney Basin (Figure 1). It seems likely that these lavas extend beneath the Harney Basin to connect with thick exposures to the east and southeast. Still farther to the east, ~300 m of Steens basalt exists in the Owyhee Mountains in Idaho [*Ekren et al.*, 1982], midway between the Oregon-Idaho graben and the Western Snake River Plain (WSRP) (Figure 1). Stratigraphic sections containing over 400 m of Imnaha and Grande Ronde Basalt on opposing sides of the WSRP [*Martin*, 1984; *Lees*, 1994] suggest that the succession may extend beneath the northern part of the WSRP near the Oregon-Idaho border.

[9] The flood basalt succession also includes limited exposures of the Bear Creek, Camp Creek, and Slide Creek basalts [*Brandon*, 1989] north of the Harney Basin (Figure 1). Some of these lavas have been modified by crustal contamination but appear to have been derived from the same mantle source as the Picture Gorge Basalt of the Columbia River Basalt Group [*Brandon et al.*, 1993]. The oldest of these lavas are identical in composition to Picture Gorge dikes exposed ~30 km northeast of the Camp Creek outcrops [*Goles*, 1986; *Brandon et al.*, 1993; *Brandon and Goles*, 1995]. The Picture Gorge lavas erupted at ~16.1 Ma [*Baksi*, 1989]. The overall age and stratigraphic data appears to suggest that the Oregon Plateau tholeiites become rapidly younger to the north, from the ~16.6 Ma Steens basalt exposed at Steens Mountain [*Swisher et al.*, 1990] to the Picture Gorge, Imnaha, and Grande Ronde

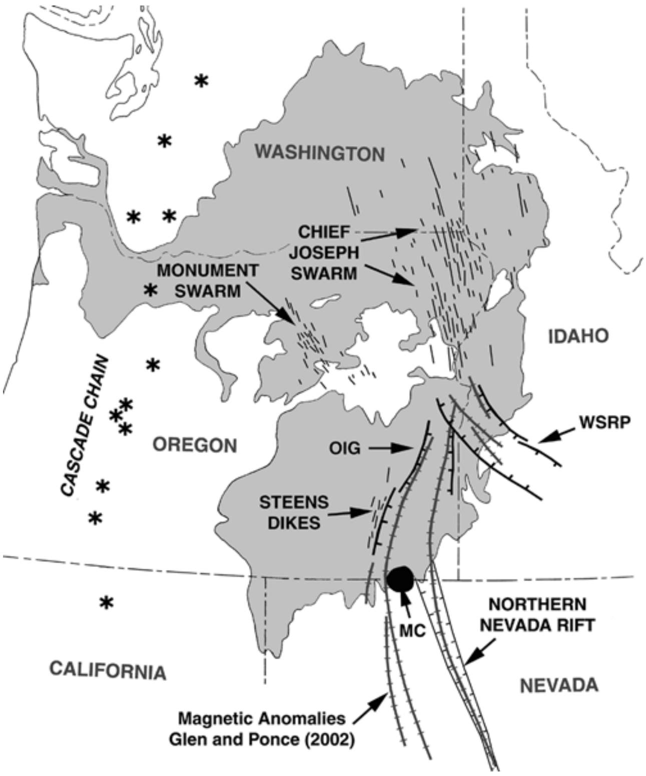

Figure 2. New distribution map for the Columbia River Flood Basalt Province. MC, McDermitt caldera; OIG, Oregon-Idaho graben; WSRP, Western Snake River Plain. See color version of this figure in the HTML.

Basalts exposed along the northern perimeter of the Oregon Plateau.

[10] The entire tholeiitic succession north of Steens Mountain, is deformed and unconformably overlain by thick accumulations of calc-alkaline to mildly alkaline volcanic rocks and intercalated sediments associated with Basin and Range extension. These include the ~15.0 to 13.1 Ma Owyhee basalts [*Bottomly and York*, 1976; *Brown and Petros*, 1985; *Ferns and Cummings*, 1992], which appear to be restricted to the Oregon-Idaho graben (Figure 1), and the ~13.5 to 10.1 Ma Keeney sequence [*Hooper et al.*, 2002], which is both more varied and more widespread, lying within the graben and across its east and west flanks [*Camp et al.*, 2003].

2.2. A New Distribution Map for the Columbia River Flood Basalt Province

[11] The stratigraphic relationships described above allow us to combine the distribution of lavas on the Oregon Plateau with those on the Columbia Plateau to produce a new distribution map for the Columbia River Flood Basalt Province (Figure 2). This map also incorporates contemporaneous lavas and dikes associated with the Northern Nevada Rift System, south of the McDermitt caldera. The flood basalts erupted from several sites, but mainly from dikes composing the Chief Joseph and Monumental swarms, and those exposed along the Northern Nevada Rift and the Steens and Pueblo Mountain escarpments. In addition, the curvilinear magnetic anomalies of *Glen and Ponce* [2002] appear to reflect a ~500-km-long system of dikes on opposing sides of the McDermitt caldera (Figure 2). These anomalies lie along the same trend as the Northern Nevada Rift and the Steens/Pueblo Mountain dikes, but they also extend farther to the north coincident with boundary faults associated with the Oregon-Idaho graben.

3. Pattern and Distribution of Dikes and Eruptive Centers

[12] *Ernst et al.* [1995] and *Magee and Head* [2001] contend that giant radiating dike swarms found on Earth, Venus, and Mars must have formed above mantle plumes or plume-like structures. Although such an origin is difficult to verify, it is worth noting that the Columbia River Basalt dikes are similar in scale and pattern to radiating swarms found on the other terrestrial planets (Figure 3). A slight variation in the overall orientation of the Chief Joseph and Monument dike swarms by 10–12° (Figure 3a) indicates a radial geometry. Using paleomagnetic data to correct for counterclockwise rotation, *Ernst and Buchan* [2003] demonstrated that the emplacement angle between these two trends was probably greater in the Miocene than today. They showed that the reconstructed orientation of the Chief Joseph swarm, the Monument swarm, and the Northern Nevada Rift triangulates to a focal point east of Steens Mountain, which may have been the central location of a mantle plume at ~17 Ma.

[13] This focal point also marks the site of the earliest flood basalt eruptions [*Hooper et al.*, 2002], the lavas of which are well exposed at Steens Mountain. This volcanic edifice has been described as shield volcano [*Mankenin et al.*, 1987], similar in size to Samodiva Mons in Figure 3b. Although faulted on its eastern flank, Steens Mountain maintains a shield-shape morphology to the west. The volcano's central vent is delineated by a circular magnetic anomaly near its crest [*Rytuba*, 1988]. Unlike the thick, simple flows typical of flood basalt volcanism, the lavas at Steens Mountain are relatively thin, complex flows typical of shield development [*Johnson et al.*, 1998]. Chemically, the lavas are tholeiitic but become mildly alkalic up section, a trend typical of the waning stages of shield evolution, as seen in Hawaii and elsewhere [e.g., *Clague*, 1987]. The location of a central volcanic edifice, similar to Steens Mountain, is a diagnostic feature of most radiating dike swarms on the terrestrial planets [e.g., *Grosfils and Head*, 1994].

[14] *Ernst et al.* [1995] have subdivided a large database of these radiating dike swarms on Earth and Venus into six geometric types. Types I and II show distinct fanning patterns. The McKenzie dike swarm of northern Canada typifies type I, with a continuous fan of dikes over an angle of ~100° [*Condie*, 2001]. The Columbia River Basalt dikes typify type II, with a gap between distinct radial subswarms in the Chief Joseph and Monument areas. The widely accepted model of *Baragar et al.* [1996] explains the difference in these radiating patterns. They suggested that numerous magma chambers typically develop above a mantle plume head, each responsible for generating its own subswarm of dikes. If the chambers are closely aligned there are no gaps between subswarms (i.e., type I); however, if they are more widely spaced, then gaps will appear, generating a type II distribution.

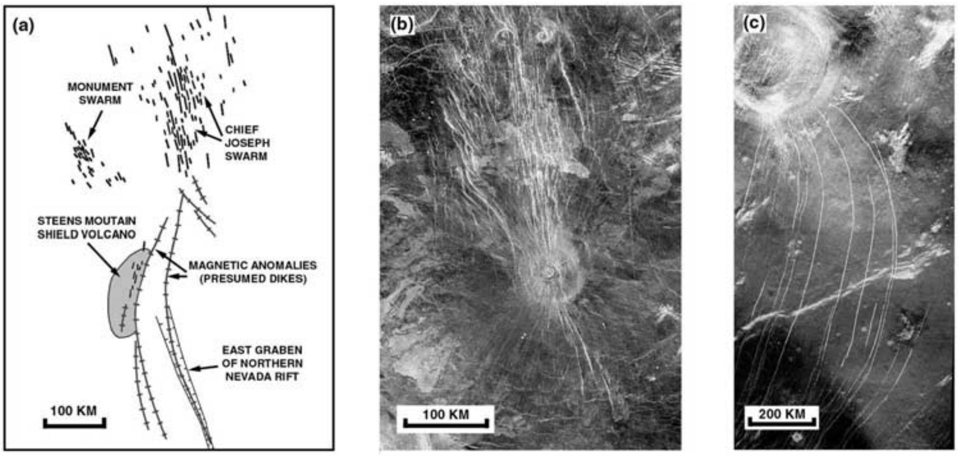

Figure 3. Comparison of the scale, spacing, and pattern of Columbia River Basalt dikes with typical, radiating graben, and fissure systems on Venus, which are thought to have formed by subsurface dike emplacement above mantle plume heads. (a) Columbia River Basalt dikes and the linear magnetic anomalies of *Glen and Ponce* [2002]. (b) Magellan radar image of supposed radiating dikes associated with the volcanic edifice of Samodiva Mons (13.5°N, 291.5°E). (c) Magellan radar image (16.5°S, 17.5°E) of long radial fractures extending from the outer edge of a large volcanic edifice (top left). See color version of this figure in the HTML.

[15] The radial distribution of types I and II suggests that they were injected from a point source, spreading outward with time. Such a scenario is consistent with limited AMS (anisotropic magnetic susceptibility) studies showing that lateral flow within individual radiating dikes is common [e.g., *Ernst and Baragar*, 1992]. A comprehensive AMS study of the Columbia River Basalt dikes has yet to be undertaken. However, the field and paleomagnetic studies described herein demonstrate that there has been a rapid migration of dike emplacement and volcanism outward from the focal point of southeastern Oregon, which we believe marks the Miocene site of plume impingement.

4. Migrating Magmatic Trends

[16] We recognize two main types of age-progressive trends in the Columbia Plateau–Oregon Plateau–Snake River Plain–Northern Nevada Rift magmatic system: (1) those with moderate migration rates, on a scale similar to estimated rates of mantle convection and plate motion (i.e., ~1–5 cm/yr), and (2) those with rapid migration rates, which are difficult to estimate, but significantly greater than rates of convection and plate motion (~10–100 cm/yr). The rapid rate migrations described herein are associated with the main phase of flood basalt eruption; those of moderate rate are defined by later eruptions emanating from the initial site of flood basalt activity in southeastern Oregon.

4.1. Rapid Rate Migrations Contemporaneous With Flood Basalt Volcanism

[17] Trends with rapid migration rates discussed herein are difficult to decipher accurately by isotopic dating, largely because the rate of motion is greater than can be determined within the error limits of Ar-Ar geochronology. The establishment of coherent petrochemical and paleomagnetic stratigraphies, however, allows us to recognize these migrations through the identification of regional lateral changes in time-stratigraphic units. We discuss here rapid migrations along three separate trends: the Chief Joseph trend, the Steens Mountain–Picture Gorge trend, and the Northern Nevada Rift trend.

4.1.1. Northward Migration Along the Chief Joseph Trend

[18] The main phase of flood basalt volcanism erupted over six paleomagnetic intervals (Figure 4). A rapid advance of volcanism from north of Steens Mountain through northeastern Oregon and into southeastern Washington is evident from (1) the northward migration and thickening of age-progressive Columbia River Basalt stratigraphic and paleomagnetic units and (2) the age-progressive northward migration of dikes composing the Chief Joseph dike swarm.

[19] Initial eruptions of Steens basalt began in southeastern Oregon during a reverse paleomagnetic interval (R_0) (Figure 4). Steens lavas continued to erupt through a magnetic transition, generating normally magnetized lavas (N_0) which appear to have their greatest thickness at the

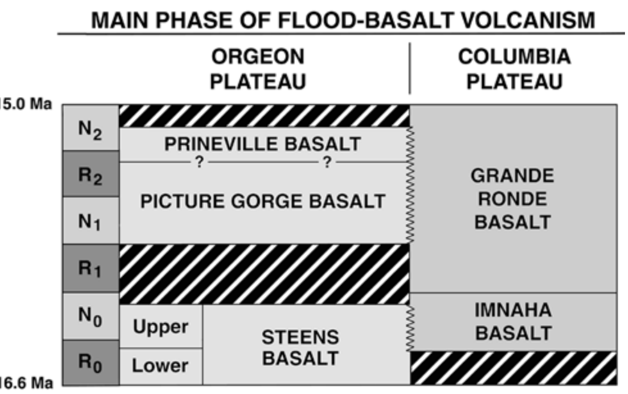

Figure 4. Magnetostratigraphy of flood basalt units on the Columbia and Oregon Plateaus during the main phase of flood basalt eruption (~16.6–15.0 Ma). See color version of this figure in the HTML.

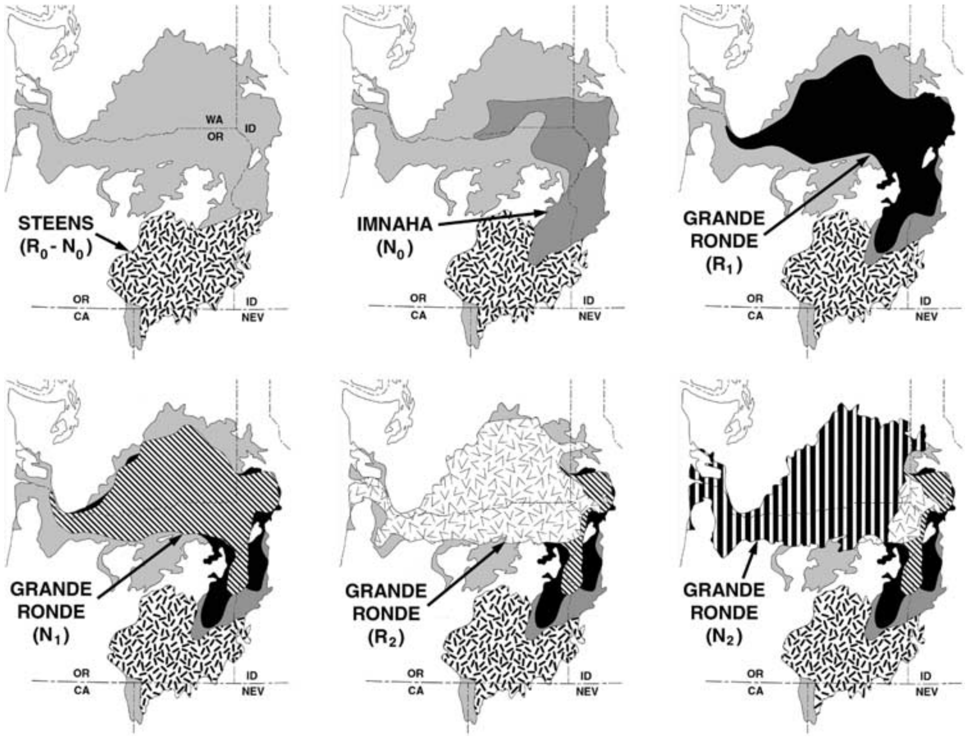

Figure 5. Age-progressive distribution of Steens basalt, Imnaha Basalt, and each of the Grande Ronde magnetostratigraphic units erupting from the Chief Joseph dike swarm. See color version of this figure in the HTML.

presumed shield volcano of Steens Mountain [*Mankinen et al.*, 1987]. The thickness of the transitional flows here indicates a rapid effusion rate during a very brief episode of eruption, perhaps only a few thousand or tens of thousands of years [*Mankinen et al.*, 1987].

[20] Most of the Imnaha Basalt flows have normal polarity. The exception is a few of the lowermost flows exposed at the southern end of the Chief Joseph dike swarm [*Hooper*, 1997]. North of Steens Mountain, Imnaha Basalt flows of unknown magnetic polarity overlie flows that are petrographically and chemically indistinguishable from lower Steens basalt [*Binger*, 1997; *Hooper et al.*, 2002]; however, these same flows appear to be interbedded with flows of upper Steens basalt [*Camp et al.*, 2003], suggesting that the bulk of the Imnaha lavas were erupted north of Steens Mountain during N_0 (Figure 4).

[21] The Imnaha succession thickens to the north, where is it is overlain by progressively younger paleomagnetic units of Grande Ronde Basalt (R_1-N_2) (Figure 4). Each magnetostratigraphic unit of Grande Ronde Basalt displays progressive offlap to the north, each thickening to the north as well (Figure 5). This pattern of northward migrating offlap and thickening has been attributed to a combination of (1) progressive uplift generating a north tilting paleoslope, and (2) a northward migration of flood basalt eruptions with advancing time [*Camp*, 1995; *Camp et al.*, 2003]. The latter is demonstrated by a greater number of Imnaha dikes in the southern part of the Chief Joseph swarm, progressively more Grande Ronde dikes in the north, and restriction of the youngest Columbia River Basalt dikes (Wanapum and Saddle Mountains Basalts) to the far north of the dike swarm [*Tolan et al.*, 1989; *Camp*, 1995].

4.1.2. Northward Migration Along the Steens Mountain–Picture Gorge Trend

[22] The stratigraphic boundary between the chemically defined Lower and Upper Steens basalts [*Binger*, 1997; *Johnson et al.*, 1998] occurs very near the Steens paleomagnetic transition of *Mankinen et al.* [1987], thus providing a potential chemical signature to differentiate the R_0 lava sequence from the upper N_0 sequence. The geochemical correlation of lower Steens flows in the Malheur Gorge area, northwest of the Oregon-Idaho graben (Figure 1) [*Binger*, 1997; *Hooper et al.*, 2002; *Hooper*, 2004] suggests that these lavas erupted during R_0. Petrochemically identical Lower Steens lavas have been mapped in the Owyhee Mountains of western Idaho [*Ekren et al.*, 1982; V. E. Camp and M. E. Ross, unpublished data, 2003], consistent with the identification of the R_0-N_0 transition in the same area [*Mankinen et al.*, 1987]. Although Steens basalt has not been recognized farther to the north, a few R_0 lavas have been identified at the base of the Imnaha Basalt stratigraphy immediately north of the WSRP [*Hooper*, 1997]. Using these chemical and paleomagnetic observations, together with the paleomagnetic data of *Mankinen et al.* [1987], *Tolan et al.* [1989], *Hooper* [1997], *Bogue et al.* [2000], and *Glen and Ponce* [2002], we delimit in Figure 6 both the restricted areal extent of the oldest lavas and dikes in the province (R_0), and the southernmost extent of the youngest lavas and dikes of the main phase of eruption (N_2). Paleomagnetic mapping on the Columbia Plateau [e.g., *Swanson et al.*, 1981; *Tolan et al.*, 1989] gives us a great deal of confidence in the accuracy of the N_2 geographic limit. Because of the stratigraphic and structural complexities on the Oregon Plateau, the R_0 geographic

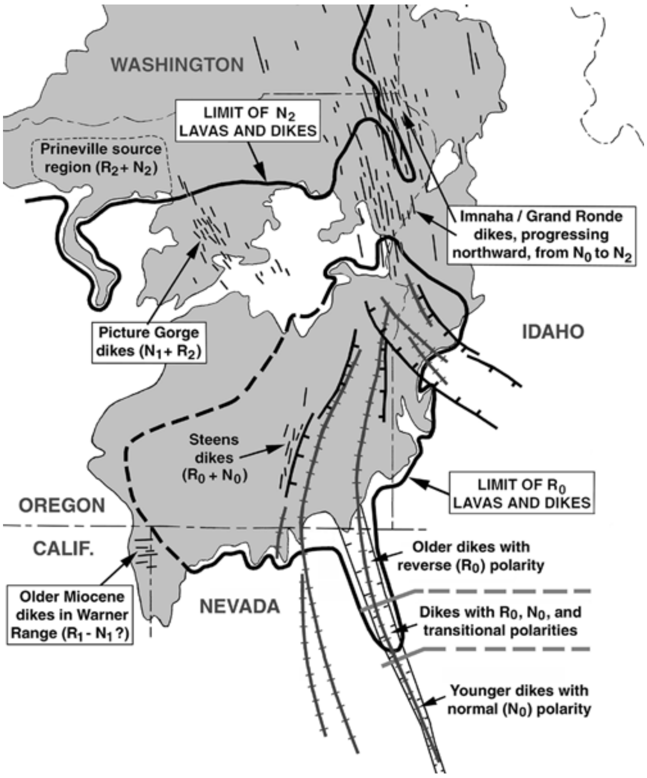

Figure 6. Map showing (1) the eruption sites of Columbia River Basalt volcanism, (2) the restricted areal extent of R_0 lavas and dikes, and (3) the southern extent of N_2 lavas and dikes associated with the main phase of eruption. Paleomagnetic boundaries are derived from chemical correlations and the paleomagnetic data of *Mankinen et al.* [1987], *Tolan et al.* [1989], *Hooper* [1997], *Bogue et al.* [2000], and *Glen and Ponce* [2002]. The northward migration of dikes along the Chief Joseph trend is described by *Camp* [1995]. See text for a specific discussion of dike ages along the Northern Nevada Rift. The east-west dikes depicted in northeastern California occur in the lower half of the basalt stratigraphy exposed in the Warner Range. These appear to correspond with a 335-m section of olivine basalt dated at ~15.7 Ma [*Duffield and McKee*, 1986]. See color version of this figure in the HTML.

limit is less well constrained, but consistent with a broad base of paleomagnetic, petrochemical, and geochronological data.

[23] If the model of a propagating plume head is correct, then the migration of volcanism should not be restricted to the Chief Joseph swarm, but it should instead be evident in all coeval dike swarms radiating from the focal point of *Ernst and Buchan* [2003] near Steens Mountain. Indeed, the existing paleomagnetic and age data (Figure 6) indicate a northward progression of discontinuous eruptions that began with Steens Basalt (R_0-N_0), migrating with an apparent hiatus (R_1) in activity, to younger eruptions of Picture Gorge Basalt (N_1-R_2) in the Monument swarm to the north, and to the still younger eruptions of Prineville Basalt (R_2-N_2) from an unknown source, either west or north of the Monument swarm (Figures 4 and 6). Adding support to the Steens–Picture Gorge migration are Pb, Nd, and Sr isotopic data demonstrating that both Steens and Picture Gorge basalts share a common mantle source [*Carlson*, 1984; *Carlson and Hart*, 1988; *Brandon and Goles*, 1995].

[24] Unlike the Chief Joseph migration, this migration appears to be spatially and temporally discontinuous. However, it is difficult to assess the degree of this discontinuity due to the burial of both Steens Basalt south of the Harney Basin, and the Picture Gorge-equivalent Bear Creek and Camp Creek Basalts [*Brandon et al.*, 1993] north of the Harney basin. Nevertheless, if the *Baragar et al.* [1996] model is correct, one might expect a hiatus in activity to occur between localized magma chambers forming above an outward radiating mantle plume head. The slight angular difference between the Chief Joseph and Steens–Picture Gorge trends, together with the northward younging along both trends, at similar migration rates, is consistent with such a model.

[25] The simultaneous eruption of basalt along these two trends is evident in interbedded relationships. During N_1 and R_2 time, Grande Ronde lavas poured to the west, down an evolving paleoslope, to interfinger with Picture Gorge lavas erupting from the Monument dike swarm [*Nathan and Fruchter*, 1974]. Later, as N_2 lavas were erupting from the far north of the Chief Joseph swarm, they flowed to the west to interfinger with Prineville basalt erupting simultaneously at an unknown site near the Washington-Oregon border [*Bailey*, 1989] (Figure 6).

4.1.3. Southward Migration Along the East Graben of the Northern Nevada Rift

[26] Rifting along the east graben of the Northern Nevada Rift occurred mostly between ~16.5 and 15.0 Ma, contemporaneous with the main phase of flood basalt volcanism. *John et al.* [2000] suggested that rifting began with thermal bulging and shallow intrusion of mafic magma near McDermitt, followed by rapid propagation to the south. The amount of extension was generally less than a few kilometers, with the widest part of the rift near McDermitt, consistent with southward propagation.

[27] A rapid migration of eruptive products is supported by the paleomagnetic data. The R_0-N_0 magnetic transition appears to be recorded in a lava section exposed near the Sheep Creek Range, in the central part of the rift. Dikes north of the Sheep Creek Range generally have magnetizations of reverse polarity, whereas those farther south have normal polarity, and those in the central part of the rift yield normal, reverse, and transitional polarities [*Bogue et al.*, 2000; *Glen and Ponce*, 2002] (Figure 6).

[28] The rift zone lacks a coherent, laterally extensive basalt stratigraphy to accurately assess a southward migration, and the existing age data for the lava flows are inconclusive [*John et al.*, 2000]. However, Ar-Ar analyses for the mafic dikes [*John et al.*, 2000; *John and Wrucke*, 2003] are consistent with such a progression, yielding ages of 16.57 ± 0.4 Ma and 16.30 ± 0.09 in the north (northern Shoshone Range), and 15.9 ± 0.1 Ma, 15.64 ± 0.11 Ma, 15.31 ± 0.09 Ma, and 15.46 ± 0.6 Ma in the south (Roberts Mountains and Cortez Range) (D. A. John, written communication, 2004). The combined data suggest that the Northern Nevada Rift evolved rapidly as a southward propagating rift zone, coeval with northward

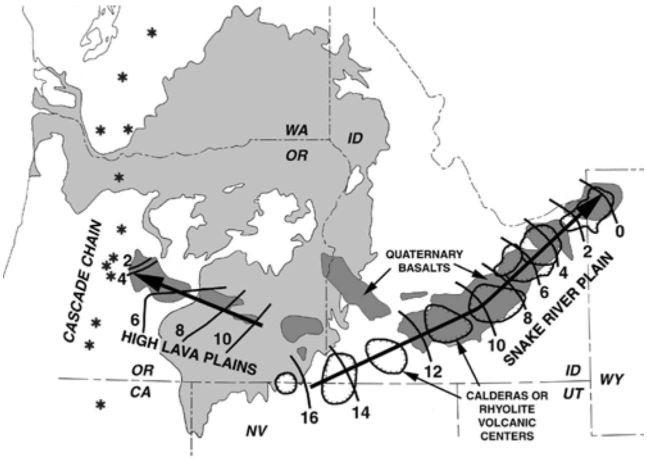

Figure 7. Moderate rate migrations of rhyolite magmatism associated with the Oregon High Lava Plains and the Snake River Plain hot spot track. Distribution of Quaternary basalt outcrops are from *Christiansen et al.* [2002]. Isochrons for rhyolitic volcanism are from *Jordan et al.* [2002] and *Christiansen et al.* [2002]. See color version of this figure in the HTML.

propagation along the Chief Joseph and Monument dike swarms.

4.2. Moderate Rate Migrations After the Flood Basalt Event

[29] Two volcanic migrations are well recognized in the Pacific Northwest, both of which originate in eastern Oregon and involve the progressive eruption of rhyolite along linear trends: (1) to the northeast, along the Snake River Plain hot spot track, and (2) to the west-northwest, along the Oregon High Lava Plains and Brothers fault zone (Figure 7).

4.2.1. Migration of Rhyolitic Volcanism

[30] The Snake River Plain hot spot track is marked by a series of large calderas and rhyolitic centers, overlain in part by younger Snake River Plain basalts. The calderas become progressively younger from the McDermitt caldera complex, at 16.1 Ma, to Yellowstone National Park, where the last caldera-forming eruption occurred at ~0.6 Ma. Although this progressive trend has been attributed to overriding of a stationary plume by the North American plate [e.g., *Pierce and Morgan*, 1992], this classic hot spot model was questioned by *Humphreys and Dueker* [1994], *Saltzer and Humphreys* [1997], and *Christiansen et al.* [2002], largely based on the lack of teleseismic evidence for a deep mantle source. More recent seismic imaging, however, is now able to resolve a low-velocity conduit beneath Yellowstone, extending to a depth of 600 km [*Smith*, 2004].

[31] The Oregon High Lava Plains represents is a complementary system of propagating rhyolite eruptions contemporaneous with the Snake River Plain propagation since ~10 Ma, but in an opposite direction. This bimodal province contains both basalts and rhyolites concentrated along the northwest trending Brothers fault zone [*Lawrence*, 1976; *Jordan et al.*, 2002]. The northwest direction of rhyolite propagation is clearly incompatible with plate motion above a stationary plume, and several workers have used this observation as an additional argument against a hot spot model for the Snake River Plain [e.g., *Hamilton*, 1989; *Christiansen et al.*, 2002].

4.2.2. Migration of Mafic Volcanism

[32] The eruption of tholeiitic basalts did not cease at the end of the main phase of flood basalt volcanism. Post-15.0 Ma eruptions at the northern end of the Chief Joseph dike swarm in southeast Washington generated periodic, voluminous flood basalts of the Wanapum and Saddle Mountains Formations. In contrast, the post-15.0 Ma period south of the Chief Joseph swarm was marked in part by the eruption of low volume, but widely disseminated tholeiitic basalt across the breadth of the northern Basin and Range and Snake River Plain. *Hart et al.* [1984] have subdivided these lavas into two main types: high-alumina olivine tholeiite (HAOT) and Snake River Plain olivine tholeiite (SROT). HAOTs are more primitive and more depleted than the SROTs, having higher Mg numbers and Ni contents, and lower incompatible element concentrations [*Hart et al.*, 1984].

[33] The SROTs are restricted to areas lying above the Precambrian craton (i.e., east of the 0.706 Sr isopleth of Figure 8), whereas the HAOTs are largely restricted to areas lying above transitional-to-oceanic lithosphere west of the 0.706 Sr isopleth. Lavas that are transitional between these two end-member types are concentrated above transitional

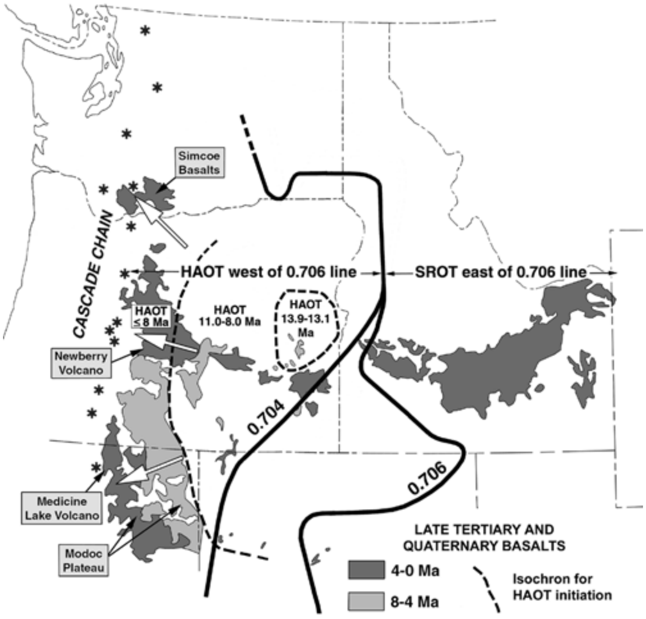

Figure 8. Distribution of Late Tertiary to Quaternary basalts, derived from *Hart et al.* [1984], *Jordan et al.* [2002], and *Christiansen et al.* [2002]. The 0.704 and 0.706 lines correspond with the initial $^{87}Sr/^{86}Sr$ isopleths of *Armstrong et al.* [1977], *Kistler and Peterman* [1978], and *Leeman et al.* [1992]. HAOT and SROT are restricted to areas lying west and east of the 0.706 line, respectively. Isocrhons (dashed lines) showing a east to west migration of initial HAOT eruptions are based the field mapping, chemical correlations, and chronological data of *Hart et al.* [1984], *Ferns et al.* [1993a], *Christiansen et al.* [2002], *Jordan et al.* [2002], *Hooper et al.* [2002], and *Camp et al.* [2003]. See color version of this figure in the HTML.

lithosphere lying between the 0.704 and 0.706 lines [*Hart et al.*, 1984]. These restricted locations are compatible with trace element and isotope data suggesting that the SROTs and HAOTs were derived from enriched and depleted mantle, respectively [*Carlson and Hart*, 1988; *Lum et al.*, 1989].

[34] Figure 8 illustrates the map distribution of the youngest of these tholeiitic basalts, with ages $\leq$8 Ma, compiled from *Christiansen et al.* [2002]. The greatest volumes of the youngest lavas are concentrated in two regions: (1) along the Snake River Plain hot spot track, and (2) along a broad, north-south belt lying east of the southern Cascades. A smaller volume is concentrated along the Brothers fault zone, and in scattered outcrops in the central part of the northern Basin and Range Province.

[35] The dashed contours in Figure 8 are isochrons for the oldest HAOT outcrops (>8.0 Ma), delineating the age of initial HAOT eruptions into three specific belts across the Oregon Plateau. The oldest post-15.0 Ma HAOT outcrops yet recognized occur in east central Oregon. These have been mapped as the Tims Peak basalts, a group of highly deformed lavas lying unconformably above equally deformed Steens and Imnaha basalts [*Ferns et al.*, 1993a; *Hooper et al.*, 2002; *Camp et al.*, 2003]. Four Ar-Ar ages from two chemical types of Tims Peak basalt vary from 13.9 ± 0.2 to 13.1 ± 0.2 Ma [*Hooper et al.*, 2002]. The oldest dates farther to the west and south demonstrate that the inception of HAOT volcanism was between 11.0 and 8.0 Ma. Still farther to the west, the initial HAOT eruptions are no older than 8.0 Ma. Within this westernmost zone, *Hart et al.* [1984] and *Christiansen et al.* [2002] recognize a systematic westward younging of HAOT outcrops across northeastern California and adjacent Oregon, with ages divisible into two belts, 8–4 Ma in the east and <4 Ma against the Cascade volcanic arc to the west.

[36] HAOT outcrops <8.0 Ma are scattered, nevertheless, across the entire Oregon Plateau, leading *Hart et al.* [1984] to correctly conclude that there is no evidence of an orderly geographic progression of HAOT ages. However, the new Ar-Ar ages for Tims Peak basalt, together with a closer examination of the existing age data, demonstrate that (1) the inception of HAOT volcanism (post-15 Ma) migrated from east to west across the Oregon Plateau, and (2) the greatest volume of HAOT occurs to the west, adjacent to the southern Cascades, in the same belt that has the youngest initial eruptions of HAOT (<8.0 Ma).

5. Discussion

[37] There has been much recent debate on the nature, and indeed the very existence, of mantle plumes on Earth and the terrestrial planets [e.g., *Anderson*, 2003]. *Hamilton* [2003] has suggested that the plume model is conjecture, feebly based, and that its widespread acceptance has retarded consideration of alternative mechanisms. However, several nonplume interpretations have been considered for flood basalt volcanism in the Pacific Northwest. These include (1) back arc extension [*Eaton*, 1984; *Hart and Carlson*, 1987; *Carlson and Hart*, 1987], (2) a meteorite impact [*Alt et al.*, 1988], (3) upper mantle convection induced by torsional stress of the plate interior [*Dickinson*, 1997], and (4) upper mantle convection along the edge of a continental plate boundary [*King and Anderson*, 1995, 1998]. Several other alternative mechanisms have been proposed for the Snake River Plain. These include (1) an eastward propagating rift [*Hamilton*, 1987], (2) volcanism along a localized crustal flaw [*Eaton et al.*, 1975], (3) plate interaction along a transform boundary zone at the northern margin of the Great Basin [*Christiansen and McKee*, 1978], (4) divergent upper mantle flow around a residuum body [*Humphreys et al.*, 2000], and (5) thermal feedback between lithospheric extension and shear melting generating a self-sustaining melting anomaly [*Christiansen et al.*, 2002].

[38] Of the alternative mechanisms for flood basalt volcanism, the boundary edge model of *King and Anderson* [1998] provides an elegant explanation for the location of the Chief Joseph dike swarm against the Precambrian boundary of North America. This model, however, is incompatible with the rifting and volcanism that occurs across the cratonic margin along the Northern Nevada Rift (Figure 9). None of the nonplume alternatives resolves the unequivocal geologic evidence of rapid volcanic migrations from an apparent focal point in southeastern Oregon. Many of these models appear adequate in explaining the geologic features of any one province; however, they are generally inadequate in explaining the geologic evolution of coeval, adjacent provinces composing the magmatic system as a whole.

[39] Although we are in agreement with those who caution against the wholesale acceptance of the mantle plume paradigm, we nevertheless believe a plume genesis provides (1) a unifying model for the entire system that is lacking in nonplume interpretations, (2) a rational mechanism to account for rapid, radiating volcanic migrations, also lacking in nonplume interpretations, and (3) a more reasonable explanation for the sudden outburst, and short duration ($\sim$1.5 Myr) of the main phase of flood basalt volcanism.

5.1. Arrival and Rapid Spreading of the Mantle Plume Head ($\sim$16.6–15.0 Ma)

[40] The broadly accepted idea that flood basalt provinces are generated above starting plume heads, and that hot spot tracks are generated above the feeding plume tails [e.g., *Morgan*, 1981; *Richards et al.*, 1989; *Griffiths and Campbell*, 1991; *Hill et al.*, 1992; *Weinberg*, 1997], is consistent with the temporal and spatial association of the Columbia River Flood Basalt Province and the Snake River Plain. Working separately in different provinces, with dissimilar sets of data, *Draper* [1991], *Pierce and Morgan* [1992], *Parsons et al.* [1994], and *Camp et al.* [2003] reached similar conclusions: 1) the onset of Columbia River flood basalt volcanism accompanied arrival of the Yellowstone plume head, and 2) the plume head was sheared off by the thick lithospheric roots of the westward moving Precambrian craton shortly after its emplacement, thus allowing the plume tail to generate a hot spot track through the overriding craton.

5.1.1. Localized Mantle Flow

[41] Geophysical considerations demonstrate that when plume heads pond at the base of heterogeneous lithosphere, they spread preferentially "uphill" beneath thin lithosphere, often forming distinct pathways of concentrated mantle flow [*Thompson and Gibson*, 1991; *Sleep*, 1997; *Ebinger and*

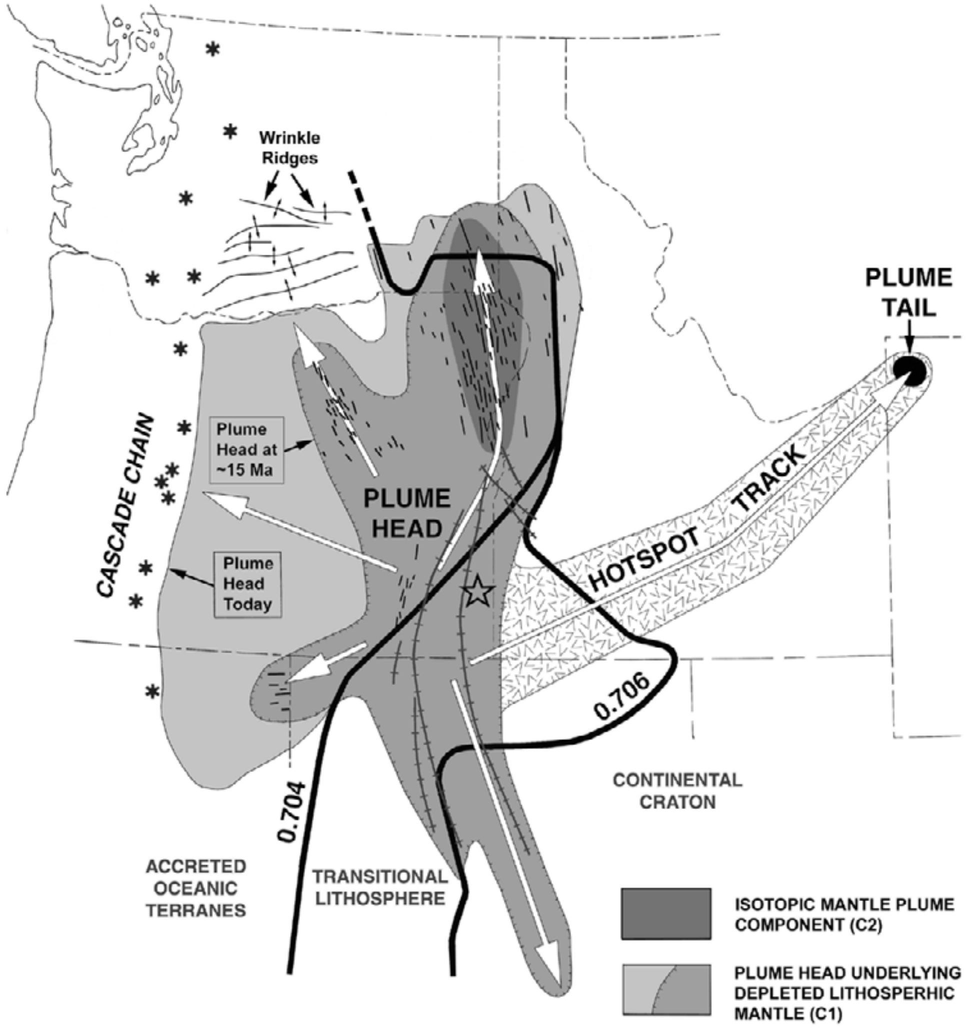

Figure 9. Two-stage spreading model of the Yellowstone mantle plume head, showing (1) the approximate position of the plume head after impingement and rapid spreading (~15.0 Ma) and (2) its approximate position today after moderate rate spreading associated with asthenospheric drag and counterflow above the subducting plate. The short lines located above the area of first-stage spreading are surficial dikes, and the longer curvilinear lines are the linear magnetic anomalies of *Glen and Ponce* [2002], which are thought to be buried intrusions or keel dikes. The open star near the Oregon-Idaho border corresponds with the focus of the dike swarms after correcting for block rotation [*Ernst and Buchan*, 2003]. Wrinkle ridges of the Yakima fold belt in south central Washington [*Reidel et al.*, 1989] appear to be the product of thin-skinned deformation [*Watters*, 1989], which *Mege and Ernst* [2001] attribute to peripheral compressive stress at the uplifted edge of plume emplacement. The approximate boundaries of distinct lithospheric domains beneath the plume head are delineated by the $^{87}Sr/^{86}Sr$ isopleths of *Armstrong et al.* [1977], *Kistler and Peterman* [1978], and *Leeman et al.* [1992]. C1 and C2 correspond to the mantle source compositions described in the text. See color version of this figure in the HTML.

Sleep, 1998]. Such channelized flow is consistent with the observation of *Baragar et al.* [1996] that plume-derived dike systems occur along linear trends propagating outward, often into distinct subswarms. The evidence for volcanic migrations described herein leads us to conclude that the Yellowstone mantle plume head arrived in SE Oregon at ~16.6 Ma, rapidly spreading in all directions, but preferentially to the north beneath thin lithosphere of the accreted oceanic terranes. Here, the plume head bifurcated into two main pathways of rapid mantle flow reflected in the age-progressive Chief Joseph trend, and in the discontinuous but equally rapid Steens Mountain–Picture Gorge trend (Figure 9). The plume head also spread rapidly to the south, beneath transitional and thicker lithosphere, producing shallow intrusions and a much smaller volume of lava along the southward propagating Northern Nevada Rift.

[42] The greatest volume of flood basalt was generated beneath the thinnest lithosphere, where the plume head banked up rapidly against the westward moving cratonic margin. Thickening of the plume head led to its rapid rise

and decompressional partial melting along the Chief Joseph dike swarm. Here, the surface manifestation of thermally driven uplift was reflected in the development of a regional paleoslope that advanced rapidly to the north, coeval with the northward migration of dike emplacement [*Camp*, 1995].

5.1.2. Mantle Source

[43] Isotopic studies using $^{207}Pb/^{206}Pb/^{204}Pb$, $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, and $\delta^{18}O$ systematics, demonstrate that the Steens and Picture Gorge basalts were derived from a depleted mantle source, the C1 component, modified slightly, either by the addition of subducted pelagic sediment [*Carlson*, 1984; *Carlson and Hart*, 1988] or by crustal contamination [*Brandon et al.*, 1993]. In contrast, many Imnaha Basalts and the least evolved Grande Ronde lavas were derived from a different isotopic component (C2), originally defined by *Carlson* [1984] as depleted mantle with ~2% subducted sediment. However, *Brandon and Goles* [1988, 1995] and *Hooper and Hawkesworth* [1993] proposed that C2 is a plume component, consistent with the high $^{3}He/^{4}He$ ratios for Imnaha Basalt described by *Dodson et al.* [1997]. Thus basalts along Chief Joseph trend are the only lavas yet identified as having a mantle plume signature.

[44] The depleted C1 mantle source for Steens and Picture Gorge lavas would be consistent with oceanic mantle at the base of the accreted terranes. Although decompressional melting of this depleted mantle could be induced by a large amount of crustal extension, it is unlikely that voluminous flood basalts could be generated without the addition of significant heat [*McKenzie and Bickle*, 1988; *White and McKenzie*, 1989]. We therefore conclude that the volcanic migrations along the Steens Mountain–Picture Gorge and Northern Nevada Rift volcanic trends resulted from progressive melting of the lithospheric mantle (C1) lying above the rapidly spreading hot plume head (C2). Unlike the Imnaha and Grande Ronde lavas, the lack of a plume component in the Steens and Picture Gorge lavas may be attributed to lateral spreading unaccompanied by the supposed deformation, rapid ascent, and melting of the plume head closer to the cratonic margin.

5.2. Later (Post-15.0 Ma) Spreading of the Mantle Plume Head

[45] Rapid migrations of the spreading plume head are distinct from the subsequent, much slower migrations along the Snake River Plain hot spot track and the High Lava Plains. We concur with other workers that the Snake River Plain trend resulted from overriding of the plume tail by the southwest migrating North American Plate [*Anders et al.*, 1989; *Westaway*, 1989; *Rodgers et al.*, 1990; *Malde*, 1991; *Draper*, 1991]. Although the opposing High Lava Plains trend has been more difficult to interpret, we believe that the age progression of rhyolites along the Brothers fault zone is only the most obvious manifestation of a much broader migration of the hot plume source since the mid-Miocene. This conclusion is based on (1) the broad distribution and westward migration of the earliest HAOT eruptions, and (2) the concentration of the youngest and most voluminous HAOT lavas against the southern Cascade arc (Figure 8).

[46] *Carlson* [1984], *Carlson and Hart* [1988], *Bailey and Conrey* [1992], *Hooper and Hawkesworth* [1993], and *Conrey et al.* [1997] have demonstrated that the HAOTs were derived from the same depleted mantle source as the Steens and Picture Gorge lavas, consistent with oceanic lithospheric mantle lying above the hot plume head. Following rapid, radial emplacement of this hot mantle beneath eastern Oregon, a subsequent, westward migration of the plume head occurred at a much slower rate. This migration rate is within the range of typical rates of asthenospheric flow, which would be expected to outpace motion of the overlying lithosphere, thus dragging the plume head westward over time. Counterflow above the subducting slab would have aided in the mantle blob's westward migration [*Draper*, 1991; *Pierce et al.*, 2000]. It is our contention, therefore, that (1) the broad distribution of HAOT in the Pacific Northwest reflects the current location of the hot plume head, and (2) the greatest volume of HAOT, and the youngest initial eruptions, are associated with the eastern margin of the Cascade arc, where elevated geotherms may have aided in source melting along the frontal edge of the mantle plume.

[47] At least some of the HAOT melts may have ponded at the crust-mantle boundary, or in the crust, generating more felsic melts from crustal anatexis [*Catchings and Mooney*, 1988]. Although the upward mobility of such magmas through the crust would normally be impeded by their high viscosities, they may have found easy access to the surface in broad fracture systems like the Brothers fault zone. The rhyolite migration along the High Lava Plains, therefore, may be an indirect manifestation of a much broader migration of the anomalous hot mantle plume by westward asthenospheric drag.

5.3. Perturbations in the Southern Cascades Volcanic Arc

[48] The two stages of plume migration described above correspond in time with two noteworthy perturbations in the southern Cascades volcanic arc. First, a hiatus in subduction-related magmatism began at ~17 Ma, generating both an angular unconformity in the southern Cascades, and a paucity of Cascade tephra interbeds in the Columbia River Basalt succession [*Priest*, 1990; *Beeson and Tolan*, 1990; *Pierce et al.*, 2000]. *Geist and Richards* [1993] suggested that the temporary cessation of arc volcanism may have been the result of plume impingement and uplift of the Farallon plate at ~17.5 Ma, followed by plate rupture and the continued ascent of the mantle plume. Second, the northward propagating High Cascades intra-arc graben was initiated in the southern Cascades at ~7–8 Ma [*Conrey et al.*, 2002], coeval with arrival of the plume head and the onset of HAOT volcanism during the second stage of spreading.

[49] The High Cascades graben is unusual, and perhaps unique, in its volcanotectonic association of a substantial volume of MORB-type lavas in an intra-arc setting [*Conrey et al.*, 2002]. These depleted lavas are identical in composition to HAOT [*Hughes*, 1990; *Bacon et al.*, 1997; *Conrey et al.*, 1997, 2002]. *Lawrence* [1976] was first to notice that the southern end of the High Cascades graben bends to the east, where it merges with the western terminus of the Brothers fault zone. The graben was initiated here, contemporaneous with the first eruptions of HAOT to arrive from the east. Once initiated, intra-arc rifting and concurrent HAOT eruption propagated northward throughout the

Plio-Pleistocene to the Oregon-Washington border. *Conrey et al.* [1997] and *Bacon et al.* [1997] have demonstrated that these low-K lavas must have been derived from a dry, unmetasomatized, depleted mantle source, which was quite different from the source associated with earlier basalts in the Cascade chain. Following the model of *Thompson and Gibson* [1991] and *Ebinger and Sleep* [1998], we suggest that the Brothers fault system may be a deep-seated lithospheric weak zone capable of channelizing mantle plume flow. Under this scenario, mantle flow may have been deflected parallel to the arc, thus generating a propagating system of hot mantle upwelling, concurrent melting of the depleted mantle lithosphere, rift propagation, and HAOT eruption.

5.4. Geophysical Constraints, Thermal Buoyancy, and Isostatic Equilibria

[50] The presence of a hot mantle blob beneath the northern Basin and Range is indicated by high surface heat flow [*Blackwell et al.*, 1982; *Morgan and Gosnold*, 1989] and slow teleseismic *P* wave travel times [*Dueker and Humphreys*, 1990; *Hearn et al.*, 1991], in association with a broad zone of regional uplift, magmatic underplating [*Catchings and Mooney*, 1988], and HAOT volcanism. The proposed northern front of the plume head, lying south of a peripheral belt of wrinkle ridges (Figure 9), appears to coincide with the approximate boundary of a major Bouguer gravity discontinuity displaying a gradient of 40–60 mGal, down to the southeast [*Riddihough et al.*, 1986]. Although these values could be attributed to an abrupt increase in crustal depths to the southeast, they could also result from a thin crust underlain by anomalous mantle of reduced density [*Thiruvathukal et al.*, 1970; *Eaton et al.*, 1978; *Veen*, 1982; *Riddihough et al.*,1986], consistent with a thermal transition across the front of the mantle plume head.

[51] Spreading of the plume head to its current location was associated with regional uplift and development of a broad lithospheric swell. The initial response to plume impingement and spreading was rapid development of the regional paleoslope described by *Camp* [1995]. Uplift from ∼16.6 to 15.0 Ma was concentrated along a broad, north-south zone centered along the Northern Nevada Rift and Chief Joseph trends. Uplift here is consistent with both paleobotanical altitude estimates, and with evidence for the development of a broad precipitation shadow to the east, which peaked at about 15 Ma [*Pierce et al.*, 2000]. Continued spreading, after 15.0 Ma, resulted in a widespread, asymmetric swell which is maintained above the still hot plume head (Figure 9). Despite being highly extended and thinned, the swell is thermally supported to an elevation >1 km above sea level, consistent with typical swells lying above mantle plume heads, which average ∼1–2 km of uplift across regions ∼1000–2000 km in diameter [*Crough*, 1983; *Sleep*, 1990]. In modeling a residual mass deficit in the mantle, both *Parsons et al.* [1994] and *Saltus and Thompson* [1995] attribute the isostatic support of this uplifted region to a broad mass of hot, low-density mantle, which they argue is the Yellowstone mantle plume head.

[52] The highest elevations of the swell appear to be coincident with the thickest accumulation of plume material, where flood basalt volcanism was initiated, and where the paleoslope above the propagating plume head first developed. *Draper* [1991] notes that there is a steady increase in elevation from west to east across the High Lava Plains, from a mean of ∼1000 m near Bend, Oregon, to more than 1375 m at the Oregon-Idaho-Nevada tristate area. Similarly, mean elevations at the site of the Chief Joseph dike swarm and along the Northern Nevada Rift are higher than progressively lower elevations to the west. These observations are consistent with the presence of a broad lithospheric swell having an asymmetric crest, coincident with the axis of flood basalt eruption.

6. Synopsis

[53] The Columbia Plateau, Oregon Plateau, Snake River Plain, and Northern Nevada Rift are temporally and genetically related, each province forming an integral part of a single magmatic system. Although a variety of nonplume models have been proposed to explain the geology of individual provinces, these have proven less effective when applied to coeval, adjacent provinces. In contrast, a plume model similar to that proposed by *Draper* [1991], *Pierce and Morgan* [1992], *Parsons et al.* [1994], and *Camp et al.* [2003], provides a unifying framework that not only satisfies the geologic constraints of each province, but more importantly, also provides a logical explanation for the inherent interrelationships of the system as a whole.

[54] These interrelationships are evident in the temporal and spatial magmatic trends described here. The trends themselves delineate three main events in the evolution of this magmatic system. (1) From ∼16.6 to 15.0 Ma, the Yellowstone mantle plume head spread rapidly outward, accompanied by radial volcanic migrations along the Chief Joseph, Steens–Picture Gorge, and Northern Nevada Rift trends. (2) The plume head was sheared off against the thick, westward advancing cratonic margin at ∼15 Ma, thus allowing the plume tail to generate a hot spot track through the overriding craton. (3) Rapid radial spreading of the plume head ceased at ∼15 Ma, when it was decapitated from its feeding plume tail. However, the plume head continued to spread slowly westward by asthenospheric drag, where it was accompanied by the progressive eruption of rhyolitic crustal melts along the High Lava Plains, and by the much broader migration of initial HAOT eruptions across the Oregon Plateau. Like the Steens and Picture Gorge lavas, the less voluminous HAOTs were derived from melting of the oceanic mantle lithosphere, heated from below by the spreading plume head.

[55] The current edge of the plume head (Figure 9) is marked by (1) the thick cratonic margin of North America to the east, lying adjacent to the initial sites of plume impingement, volcanism and uplift; (2) a broad, ill-defined zone of transitional lithosphere to the south, lying between the 0.704 and 0.706 Sr isopleths; (3) a gravity discontinuity [*Riddihough et al.*, 1986] and an adjacent belt of wrinkle ridges in the north (Figure 9), generated largely during the first phase of rapid spreading; and (4) a prominent belt of voluminous HAOT lavas and young basaltic volcanoes in the west, generated toward the end of the subsequent phase of slower spreading. These four belts delineate the approximate boundaries of a broad, highly deformed lithospheric swell thermally supported above a still hot mantle plume head.

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