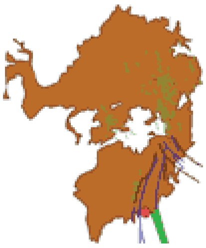
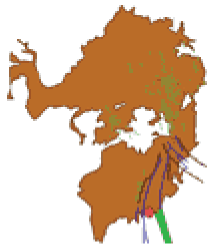


Radiating Volcanic Migrations: An example from the Pacific Northwest, U.S.A.



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This webpage is a abstracted from a more thorough discussion of the CRB magmatic system in *Camp & Ross (2004)*

Introduction

A great variety of criteria have been used in assessing the validity of plume and non-plume models (*e.g.*, *Foulger et al.*, 2002; *Anderson*, 2003; *Courtillot et al.*, 2003; *Ernst & Buchan*, 2003), not the least of which is the recognition of temporal and spatial trends in the eruption sequence of large igneous provinces. The geometry and presumed outward propagation of giant radiating dike swarms, for example, appears to be more compatible with a plume origin than with non-plume alternatives, such as EDGE convection or lithospheric rifting along linear trends (see Giant Radiating Dike Swarm page, and EDGE convection page). Lateral flow away from the focal point of such swarms appears to be supported by limited AMS (anisotropy of magnetic susceptibility) studies (e.g., *Ernst and Baragar*, 1992). However, questions on the magnetic fabric of individual dikes have introduced doubt on the reliability of AMS measurements as predictors of long-distance horizontal flow (see Giant Dike Patterns page). This doubt places greater emphasis on the application of field and stratigraphic data to the assessment of migratory trends in large igneous provinces.

Migrating Magmatic Trends in the Pacific Northwest

Recent mapping, together with petrochemical and paleomagnetic correlations (*Ferns et al.,* 1993a, b; *Lees,* 1994; *Binger,* 1997; *Johnson et al.*, 1998; *Cummings et al.,* 2000; *Hooper et al.,* 2002; *Glen and Ponce,* 2003; *Camp et al.*, 2003) demonstrate a series of temporal and spatial trends in the Miocene flood-basalt succession of the Pacific Northwest. These appear to delineate the outward propagation of magmatism from a centralized source, analogous to similar trends denoted by the AMS studies on giant radiating dike swarms.

Two types of age-progressive trends have been recognized in the Columbia Plateau-Oregon Plateau-Snake River Plain-Northern Nevada Rift magmatic system (*Camp and Ross*, 2004):

1. those with rapid migration rates, significantly greater than rates of convection and plate motion (~10-100 cm/yr), and

2. those with moderate migration rates, similar to estimated rates of mantle convection and plate motion (~1-5 cm/yr).

The rapid-rate migrations are associated with the main phase of flood-basalt volcanism, propagating outward from a centralized source in southeastern Oregon. The moderate-rate migrations are defined by later eruptions emanating outward from the same central site.

Rapid-Rate Migrations Contemporaneous with Flood-Basalt Volcanism

The main eruptive phase of flood-basalt volcanism occurred over a period of six paleomagnetic intervals (R_0-N_2), from ~16.6 to 15.0 Ma (Figure 1). The initial eruptions began in southeastern Oregon, generating the Steens Basalt succession. These lavas are well exposed at Steens Mountain (*Johnson et al*., 1998), where more than 900 m of basalt erupted over the R_0-N_0 paleomagnetic transition (*Mankinen et al.*, 1987). Mapping of the paleomagnetic and petrochemical stratigraphy, in concert with Ar-Ar geochronology, demonstrate that flood basalt volcanism migrated rapidly outward along three primary trends (Figure 2):

1. the Chief Joseph trend, marked by the northward advance of dikes and progressively younger lavas of the Imnaha and Grande Ronde Basalts during N_0-N_2 (*e.g.*, *Camp,* 1995),

2. the Steens-Picture Gorge trend, marked by the discontinuous northward advance of progressively younger eruptions of Steens (R_0-N_0), Picture Gorge (N_1-R_2), and Prineville (R_2-N_2) Basalts, from Steens Mtn. to the northern end of the Monument dike swarm, and

3. the Northern Nevada Rift trend, marked by the southward advance of dikes and a diminished volume of Steens Basalt (R_0-N_0) and younger intermediate to felsic volcanic rocks (*e.g.*, *Glen & Ponce,* 2002).

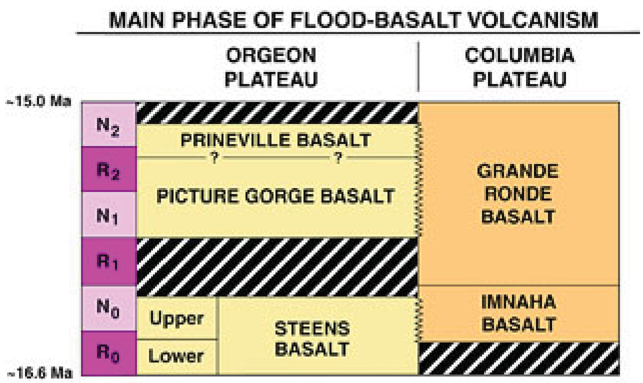

Figure 1. Magnetostratigraphy of the flood basalt units on the Columbia and Oregon Plateaus during the main phase of eruption (~16.5-15.0 Ma).

Figure 2. Distribution map for the Columbia River Flood Basalt Pronvince. MC, McDermitt caldera; OIG, Oregon-Idaho graben; WSRP, western Snake River Plain. Click on figure for enlargment.

Moderate-Rate Migrations after the Flood-Basalt Event

Flood-basalt volcanism was followed by the progressive eruption of rhyolite along two well-recognized trends (Figure 3):

1. to the northeast, along the Snake River Plain hotspot track, and
2. to the west-northwest, along the Oregon High Lava Plains (see [High Lava Plains page]).

Whereas the Snake River Plain hotpsot track was generated above Precambrian continental lithosphere lying east of the cratonic margin (the 0.706 Sr isopleth in Figure 3), the Oregon High Lava Plains trend was generated above oceanic lithosphere west of the cratonic margin.

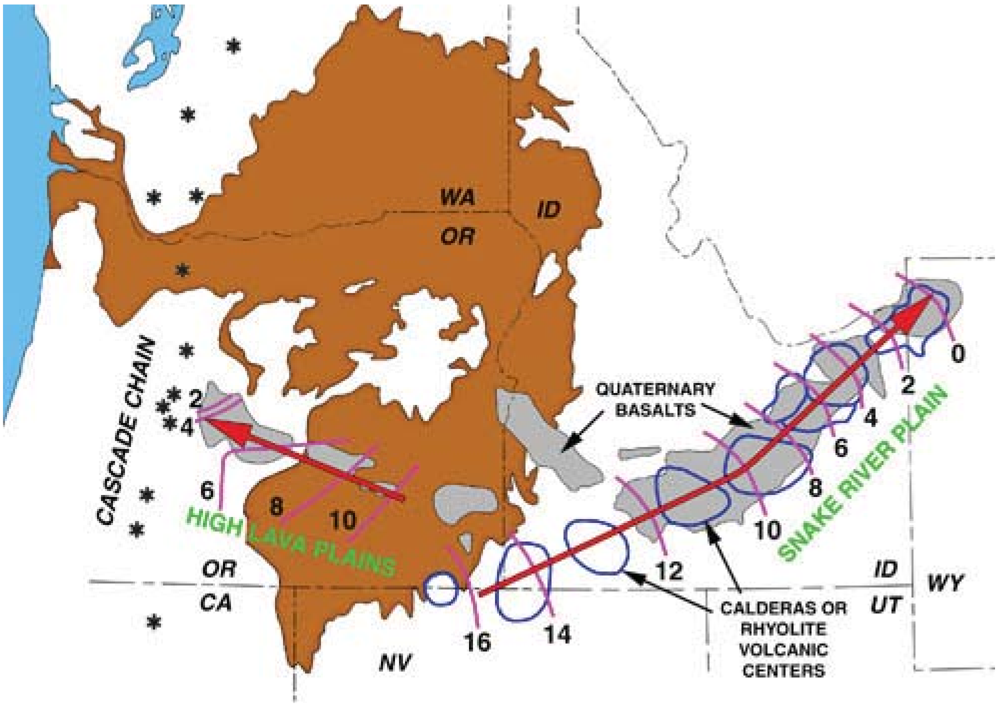

Figure 3. Moderate-rate migrations of rhyolte magmatism associated with the Oregon High Lava Plains and the Snake River Plain hotspot track. Distribution of Quaternary basalt and isochrons for rhyolitic volcanism from Jordan et al. (2002) and Christiansen et al. (2002).

The post-15 Ma felsic eruptions west of the cratonic margin were contemporaneous with sporadic eruptions of low-volume, but widely scattered, high-alumina olivine tholeiite (HAOT) (*Hart et al.*, 1984). Figure 4 illustrates the map distribution of the youngest of these HAOTs, with ages < 8 Ma. Although these young HAOTs are widespread and exhibit a lack of orderly age-progression across eastern Oregon, the initial eruptions of HAOT appear to have progressed westward away from the cratonic boundary, as denoted by the dashed contours in Figure 4. The oldest post-15.0 Ma HAOTs yet recognized are the ~13.9-to-13.1 Ma Tims Peak basalts of east-central Oregon. The oldest dates farther to the west and south indicate that 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.
In this westernmost zone, there is 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.

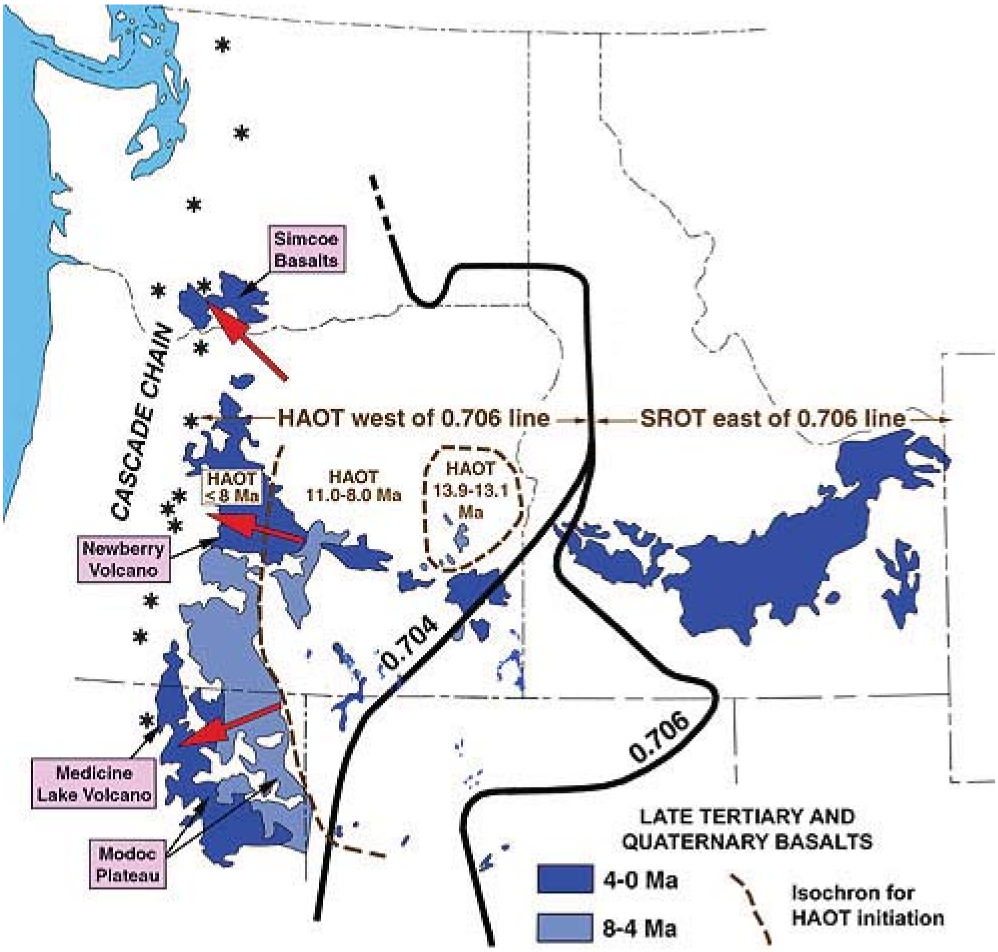

Figure 4. Distribution of Late Tertiary to Quaternary basalts, derived from Hart et al. (1984), Jordan et al. (2002), and Christiansen (2002). The 0.704 and 0.706 lines correspond with the initial $^{87}Sr/^{86}Sr$ isopleths of Kistler and Peterman (1978) and Leeman et al. (1992). HAOT and SROT are restricted to areas lying west and east of the 0.706 line, respectively. Isocrhons (dashed lines) showing a west to east 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), Hooper et al. (2002), and Camp et al. (2003).

Assessing Tectonomagmatic Models for the Pacific Northwest

A great variety of non-plume models have been proposed for the Columbia Plateau, the Oregon Plateau, the Northern Nevada Rift, and the Snake River Plain provinces. Some of these include back-arc extension for the Oregon Plateau (*Carlson & Hart*, 1988), EDGE convection for the Oregon and Columbia Plateaus (*King & Anderson*, 1998), Basin and Range rifting for the Northern Nevada Rift (*Zoback & Thompson,* 1978), an eastward propagating rift for the Snake River Plain (*Hamilton,* 1987), divergent upper mantle flow around a residuum body for the Snake River Plain and High Lava Plains (*Humphreys et al.*, 2000), and a self-sustaining melting anomaly generated by thermal feedback between lithospheric rifting and shear melting along the Snake River Plain hotspot track (*Christiansen et al.*, 2002). However, to develop separate models for each province is at odds with the geologic evidence that they are contemporaneous and genetically related, each province forming an inherent part of a single magmatic system. Although many of these models are adequate in explaining the geologic features of any one province, they are generally inadequate in explaining the geologic evolution of coeval adjacent provinces composing the magmatic system as a whole.

Of the non-plume alternatives for flood-basalt volcanism, the boundary edge model of *King & Anderson* (1998) provides an elegant explanation for the location of the Chief Joseph dike swarm against the Precambrian boundary of North America. However, this model is incompatible with rifting and volcanism across the cratonic boundary along the Northern Nevada Rift. Neither the EDGE model nor the other non-plume alternatives offers a reasonable mechanism to explain the rapid outward migration of volcanism along the Chief Joseph, Steens-Picture Gorge, and Northern Nevada Rift trends. The outward progression of volcanism away from a focal point in southeastern Oregon is more compatible with a plume model, as originally suggested by *Draper* (1991), and consistent with AMS studies on the propagation of dikes in giant radiating dike swarms.

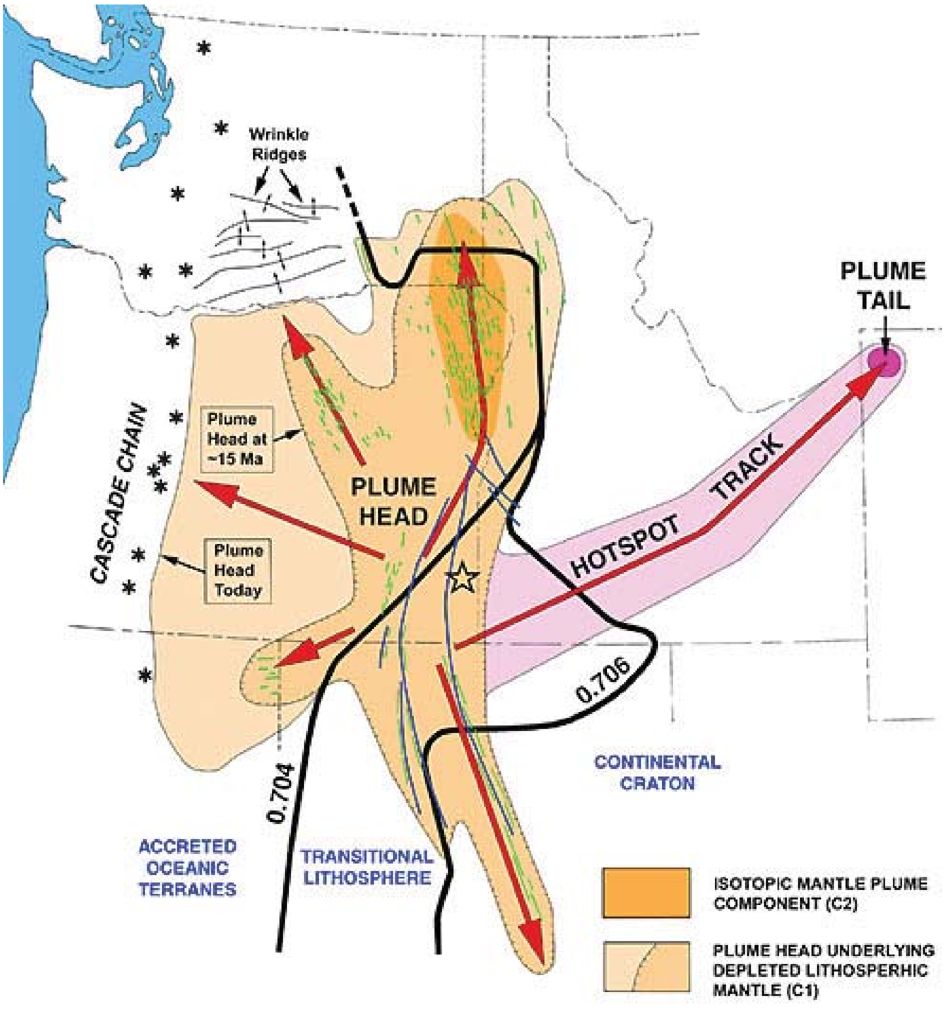

Figure 5. Two-stage spreading model of the proposed Yellowstone mantle plume head, showing (1) the approximate position of the proposed plume head after impingement and rapid spreading (~15.0 Ma), and (2) the approximate position of the proposed plume head today after moderate-rate spreading associated 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 & Buchan, 2001). The approximate boundaries of distinct lithospheric domains beneath the plume head are delineated by the $^{87}Sr/^{86}Sr$ isopleths of Kistler & Peterman (1978), and Leeman et al. (1992).

A two-stage spreading model for the Yellowstone mantle plume is shown in Figure 5. The model suggests that impingement of a mantle plume head in the Pacific Northwest resulted in rapid spreading in all directions, but preferentially to the north beneath thin lithosphere of the accreted oceanic terranes. Spreading to the south, beneath thicker transitional to continental lithosphere produced shallow intrusions and a much smaller volume of lava along the southward propagating Northern Nevada Rift system (*Glen & Ponce*, 2003). Shearing off of the plume head against the westward-advancing, thick cratonic margin at ~15 Ma allowed the plume tail to generate a hotspot track through the overidding craton. Once decapitated from its feeding plume tail, the plume head continued to advance westward, at a much slower rate, by asthenospheric drag and by counterflow above the descending Juan de Fuca plate (see High Lava Plains page), thus generating a westward migration of HAOTs and rhyolitic melts, at a rate consistent with mantle convection.

Summary

Although we are open to alternative views, we believe that the existing non-plume models are inadequate in explaining the overall geology of mafic magmatism in the Pacific Northwest. A plume genesis, however, appears to provide:

1. a unifying model for the entire system, which is lacking in nonplume interpretations,

2. a rational mechanism to account for rapid, radiating volcanic migrations, also lacking in non-plume interpretations, and

3. a more reasonable explanation for the sudden outburst and short duration (~1.5 million years) of the main phase of flood-basalt volcanism.

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