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Initial impingement of the Yellowstone plume located by widespread silicic volcanism contemporaneous with Columbia River flood basalts

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ABSTRACT

During the main phase of Steens and Columbia River (United States) flood basalt eruptions between 16.7 and 15.0 Ma, ~3900 km³ of silicic magma erupted from centers dispersed across ~25,000 km². The largest and oldest silicic centers, High Rock, McDermitt, and Lake Owyhee caldera complexes, lie along a narrow NNE trend at the transition between the craton and accreted oceanic crust, suggesting that silicic magma generation was greatest where mafic magma intruded more-felsic crust. Less voluminous and younger silicic centers track the spread of mafic dikes to the north. The High Rock caldera complex forms the western end of the Snake River Plain–Yellowstone trend of eastward-younging silicic centers. We attribute a regional lull in volcanism between ca. 23 and 7 Ma to lifting of the Juan de Fuca slab by a mantle plume beginning at ca. 25 Ma, and the distribution of main-stage flood basalts and coeval rhyolites to breakthrough of plume material at ca. 17 Ma to form a smaller plume head centered beneath Steens Mountain.

INTRODUCTION

The origin of continental flood basalt provinces is a first-order problem in petrology and geodynamics. Flood basalt volcanism in the northwestern United States began at ca. 16.7 Ma with eruption of ~60,000 km³ of Steens basalts in southern Oregon, the youngest of which overlap in age with more voluminous (174,000 km³) Columbia River basalt (CRB) eruptions farther north (Fig. 1) (e.g., Camp et al., 2003). Recent ⁴⁰Ar/³⁹Ar dating and paleomagnetic studies (Brueseke et al., 2007; Jarboe et al., 2010; Barry et al., 2010) have shown that the predominant volume of these flood basalts erupted over short intervals: 16.7–16.0 Ma for Steens basalts and 16.3–15.0 Ma for the main phase of the CRB (see the GSA Data Repository¹).

Such rapid production of large volumes of basalt lends support to models that involve singular events, such as melting in the head of a deep-mantle plume and associated effects as it spreads along the base of the lithosphere (e.g., Takahashi et al., 1998; Jordan et al., 2004; Camp and Ross, 2004; Hooper et al., 2007; Wolff et al., 2008). Mantle melting associated with impingement of a plume head should have a profound thermal effect on continental crust; indeed, silicic volcanism contemporaneous with main-phase Steens and CRB activity is widespread (Christiansen and Yeats, 1992; Brueseke et al., 2008; Shervais and Hanan, 2008).

In this paper, we synthesize previously published data on regional silicic volcanism with new data on the High Rock caldera complex in northwest Nevada, which provide evidence for the “footprint” of a mantle plume head on the lithosphere. We also elaborate on previous models for the path of the Yellowstone plume as it

arrived beneath North American lithosphere to explain the time-space patterns of Miocene volcanism in the Pacific Northwest.

DISTRIBUTION AND VOLUME OF SILICIC VOLCANISM CONTEMPORANEOUS WITH FLOOD BASALT ERUPTIONS

Silicic volcanic rocks contemporaneous with flood basalt eruptions vented over an area of ~25,000 km² (Fig. 1). Three volcanic fields account for ~90% of the erupted volume: Lake Owyhee, McDermitt, and High Rock. Lake Owyhee volcanic field includes Mahogany Mountain and Three Fingers calderas, and Castle Rock center, which are sources of weakly peralkaline to metaluminous rhyolite ignimbrites and lavas (e.g., Rytuba and Vander Meulen, 1991; Cummings et al., 2000) that we estimate total ~1115 km³. At McDermitt caldera complex, several peralkaline rhyolite to trachyte

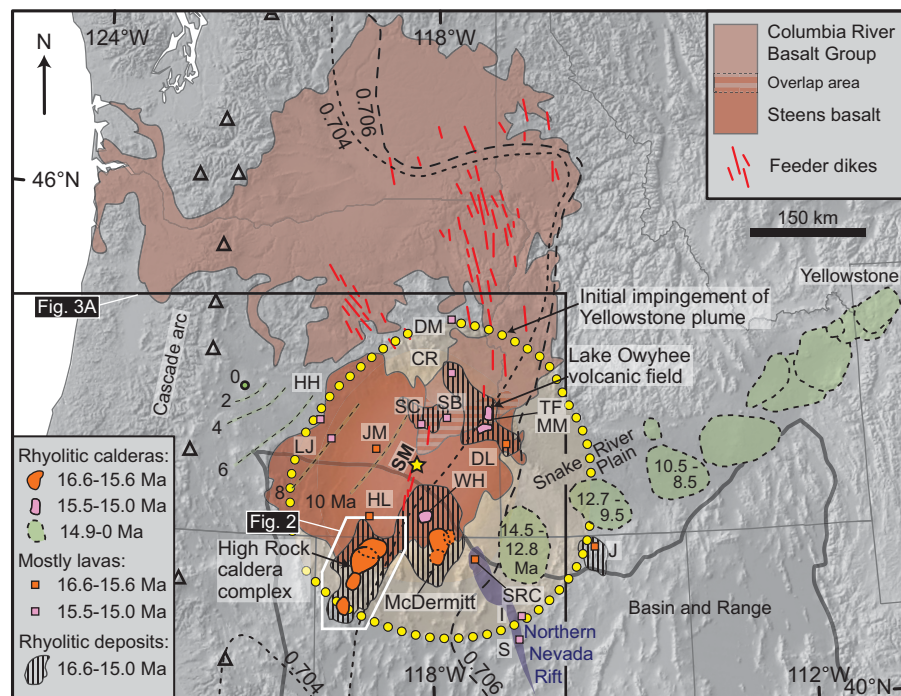


Figure 1. Location of mid-Miocene silicic volcanic centers contemporaneous with flood basalt volcanism. Sr isotopic isopleths modified from Pierce and Morgan (2009). Green lines show 2 Ma isochrons for inception of rhyolitic volcanism in the High Lava Plains (Oregon, United States). Yellow dotted line depicts proposed “footprint” of the Yellowstone plume head at 16.7–16.5 Ma, centered at Steens Mountain (SM). CR—Castle Rock; DL—DeLamar caldera—Silver City; DM—Dooley Mountain; HH—Horsehead Mountain; HL—Hawks Valley—Lone Mountain; I—Ivanhoe; J—Jarbridge Rhyolite; JM—Jackass Mountain; LJ—Little Juniper Mountain; MM—Mahogany Mountain caldera; S—Sheep Creek Range; SB—Saddle Butte; SC—Swamp Creek Rhyolite; SRC—Santa Rosa—Calico volcanic field; TF—Three Fingers caldera; WH—Whitehorse caldera. See the Data Repository (see footnote 1) for sources of data.

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¹GSA Data Repository item 2012188, summary of High Rock caldera complex stratigraphy and discussions of new and recalculated ⁴⁰Ar/³⁹Ar ages, our compilation of published ages, and volume calculations for rhyolitic centers coeval with flood basalt magmatism, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

ignimbrites totaling ~1600 km³ erupted between 16.5 and 15.0 Ma from the composite McDermitt caldera and satellite Whitehorse caldera (Rytuba and McKee, 1984; Castor and Henry, 2000). Our new geologic and geochronologic studies west of McDermitt demonstrate that compositionally similar silicic ignimbrites and lavas erupted from four major overlapping calderas that were active 16.4–15.7 Ma. We estimate that >700 km³ of magma erupted from this area, which we refer to as High Rock caldera complex (HRCC), after Ach and Swisher (1990) (Fig. 2; see the Data Repository).

The Virgin Valley caldera is the one caldera in HRCC (Fig. 2) previously documented in the published literature (Greene, 1984). Castor and Henry (2000) attributed its formation to eruption at ca. 16.4 Ma of the alkali rhyolite Idaho Canyon Tuff of Noble et al. (1970). We suggest that the largest caldera (~30 km × 40 km) in HRCC, which we term Badger Mountain caldera, collapsed as a result of eruption of the trachytic Summit Lake Tuff of Noble et al. (1970) at ca. 16.34 Ma. The southwestern margin of Badger Mountain caldera is truncated by

a younger caldera that we call Hanging Rock caldera. We identify the 16.0 Ma, strongly peralkaline rhyolite Soldier Meadow Tuff of Noble et al. (1970) as the caldera-forming unit. The youngest and southernmost caldera we term Cottonwood Creek caldera after Bussey (1995). We suggest that eruption of the newly recognized alkali rhyolite to trachyte tuff of Yellow Rock Canyon at 15.7 Ma led to collapse of this 24 km × 28 km caldera. In all four HRCC calderas, postcaldera silicic lavas and associated pyroclastic units erupted along ring fractures and resurgence-related faults until 15.5 Ma.

Numerous smaller-volume centers were active in eastern Oregon, western Idaho, and northern Nevada during the main phase of flood basalt volcanism (Fig. 1; see the Data Repository). Most are composed of small metaluminous rhyolite lava domes or flows, and lack evidence for calderas or extensive ignimbrites, the exception being Jarbidge (Fig. 1), where individual rhyolitic lava flows appear to be voluminous (Callicot, 2010). We estimate the total volume of silicic magma erupted at these smaller centers to be ~400 km³.

The most voluminous silicic eruptions, occurring at multiple calderas at HRCC and McDermitt, are the earliest ones, starting at ca. 16.5 Ma, shortly after initiation of flood basalt eruptions at Steens Mountain at ca. 16.7 Ma. The younger ages of caldera-forming eruptions northwest of Steens Mountain (Fig. 1) track the rapid northward migration of CRB dikes (Camp and Ross, 2004), though the ages of individual silicic centers are typically younger than locally derived flood basalt lavas. High Rock, McDermitt, and Lake Owyhee caldera complexes lie along a NNE trend near the projection of the initial Sr (⁸⁷Sr/⁸⁶Sr_i) = 0.704 isopleth (Fig. 1), interpreted as the boundary between accreted oceanic terrains and transitional continental crust. They are located near the edge of the distribution of the Steens basalts, and all the mid-Miocene silicic centers occur where feeder dikes for flood basalts are *not* abundant (Fig. 1).

DISCUSSION AND CONCLUSIONS

“Footprint” of the Yellowstone Plume Head Defined by Silicic Volcanism

Mid-Miocene silicic volcanism contemporaneous with the main phase of flood basalt eruptions in the northwestern United States is more voluminous and occurs over a wider area than commonly appreciated: a minimum of ~3900 km³ of silicic magma erupted from centers dispersed over ~25,000 km². We suggest that the pattern of 16.5–15.0 Ma silicic centers reflects the initial spreading of the Yellowstone plume head beneath North American lithosphere (Fig. 1).

In many models for CRB magmatism, a plume head is illustrated as initially impinging on North American lithosphere beneath McDermitt caldera; McDermitt is also commonly cited as the starting point for a northeast-younging trend of silicic centers along the Snake River Plain–Yellowstone (SRP–Y) trend interpreted as reflecting passage of the North American plate over the tail of the Yellowstone plume (e.g., Pierce and Morgan, 1992, 2009; Camp and Ross, 2004; Nash et al., 2006; Hooper et al., 2007; Leeman et al., 2008; Shervais and Hanan, 2008). Our new geologic and geochronologic work on HRCC firmly establishes that the oldest part of the SRP–Y trend extends west of McDermitt caldera into northwest Nevada.

In our model, the main volume of the plume head was focused beneath Steens Mountain, with far-traveled mafic dikes emanating from this area (e.g., Glen and Ponce, 2002). This is consistent with Steens Mountain having been the source for the earliest flood basalts, with its shield being the largest edifice constructed by the flood basalts, and with initiation of silicic and mafic volcanism generally younging away from Steens Mountain (Fig. 1). The plume head spread south and east only a short distance due

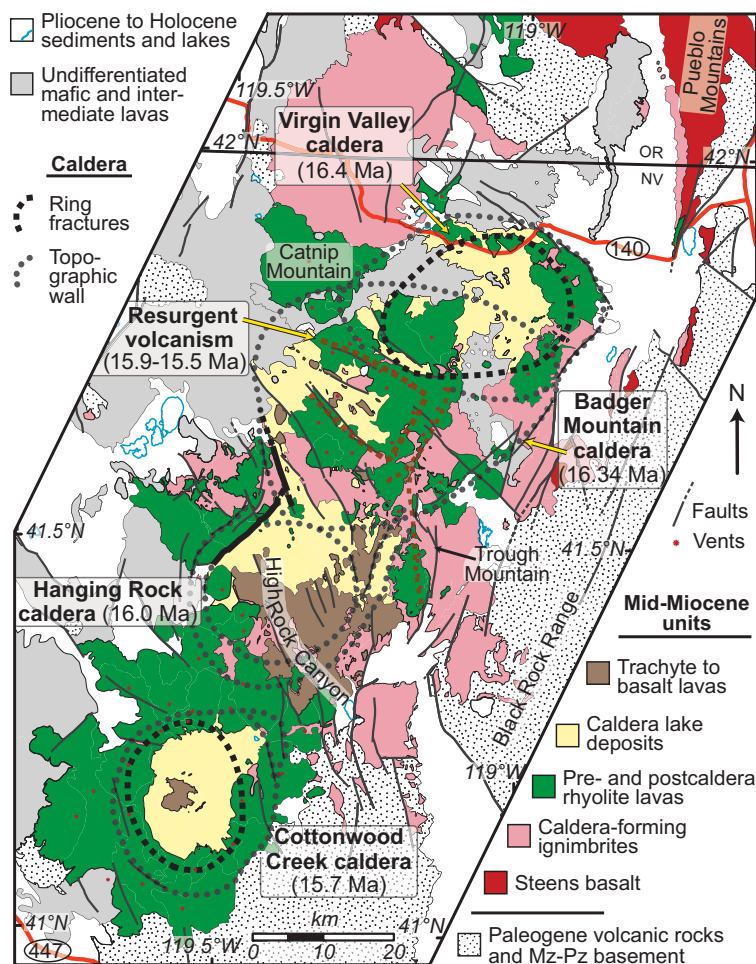


Figure 2. Simplified geologic map of High Rock caldera complex (Nevada and Oregon, United States). Ages of caldera collapse young southward. Life spans of ~0.4 m.y. lead to overlapping of activity at adjacent calderas.

to encountering thicker, transitional crust (e.g., Thompson and Gibson, 1991; Camp and Ross, 2004; Jordan et al., 2004; Shervais and Hannan, 2008; Pierce and Morgan, 2009). There, mafic magma intruded along zones of preexisting crustal weakness—southwest and north-northeast along the edge of transitional crust, and southeast into the Northern Nevada Rift (Fig. 1)—where it caused crustal melting that gave rise to High Rock, McDermitt, and Lake Owyhee caldera complexes and smaller silicic centers (John et al., 2000; Brueseke and Hart, 2008). Elsewhere, less-fertile, accreted, oceanic crust yielded small volumes of rhyolite on injection by basaltic dikes. Rapid northward shift of the locus of mafic intrusion during the 16.7–15.0 Ma interval resulted in more dispersed silicic volcanism than in the SRP-Y trend. Although individual ignimbrites erupted 16.5–15.0 Ma are smaller than many of those associated with calderas along the eastern SRP-Y trend, the estimated minimum eruptive rates are similar, ~2000–3000 km³/m.y. (Leeman et al., 2008).

Formation of Hybrid Magmas by Intrusion of Basalt Magmas into the Crust

The ratio of the estimated volumes of silicic ignimbrites and lavas to flood basalts for the Steens and CRB overall is 0.017, comparable to ratios of 0.010, 0.022, 0.060, and <0.014 for the Deccan, Paraná-Etendeka, North Atlantic, and Yemen-Ethiopia large igneous provinces, respectively (data from Pankhurst et al., 2011). These ratios, even if doubled to account for intracaldera fill or eroded nonwelded deposits, are much smaller than what is theoretically possible for crustal melting given the large mafic intrusion rates (e.g., Annen and Sparks, 2002). Together with the observation that silicic centers active during main-phase Steens and CRB magmatism developed peripheral to the zones of most-intense basaltic diking (Fig. 1), this suggests that where mafic intrusion was strongly focused, partial melts of the crust were incorporated into the basalt, and later basalts intruded earlier contaminated basalts or their gabbroic equivalents (e.g., Hildreth et al., 1991). Where mafic flux was small, the crustal melts erupted as small volumes of rhyolite or hybrid intermediate rocks (e.g., Brueseke and Hart, 2008) or were insufficient to accumulate and erupt. Between these two extremes, where the intensity of mafic diking was intermediate, accumulations of crustal melts became density barriers to the rise of later basalt, which provided heat for further crustal melting. This feedback mechanism drove rapid transitions, in both space and time, from eruptions of voluminous basalt to eruptions of rhyolite. Geologic evidence for this process is found in the Pueblo Mountains (Fig. 2), where exposures of >1000 m of Steens flood basalts thin abruptly southward toward

HRCC and McDermitt caldera over a distance of ~75 km, and are overlain by ignimbrites from these centers.

Our interpretations add to arguments that the CRB lavas contain a significant component of crustal melt (e.g., Carlson and Hart, 1987; Brandon et al., 1993) and support the idea of a centralized source for the CRB (e.g., Wolff et al., 2008). They also imply that the rhyolites are derived from mixtures of crustal melts and coeval basalts or melts of hybridized crust (Brueseke and Hart, 2008) as has been suggested for other centers along the SRP-Y trend (e.g., Hildreth et al., 1991; Nash et al., 2006; Leeman et al., 2008).

Interaction of the Yellowstone Plume with the Farallon–Juan de Fuca (F-JdF) Slab

The area we propose for initial impingement of the Yellowstone plume head, ~400 km in diameter (Fig. 1), is small compared to predicted sizes for deep-mantle plumes (Griffiths and Campbell, 1990). A relatively small plume head is consistent with the CRB having the smallest volume of known flood basalt provinces. A mantle plume that ultimately impinged on the lithosphere beneath southern Oregon would likely have first encountered a shallowly subducting Farallon plate (e.g., Geist and Richards, 1993; Pierce and Morgan, 2009). Seismic tomographic studies show that the Juan de Fuca slab currently terminates at ~400 km depth; fast anomalies farther east are interpreted as Farallon slab fragments (e.g., Xue and Allen, 2007; Obrebski et al., 2010). Plume material that broke through and disrupted the subducting F-JdF slab would have risen only a short distance before impinging on the lithosphere, resulting in a small plume head (Fig. 3).

Evidence for the timing of the disruption of the F-JdF slab is found in the record of regional volcanism. Beginning in the Eocene, the Pacific Northwest was a site of arc volcanism, with metaluminous and weakly peralkaline silicic and minor mafic volcanism erupting behind the arc. Based on a compilation of K-Ar and ⁴⁰Ar/³⁹Ar ages for the area of interest (Fig. 3A), a hiatus in volcanism first noted by McKee et al. (1970) began at ca. 23 Ma and ended with the outbreak of flood basalt volcanism at ca. 16.7 Ma. We speculate that the buoyancy of the large head of a deep-mantle plume lifted the subducting F-JdF slab, which prevented corner flow and shut off volcanism behind the arc (Fig. 3B). We envision the upbowed slab eventually failing under its own weight. Some of the original plume-head material would rise beneath the truncated F-JdF slab (Xue and Allen, 2007) or be trapped beneath disrupted slab fragments. The part that penetrated the slab formed a new, smaller plume head as it rose. Decompression melting of this small plume head (± entrained fragments of

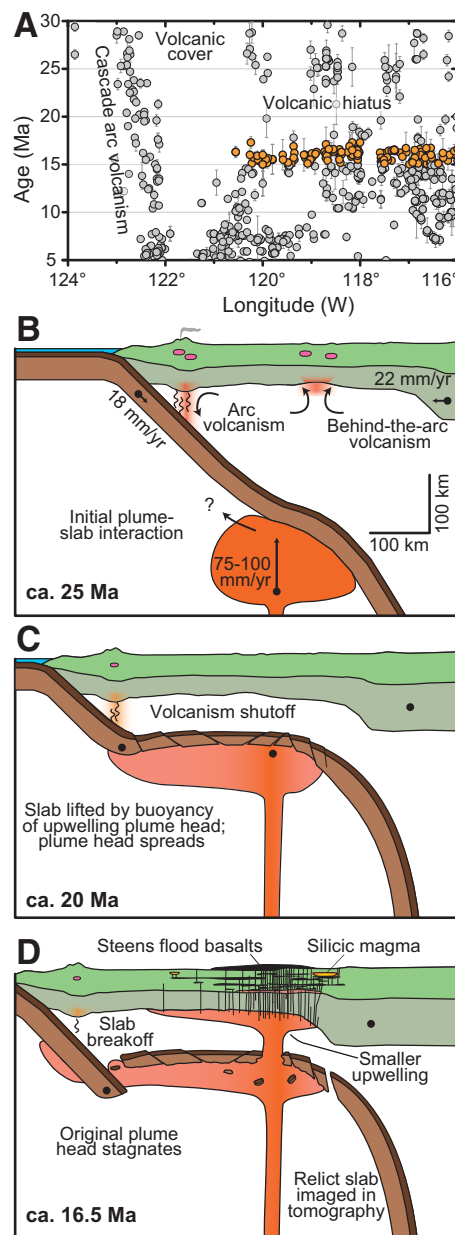


Figure 3. A: Ages of volcanic rocks for area shown in Figure 1 compiled from this study and the North American Volcanic and Intrusive Rock Database (NAVDAT, <http://www.navdat.org>). Orange dots represent 16.7–15.0 Ma ages. B–D: Schematic northwest-southeast cross sections across same area, illustrating a model for the evolution of Yellowstone plume that could explain the age distribution. Panels are drawn with a stationary plume tail. See text for discussion.

disrupted slab) generated flood basalts (e.g., Geist and Richards, 1993; Pierce and Morgan, 2009; Obrebski et al., 2010), which first erupted at Steens Mountain, near the center of the plume head (Fig. 1). The scarcity of Cascade arc volcanism in the age range 17–7 Ma (Priest, 1990) may reflect the time required for the uplifted JdF slab to sink and allow re-establishment of corner flow.

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