Ages of the Steens and Columbia River flood basalts and their relationship to extension-related calc-alkalic volcanism in eastern Oregon

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ABSTRACT

Stratigraphic and chemical correlations of Tertiary volcanic units in eastern Oregon confirm that the Steens Basalt represents the earliest eruptions of the Columbia River flood-basalt province. Field correlations are supported by major and trace element analyses and confirmed by $^{40}Ar/^{39}Ar$ dates. Within the basalt of Malheur Gorge, situated between Steens Mountain and the southernmost extent of the previously mapped Columbia River Basalt Group, the lowest unit correlates with the Steens Basalt, and the conformably overlying middle and upper units correlate with the Imnaha and Grande Ronde Basalt Formations of the Columbia River Basalt Group. New dates indicate that Imnaha and Grande Ronde Basalt Formations on the Columbia Plateau (>90% of the Columbia River Basalt Group) erupted between 16.1 and 15.0 Ma. These were immediately preceded by the Steens Basalt, a plagioclase-phyric tholeiite that erupted above the calculated position of the Yellowstone hotspot at 16.6 Ma. In eastern Oregon, the flood-basalt tholeiites of Steens Mountain and Malheur Gorge form a voluminous but brief interlude (16.6–15.3 Ma) superimposed on the low-volume, calc-alkalic to mildly alkalic, volcanism associated with continuing Eocene to present east-west extension.

Keywords: calc-alkalic volcanism, Columbia River Basalt, extension, hotspot, Steens Basalt.

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INTRODUCTION

The unusually large volumes of tholeiitic basalt, erupted within short time spans, that characterize continental flood-basalt provinces are typically associated with lithospheric extension (White and McKenzie, 1989). In some large-scale flood-basalt provinces, extension is accompanied by lithospheric thinning and anticipates the separation of major tectonic plates. More controversial is whether extension was the cause or consequence of the massive flood-basalt eruptions (White and McKenzie, 1989; Richards et al., 1989; Hooper, 1990).

The prevalent view of the origin of the Columbia River and other continental flood basalts is that the large magma volumes that distinguish flood basalts require a hotspot in the upper mantle. Many workers have ascribed this hotspot to a plume arising from deep within the mantle (Campbell and Griffiths, 1990), with or without the additional processes of significant lithospheric extension and thinning (White and McKenzie, 1989; Richards et al., 1989; Hooper, 1990). In contrast, Carlson and Hart (1987) have ascribed the Columbia River basalt eruption to extension associated with backarc spreading. Anderson (1994) and his coauthors have argued that continental flood basalts tend to occur along boundaries between lithospheric plates of contrasting thickness, which would allow creation of convection systems adequate to account for the large magma volumes.

East-west extensional stress was prevalent during the eruption of the Columbia River Basalt Group, as graphically illustrated by the consistent north-northwest–east-southeast orientation of the feeder dikes (Hooper, 1997). But the causal relationship between extension and the Columbia River flood-basalt eruption is more difficult to establish. The problem is complicated by uncertainty about the relationships between the eruption of Steens Basalt (Carlson and Hart, 1987) over the impinging Yellowstone hotspot in southeast Oregon and the larger eruption of the Columbia River Basalt Group almost 300 km farther north on the Columbia Plateau. Similarity in age and composition has led many authors to assume that the Steens Basalt was the earliest eruption of the Columbia River flood-basalt province (Brandon and Goles, 1988; Geist and Richards, 1993; Camp, 1995; Hooper, 1997; Takahashi et al., 1998, among others), but the stratigraphic relationships between the two tholeiitic eruptions have never been established. Furthermore, the radiometric ages suggested that the Imnaha Basalt, the lowest formation of the Columbia River Basalt Group, was older (17.2 Ma ± 0.5 Ma; McKee et al., 1981) than more recent and precise $^{40}Ar/^{39}Ar$ dates of the Steens Basalt (16.60 Ma ± 0.02 Ma; Swisher et al., 1990).

Subsequent mapping of the Tertiary volcanic rocks in part of east-central Oregon (Ferns et al., 1993a, 1993b; Cummings et al., 2000), together with analyses for major and trace elements and new $^{40}Ar/^{39}Ar$ dates,[1] has clarified the stratigraphic relationship between the Steens Basalt and the Columbia River Basalt Group, allowing them both to be linked to impingement of the Yellowstone hotspot beneath

[1] GSA Data Repository item 2002014, major and trace element analyses, details of $^{40}Ar/^{39}Ar$ dates, and petrographic descriptions of the volcanic units of east-central Oregon, is available on the Web at http://www.geosociety.org/pubs/ft2002.htm. Requests may also be sent to editing@geosociety.org.

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eastern Oregon at 16.6 Ma (Engebretson et al., 1985; Pierce and Morgan, 1992). This study provides improved dates for the initial eruptions of the whole flood-basalt province and emphasizes the distinction between the calc-alkalic to mildly alkalic magmatism associated with east-west lithospheric extension and the tholeiitic flood basalts associated with the Yellowstone hotspot—a distinction with important implications for interpreting the origin of flood basalts.

VOLCANIC STRATIGRAPHY IN EAST-CENTRAL OREGON

Many of the volcanic units in east-central Oregon have been given formal names by earlier workers (e.g., Kittleman et al., 1965, 1967). Lees (1994) grouped these and other units into informal sequences of similar age (Table 1), a convenient nomenclature that is followed here.

Basalt of Malheur Gorge

The oldest Tertiary volcanic sequence in the area studied, between Farewell Bend, Vale, and Juntura (Fig. 1), is the basalt of Malheur Gorge (Evans, 1990a, 1990b). It is divided into three distinct stratigraphic and compositional units (Table 1; Lees, 1994; Binger, 1997). At the base, the Lower Pole Creek unit is composed of dark, coarsely plagioclase-phyric basalt. Both chemically and petrographically, the Lower Pole Creek flows are similar to flows with reversed magnetic polarity in the lower part of the Steens Basalt section at Steens Mountain, 100 km to the southwest (Fig. 2; Binger, 1997; Johnson et al., 1998a). Analogous, coarsely plagioclase-phyric basalts with reversed magnetic polarity form the basal flow unit of the Columbia River Basalt Group at Squaw Butte, a few kilometers northwest of Boise, Idaho (Figs. 1 and 2; Fitzgerald, 1984; Martin, 1984), and also form the magnetically reversed flows at the base of the otherwise magnetically normal Imnaha Basalt along the southern margin of the Wallowa Mountains in northeast Oregon (e.g., sample C1 of Carlson, 1984; Hooper, 1997).

The Lower Pole Creek flows are succeeded upward, without apparent break, by the moderately plagioclase-phyric Upper Pole Creek tholeiitic flows with higher concentrations of SiO_2, Al_2O_3, K_2O, Ba, Rb, and Zr than are found in the Lower Pole Creek unit (Fig. 2). The compositional range of the Upper Pole Creek flows is similar to the main magnetically normal section of the Imnaha Basalt of the Columbia River Basalt Group (Fig. 2; Hooper et al., 1984). The Upper Pole Creek flows are overlain by the aphyric basaltic andesites of the Birch Creek unit, which are petrographic and chemical equivalents of the Grande Ronde Basalt Formation of the Columbia River Basalt Group (Fig. 2; Lees, 1994). Only a few Birch Creek flows are present at Malheur Gorge, and they have not been recognized farther south. The number of Grande Ronde type flows and their total thickness increase progressively north to the Columbia Plateau (Lees, 1994; P.R. Hooper, unpublished mapping, 1981).

Flows of Steens Basalt on Steens Mountain are dated at 16.60 Ma ± 0.02 Ma (base) and 16.59 Ma ± 0.02 Ma (top) (Swisher et al., 1990). Two new dates for the Lower Pole Creek flows (basalt of Malheur Gorge) have a weighted mean of 16.9 ± 0.8 Ma. Four new dates for Upper Pole Creek flows have a mean of 16.5 Ma ± 0.3 Ma, and three from the Birch Creek unit have a mean of 15.7 Ma ± 0.1 Ma (Table 1). Two flows from original sections of Imnaha basalt on the Columbia Plateau (Hooper et al., 1984) provide new ages of 15.4 Ma ± 0.2 Ma and 15.5 Ma ± 0.3 Ma, determined by using the same $^{40}Ar/^{39}Ar$ techniques in the laboratory used to date the Grande Ronde Basalt on the Columbia Plateau at between 16 and 15 Ma (Long and Duncan, 1982; R.A. Duncan, Oregon State University, 1998, personal commun.). Dates of the Imnaha and Grande Ronde Basalt flows show no discernible correlation with stratigraphic position (Long and Duncan, 1982). More recent $^{40}Ar/^{39}Ar$ dates for Grande Ronde Basalt by Baksi (1989) have a similar range (15.5 Ma to 16.1 Ma). The often quoted older K/Ar dates for flows of the Imnaha Basalt Formation fall outside this range at 17.2 Ma ± 0.2 Ma (McKee et al., 1981). We suggest that

TABLE 1. STRATIGRAPHY AND $^{40}Ar/^{39}Ar$ DATES FOR VOLCANIC UNITS OF EAST-CENTRAL OREGON

Sequence	Unit	Sample	Age (Ma)	Error (1σ)	Mean	Source
Kivett	Malheur Butte	KL329	0.8	0.7		1
	Brogan	KL060	1.7	0.1		1
		KL313	1.9	0.3		1
Sourdough	Rock Springs	UO123	7.8	0.5		3
	Double Mountain	M4115	8.1	0.2		3
Devine Canyon Ash-Flow Tuff (Bully Creek Formation)			9.2			2
			9.5		9.5	3
			9.7			4
Keeney	Bully Creek	KL293	10.4	0.8		1
	Kern Top	KL110	10.3	1.2		1
	Vines Hill	KL251	10.1	1.4		1
	Freezeout Mountain	90BO75	11.5	2.0		1
	Cherry Creek	MP050	12.2	0.2		5
		MP050	11.5	0.4		1
	Negro Rock	KL326	13.4	0.8		1
Wildcat Creek Ash-Flow Tuff		SC054	15.9*	0.2		1
Tims Peak	Hat Top	KL273	13.4	3.6		1
		BB080	13.6	0.2		5
	Prava Peak	MP028	13.1	0.2	13.5	5
		MP028	13.9	0.2		1
Hog Creek	Westfall Bt basalt	WB104	14.5	0.3		5
	Westfall Bt rhyolite	WB134	15.0	0.1		5
	Spring Creek	SK078	15.3	0.1		5
		SK078	15.4	0.2		1
	Littlefield Rhyolite	KL276	16.6*	0.1		1
	Hunter Creek Basalt	HOR09	15.8	0.3	15.3	1
	Rhyolite of Cottonwood Mountain	KL046	15.5	0.7		1
		Kl046	15.7	0.2		1
		KL230	14.6	1.0		1
	Dinner Cr Ash-Flow Tuff	KL246	15.1	2.0		1
		KL206	15.4	0.6		1
		DC270	15.3	0.4		6
Basalt of Malheur Gorge (BMG)	Birch Creek	KL034	14.4	0.4		1
		KL220	15.1	0.3	15.2	1
		KL278	15.9	0.1		1
	Upper Pole Creek (UPC)	KL319	15.2	2.8		1
		KL001	15.5	0.6		1
		KL248	16.6	0.8	16.0	1
		KL164	16.8	0.3		1
	Lower Pole Creek (LPC)	KL049	17.0	0.8	16.4	1
		KL333	15.8	2.8		1

Note: Sources: 1—this paper (see text footnote 1); 2—Ferns et al. (1993a, 1993b); (3)—Fiebelkorn et al. (1982); 4—A.L. Deino and A.L. Grunder (1993, personal commun.); 5—R.A. Duncan (1998, personal commun.); 6—Laurson and Hammond (1974).
*Dates considered invalid because they are older than stratigraphic age.

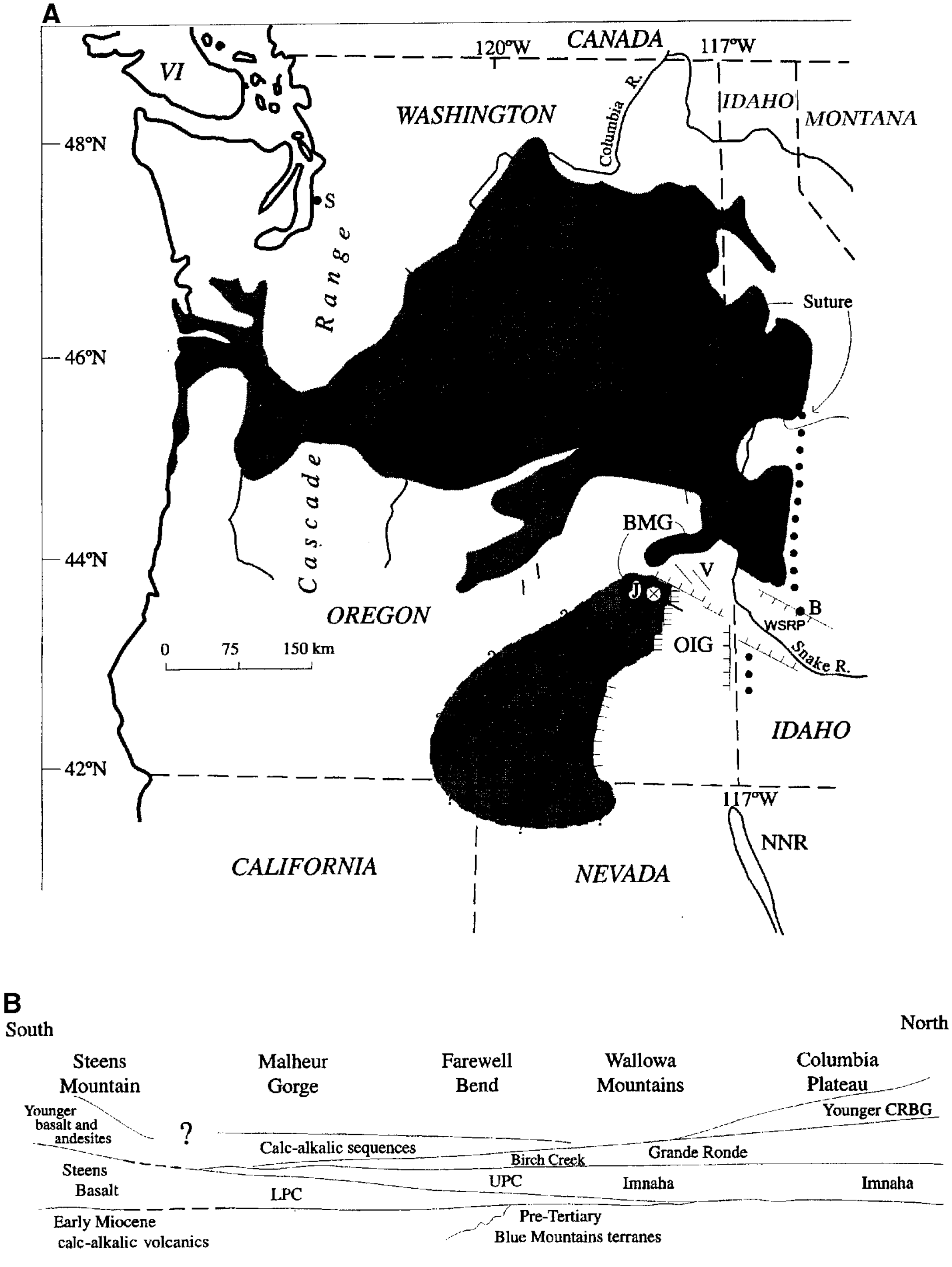

Figure 1. (A) Regional sketch map showing the distribution of Miocene flood basalts in the Pacific Northwest. These include the Steens Basalt, the basalt of Malheur Gorge (BMG), and the Columbia River Basalt Group (CRBG). Note that the Steens Basalt may have been displaced to the west by posteruptive east-west extension that formed the Oregon-Idaho graben (OIG) and by oblique right-lateral movement along the western Snake River Plain (WSRP) (Hooper et al., 2002). B—Boise, C—Cornucopia dike swarm, D—John Day basin filled with the Picture Gorge Basalt (Columbia River Basalt Group) fed by the Monument dike swarm, F—Farewell Bend, GR—Grande Ronde dike swarm, J—Juntura and Malheur Gorge, cut by the west-northwest–trending Malheur Gorge fault, NNR—North Nevada rift, OWL—Olympic-Wallowa lineament, P—Portland, S—Seattle, SB—Squaw Butte, SM—Steens Mountain, V—Vale fault zone, VI—Vancouver Island, W—Wallowa Mountains (horst). "Suture" refers to the Idaho suture zone, a lithospheric boundary in Idaho and Washington between the older, thicker, North American craton to the east and north and the Blue Mountains accreted oceanic terranes to the west (Armstrong et al., 1977; Fleck and Criss, 1985). (B) Cartoon of stratigraphic relationships among the Steens Basalt, the basalt of Malheur Gorge (including LPC—Lower Pole Creek, UPC—Upper Pole Creek, and Birch Creek) and the formations of the Columbia River Basalt Group (CRBG) between Steens Mountain and the Columbia Plateau. Not to scale.

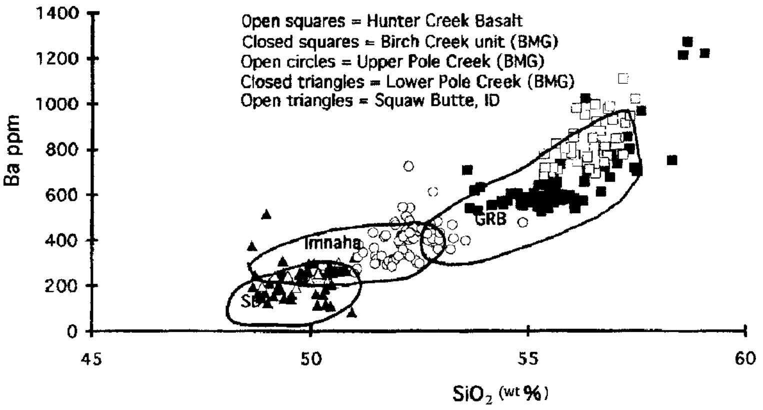

Figure 2. Ba vs. SiO_2 plot of the Hunter Creek Basalt, the three units of the basalt of Malheur Gorge (BMG), and the magnetically reversed flows at the base of the Squaw Butte section (in Idaho; see Fig. 1 for location) of the Columbia River Basalt Group (Martin, 1984, and this study). Fields for comparison are Grande Ronde Basalt (GRB) and Imnaha Basalt of the Columbia River Basalt Group (Hooper et al., 1984; Hooper, 2000) and the lower 43 magnetically reversed flows of Steens Basalt (SB) at Steens Mountain (Binger, 1997; Johnson et al., 1998a). Note the similarity in chemical composition (1) between the lowest of the three units (Lower Pole Creek) of the basalt of Malheur Gorge, the magnetically reversed flows at the base of the basalt section at Squaw Butte, and the field of reversely magnetized lower flows of the Steens Basalt; and (2) between the upper two units (Upper Pole Creek and Birch Creek) of the basalt of Malheur Gorge and the fields of the Imnaha and Grande Ronde Basalts of the Columbia River Basalt Group on the Columbia Plateau. Note also that the Hunter Creek Basalt is stratigraphically part of the Hog Creek sequence but is interpreted as the final eruption of the tholeiitic magma (basalt of Malheur Gorge). The results of 700 major and trace element whole-rock X-ray fluorescence analyses from east-central Oregon used in this study are available (see footnote 1) from prhooper@mail.wsu.edu.

these older dates can now be discounted, and we concur with R.A. Duncan (1999, personal commun.) that all Imnaha and Grande Ronde Basalt flows (>90% of the Columbia River Basalt Group on the Columbia Plateau) were erupted between 16.1 Ma and 15.0 Ma.

Hog Creek Sequence

In the Malheur Gorge area on the northwest shoulder of the Oregon-Idaho graben (Fig. 1; Cummings et al., 2000), the Birch Creek flows of the basalt of Malheur Gorge are overlain conformably by a conspicuous suite of volcanic units of similar age that is assigned to the Hog Creek sequence (Lees, 1994). These include the Dinner Creek Ash-Flow Tuff (DCT; Table 1; Haddock, 1967), the rhyolite of Cottonwood Mountain, the Hunter Creek Basalt, and the Littlefield Rhyolite (Kittleman et al., 1965, 1967; Ferns et al., 1993a, 1993b; Binger, 1997; Cummings et al., 2000).

These units are all conformable on the basalt of Malheur Gorge, and field evidence implies that all units of the Hog Creek sequence erupted over a very short period of time. Intercalated bands and rock fragments of Hunter Creek Basalt composition are present in the Dinner Creek Ash-Flow Tuff (Evans, 1990a), whereas the rhyolite of Cottonwood Mountain occurs both below and, more typically, above the Hunter Creek Basalt (Binger, 1997), suggesting that these two eruptions were contemporaneous. As both the rhyolite of Cottonwood Mountain and the Littlefield Rhyolite are aligned along the faults that form the western margin of the Oregon-Idaho graben—cutting across some of the graben boundary faults and cut by others—both rhyolites are broadly contemporaneous with the initial faulting that formed the graben and with each other as observed by Ferns et al. (1993a) and Cummings et al. (2000).

The Hunter Creek Basalt lies on the same chemical trend as the basalt of Malheur Gorge. Thus, although stratigraphically a member of the Hog Creek sequence, the Hunter Creek Basalt is interpreted genetically as the final eruption of the tholeiitic magma (Fig. 2). In contrast, the various silicic units display scattered trace element concentrations (Fig. 3A) and lack a positive geochemical trend toward higher incompatible element abundances, so they cannot have been derived from a basaltic parent along a single fractionation trend. These units were derived from distinct, probably crustal, sources.

Seven units of the Hog Creek sequence have been dated (Table 1). Their ages overlap and generally lie within the range of a single unit (Table 1). Of these, the older dates obtained for the Littlefield Rhyolite are discarded as unreliable because this rhyolite is demonstrably the youngest Hog Creek unit in the stratigraphic sequence. The weighted mean of the remaining dates is 15.3 Ma ± 0.1 Ma.

In summary, the final products of the tholeiitic eruptions (the Hunter Creek Basalt) are interfingered with the silicic units of the Hog Creek sequence, and both are contemporaneous with the initial opening of the Oregon-Idaho graben (Table 1). The date 15.3 Ma ± 0.1 Ma represents both the end of the flood-basalt eruption in this part of east-central Oregon and the of the formation of the Oregon-Idaho graben.

Tims Peak Basalt

The Hog Creek sequence is unconformably overlain by a series of distinct primitive, diktytaxitic, nonporphyritic, olivine-bearing basalt flows that erupted from a number of different centers along the northwest margin of the Oregon-Idaho graben (Fig. 1; Table 1). These flows were formally named the Tims Peak Basalt by Kittleman et al. (1965, 1967). The Tims Peak Basalt has a chemical trend distinct from that of the tholeiitic basalt of Malheur Gorge, which coincides with the primitive end of the younger Keeney calc-alkalic rock types (Fig. 4). The geographically separate Tims Peak Basalt eruptive centers each produced magmas with subtle but distinctly different compositions (Fig 3B; Binger, 1997). New age determinations of the Tims Peak Basalt have a weighted mean of 13.5 Ma ± 0.1 Ma (Table 1).

Younger Eruptions Across the Oregon-Idaho Graben

Younger volcanic activity occurs as small local eruptions spread across the Oregon-Idaho graben. All are calc-alkalic or mildly alkalic, separated by thick sequences of terrestrial sediment that accumulated in the developing subsidiary grabens (Cummings et al., 2000). The Keeney sequence (13.4 Ma to 10.1 Ma; Table 1; Lees, 1994) includes numerous eruptive calc-alkalic centers. Despite their overall chemical similarities, each Keeney eruptive center is distinguished by subtle but distinctive chemical differences (Fig. 3B).

At the northern end of the Oregon-Idaho

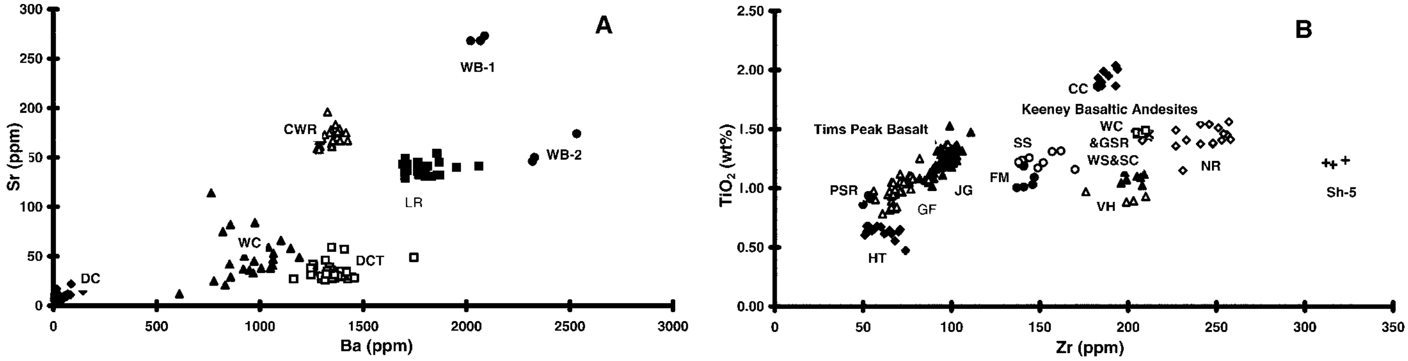

Figure 3. Plots illustrating the consistent differences in chemical composition between volcanic units in east-central Oregon. (A) The Sr vs. Ba plot distinguishes the most important silicic units. CWR—rhyolite of Cottonwood Mountain, DC—Devine Canyon Ash-Flow Tuff, DCT—Dinner Creek Ash-Flow Tuff, LR—Littlefield Rhyolite, WB-1 and WB-2—two ignimbrites in the Westfall Butte Complex, WC—Wildcat Creek Ash-Flow Tuff. (B) The TiO_2 vs. Zr plot distinguishes the more primitive Tims Peak Basalt from the various basaltic andesites and andesites of the Keeney sequence. The plot also distinguishes flows from the geographically distinct eruptive centers of both the Tims Peak Basalt and the Keeney basaltic andesite centers. Tims Peak Basalt: GF—Grasshopper Flat type, HT—Hat Point type, JG—Juniper Gulch type, PSR—Pence Spring Reservoir sill. Keeney sequence: CC—Cherry Creek, FM—Freezeout Mountain, GSR—Gray Stud Reservoir, NR—Negro Rock, SC—Spring Creek, SS—Skull Spring, VH—Vines Hill, WC—Wire Corral, WS—Willow Springs. GSR, SC, SS, and WS are included by Kittleman et al. (1965) in the basalt of Cedar Mountain, whereas WC, CC, and Sh-5 are eruptive cenber assigned by them to the "Shumway Ranch Basalt."

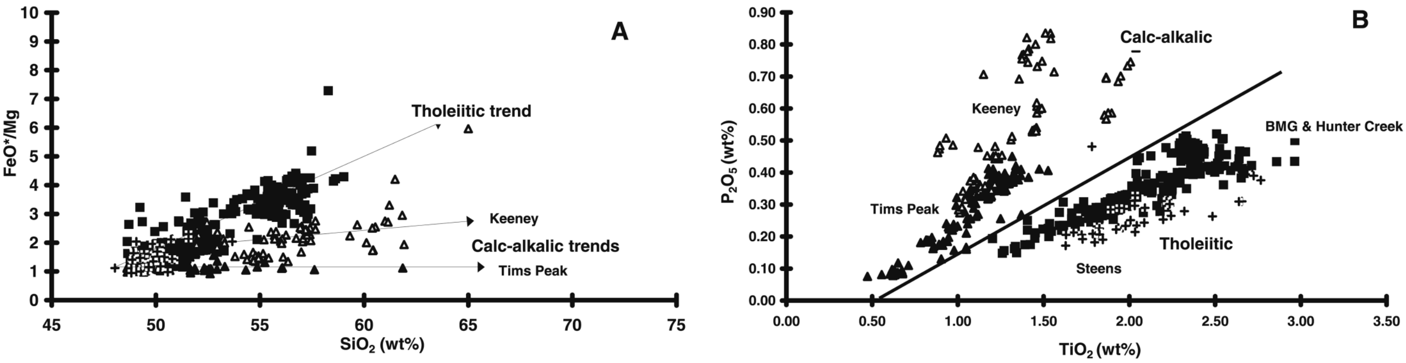

Figure 4. Plots to illustrate the chemical distinction between the 16.4 Ma to 15.3 Ma tholeiitic flood basalts (Steens Mountain Basalt = plus signs; basalts of Malheur Gorge = filled squares) and the extension-related calc-alkalic Tims Peak Basalt (filled triangles) and basaltic andesites of the Keeney sequence (open triangles), both of which postdate the initiation of the Oregon-Idaho graben at 15.3 Ma. (A) FeO*/MgO vs. SiO_2 plot demonstrates the iron enrichment that accompanies increasing SiO_2 in the tholeiites and the lack of such enrichment in the calc-alkalic sequences. (B) P_2O_5 vs. TiO_2 plot illustrates the higher P_2O_5/TiO_2 ratio of the calc-alkalic over the tholeiitic trends.

graben, a thick basin sequence of volcanic and sedimentary strata (the Bully Creek Formation; Ferns et al., 1993a) overlies the Keeney sequence and includes the Devine Canyon Ash-Flow Tuff (Walker, 1990), which has a mean age of 9.5 Ma (Table 1). The Bully Creek Formation is locally capped by flows of porphyritic olivine basalt assigned to the Sourdough sequence (Lees, 1994). The olivine basalts are mildly alkalic, with lower silica contents and higher TiO_2/Zr ratios than flows of either the Keeney sequence below or the Kivett sequence above. Equivalent flows of olivine basalt farther south have been dated at 7.8 Ma ± 0.5 Ma (Table 1; Fieblekorn et al., 1982; Hart, 1982).

The youngest volcanic units in the study area lie within the western Snake River Plain (Fig. 1) and are assigned to the Kivett sequence. They form small volcanic vents surrounded by local flows of andesite and alkali basalt lying along or parallel to the northwest-trending faults of the Vale fault zone (Fig. 1). The andesites are calc-alkalic with major element contents similar to those of flows of the Keeney sequence. The basalts are alkalic with calcic clinopyroxenes and low silica concentrations. The vent that forms Malheur Butte yields a date of 0.8 Ma (± 0.7 Ma), and two samples from Brogan Summit give ages of 1.7 Ma (± 0.1 Ma) and 1.9 Ma (± 0.3 Ma) (Table 1).

DISCUSSION

Volcanic-Tectonic Relationships

Two physically and chemically distinct types of Tertiary magmatism are observed in eastern Oregon; tholeiitic and calc-alkalic. The large-volume tholeiitic flood-basalt type includes typical Columbia River basalts lying conformably on the Steens Basalt. Clarification of the stratigraphic relationship between the Steens Basalt and Columbia River basalts, backed by more precise $^{39}Ar/^{40}Ar$ dates, permits the Steens Basalt to be regarded with some confidence as the earliest manifestation of the flood-basalt eruption. The coincidence

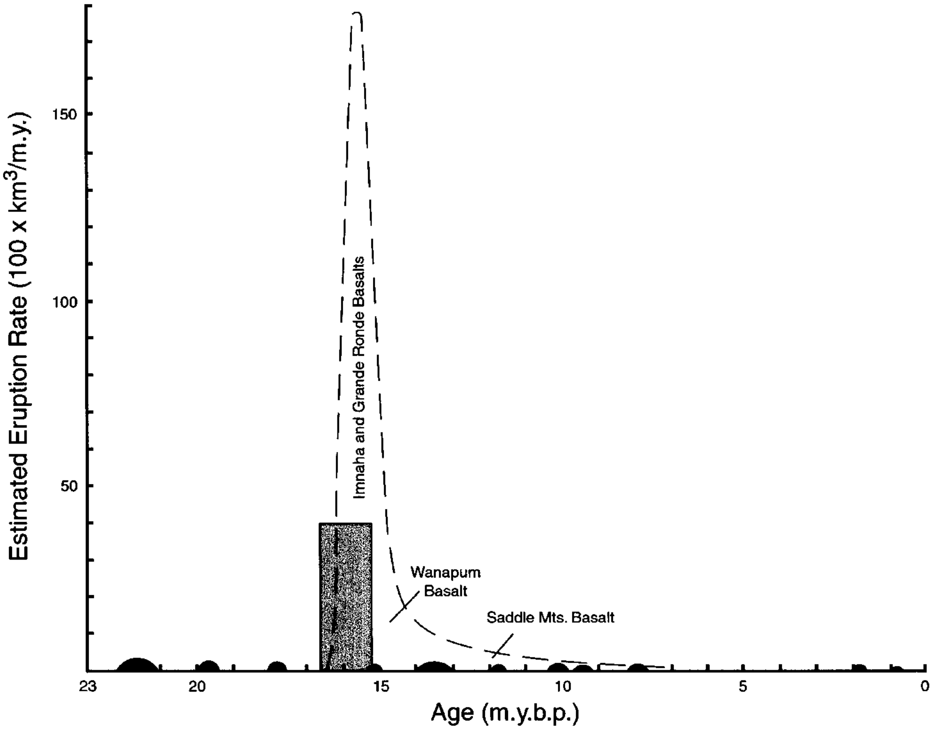

Figure 5. Estimated volcanic eruption rates in east-central Oregon over the past 23 m.y. Pale shading is the Steens Basalt and the basalt of Malheur Gorge tholeiites (estimated from Carlson and Hart, 1987, and this study). In black are the small extension-related calc-alkalic eruptions discussed in the text and Table 1. Dashed line indicates estimated eruption rates with time for the Columbia River Basalt Group on the Columbia Plateau (see Tolan et al., 1989).

in space and time of the Steens Basalt eruption with the calculated impingement of the Yellowstone hotspot beneath southeast Oregon (Engebretson et al., 1985; Pierce and Morgan, 1992) supports the model that connects the origin of this flood-basalt province with the arrival of the Yellowstone hotspot.

In contrast to other classic flood-basalt provinces (Ellam and Cox, 1991; Peng and Mahoney, 1995), these early flows of the flood-basalt province are normal phyric tholeiites that apparently lack alkalic or picritic members other than simple cumulates (Gunn and Watkins, 1970; Carlson and Hart, 1987; Johnson et al., 1998a; J.G. Evans, 1997, personal commun.).

The flood-basalt tholeiites were erupted during a short interval (16.6 Ma to 15.3 Ma) between numerous, small-volume, calc-alkalic volcanic units that lie beneath the Steens Basalt at Steens Mountain and above the tholeiites in the Malheur Gorge (Fig. 5). At Steens Mountain, the pretholeiitic calc-alkalic units are dated, from the base upward, at 21.3 Ma, 22.1 Ma, 19.5 Ma, and 17.8 Ma (Everden et al., 1964; Laursen and Hammond, 1974; Anita L. Grunder, 1998, personal commun.; Johnson et al., 1998a). In the Malheur Gorge, the Hog Creek and younger (post–15.3 Ma) calc-alkalic to mildly alkalic volcanic units are directly associated with formation of the Oregon-Idaho graben.

Calc-alkalic Eocene to Holocene magmatic events occurred from British Columbia to Nevada. They are consistently associated with east-west extension and widely attributed to decompressional melting of lithospheric source components (Robyn, 1979; Thorkelson, 1989; Fitton et al., 1991; Janecke, 1992; Hawkesworth et al., 1995; Hooper et al., 1995; Morris and Hooper, 1997; Morris et al., 2000). The association of these small-volume calc-alkalic eruptions with east-west extension is particularly clear in east-central Oregon. In the Malheur Gorge area on the northeast shoulder of the Oregon-Idaho graben (Fig. 1), the Hog Creek sequence includes the last flows of the tholeiitic sequence (Hunter Creek Basalt) that interfinger with the silicic units directly associated with the graben boundary faults. A short but significant hiatus in volcanic activity, from 14.5 Ma to 13.5 Ma, separates the Hog Creek sequence from the primitive calc-alkalic Tims Peak Basalt (Table 1). During the volcanic hiatus, east-west extension continued. The Oregon-Idaho graben boundary faults continued to form, cutting the rhyolite of Cottonwood Mountain and the Littlefield Rhyolite, and a combination of right-lateral and vertical movement displaced members of the Hog Creek sequence along the west-northwest–trending Malheur Gorge fault, which acted as a pull-apart structure to form a narrow graben along the eastern end of the gorge (Hooper et al., 2002). As a result of this extensional deformation, the Tims Peak Basalt lies unconformably on units of the Hog Creek sequence and is not displaced by the Malheur Gorge fault (Johnson et al., 1998b). Younger volcanic activity (Keeney, Sourdough, and Kivett sequences) occurred as small-volume eruptions across the developing Oregon-Idaho graben. These units are calc-alkalic to mildly alkalic and accompanied the continued evolution of the graben as it filled with thick units of terrestrial sediment and pyroclastic horizons (Cummings et al., 2000).

Wider Tectonic Implications

The eruption of the Miocene flood basalts of eastern Oregon, Washington, and Idaho can be seen as a single brief but dramatic interlude (16.6–14.5 Ma) within the long-standing calc-alkalic to mildly alkalic volcanism associated with the east-west extension that has dominated Eocene to the present tectonics of the inland Pacific Northwest at the northern end of the Basin and Range province.

The flood-basalt eruption began with the Steens Basalt, which covered an estimated 65 000 km^2 of southeastern Oregon (Carlson and Hart, 1987) at 16.6 Ma, a time when plate reconstruction (Engebretson et al., 1985) and the track of the Yellowstone hotspot (Pierce and Morgan, 1992) both place the hotspot beneath southeast Oregon. Eruption of the Steens Basalt, therefore, correlates both in space and time with the arrival of the hotspot. The Steens Basalt was followed, without a detectable hiatus, by flows typical of Imnaha and Grande Ronde basalt eruptions (Fig. 1B). We conclude this continuum implies a causal relationship between the impingement of the hotspot on the base of the lithosphere and the eruptions in the whole Columbia River flood-basalt province.

The clear distinction between the two types of magmatism in east-central Oregon and their respective associations with a long-continuing extensional regime on the one hand and with the abrupt impingement of the hotspot on the other, are critical to interpreting the origin of the flood basalts. There is now little evidence to support backarc spreading as the prime cause of the flood-basalt eruptions (Carlson and Hart, 1987); the pervading extension was indeed present, but its association was with the small-scale calc-alkalic volcanism, not with the flood basalts.

Formation of the 50-km-wide Oregon-Idaho graben, immediately following the early eruptions of flood basalt, presumably displaced the Steens Mountain volcanic center westward from an original position closer to the Idaho lithospheric suture zone (the $^{87}Sr/^{86}Sr$ line of Armstrong et al., 1977) (Fig. 1A). Restoration of the Steens Mountain eruption up to 50 km to the east strengthens the concept of the flood basalts erupting along an approximately north-south linear zone of weakness or ''thin zone'' (Thompson and Gibson, 1991; Zoback et al., 1994; Camp, 1995) extending from Steens Mountain north to the Washington State border, parallel to and just west of, the old lithospheric suture. In all probability this was a relatively narrow zone of weakness, perhaps an older graben developed by earlier extension in the relatively thin accreted lithosphere to the west of the suture. This ''thin zone'' probably did not include either the North Nevada rift (NNR, Fig. 1; Zoback et al., 1994) or the west-northwest–trending western Snake River Plain (Hooper et al., 2002), both of which are more obviously associated with calc-alkalic to mildly alkalic magmatism and/or east-west extension.

Although not the direct cause of the flood-basalt magmatism, extension may have been influenced by the proximity to the Yellowstone hotspot. Softening of the lithosphere by the hotspot and accompanying massive tholeiitic extrusions, may account for the rapid east-west extension that formed the 50 km wide Oregon-Idaho immediately following the first tholeiitic eruptions. It is also possible that this enhanced extension dragged part of the cratonic lithospheric keel westward to inhibit further eruptions from immediately above the hotspot and to channel the tholeiitic magmas northward along the lithospheric ''thin zone'' toward the Washington border. This model provides a plausible explanation for the sudden cessation of flood-basalt activity in east-central Oregon at 13.5 Ma and is a further possible explanation (see Geist and Richards, 1993, and Camp, 1995) for the northward migration of the flood-basalt magma to the Columbia Plateau, where it continued to erupt for another 7 m.y. (Tolan et al., 1989).

It is also plausible, if speculative, that the lateral spreading of the plume head of the hotspot contributed not only to the northward migration of the eruption, but also both to the east-to-west migration of silicic activity along the previously weakened Brothers fault zone and to the increased volume of magmatism along the North Nevada rift.

Eruption of the flood basalts from linear vent systems parallel and adjacent to the edge of older, thicker cratonic crust resembles the geometry advocated by Anderson (1994) for the origin of these massive eruptions by means of convection induced by lithospheric boundaries of different thickness. But the coincidence of the first eruptions occurring precisely where and when the Yellowstone hotspot is first recognized appears to confirm the association of these eruptions with the arrival of a hotspot. The origin of the hotspot remains unclear, but given elevated upper-mantle temperatures and the consequent production of exceptionally large volumes of basaltic melt along such a cratonic boundary, that melt would inevitably migrate to the shallower crust-mantle boundary beneath the accreted terranes to the west of the lithospheric suture.

CONCLUSIONS

Stratigraphic, petrographic, and chemical correlations demonstrate that the Columbia River flood-basalt province began with the eruption of the Steens Basalt in southeast Oregon at 16.6 Ma, at the time and place of the independently calculated impingement of the Yellowstone hotspot. The focus of the flood-basalt eruption then moved north to the southeast corner of the Columbia Plateau, where 90% of the eruption of the Columbia River Basalt Group (the Imnaha and Grande Ronde Basalt Formations) took place between 16.1 and 15.0 Ma. In east-central Oregon, the voluminous flood-basalt eruptions were superimposed in a short interval (16.6–15.3 Ma) on the intermittent, small, and compositionally variable calc-alkalic to mildly alkalic volcanism that has accompanied east-west extension here, and in the whole inland Pacific Northwest, since the Eocene.

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