

Origin and Evolution of the Western Snake River Plain: Implications From Stratigraphy, Faulting, and the Geochemistry of Basalts Near Mountain Home, Idaho

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ABSTRACT

Most models for the origin and evolution of the Snake River Plain (SRP) volcanic province focus on the central role of the Yellowstone hot spot and its effects on the lithosphere of North America in response to plate motions relative to this hot spot. Movement of the North American plate over the Yellowstone hot spot has resulted in a linear track of volcanism that parallels this plate motion, represented today by volcanic rocks of the eastern SRP.

The western SRP is a structural graben oriented at a high angle to the trace of the Yellowstone plume and to the axis of the eastern SRP. It is filled largely with lacustrine sediments related to Pliocene Lake Idaho, a large, long-lived lake system that formed first at the northwestern end of the graben (near Oregon) and extended to the southeast along with the structural graben. High-temperature rhyolite lavas that mark the onset of extension also become younger to the southeast.

Basaltic volcanism in the western SRP occurred in two distinct episodes. The first episode, represented by samples from a deep drill core near Mountain Home and by older surface outcrops that sit directly on rhyolite, is characterized by ferrobasalts that are distinct from other

SRP basalts. The second episode is represented by surface flows of Pleistocene age that overlie lacustrine and deltaic sediments of Lake Idaho. These basalts are associated with young faults that reflect Basin and Range extension.

We propose that the western SRP graben represents an aulocogenlike structure formed in response to thermal tumescence above the Yellowstone plume head as it rose under eastern Oregon and Washington. The plume head was deflected northwards either by subduction of the Farallon plate (Geist and Richards, 1993) or by impingement of North American plate lithosphere (Camp, 1995). Basaltic volcanism in the western SRP may be related to the flow of depleted plume source mantle along a sublithospheric conduit beneath the western SRP graben from the Columbia River Plateau. The basalts would form by pressure-release melting of this previously depleted material, along with the overlying mantle lithosphere. The younger volcanic episode apparently formed in response to Basin and Range extension, in a fashion analogous to young basaltic volcanism in the eastern SRP. The source of these basalts is uncertain, but may be plume-modified subcontinental lithosphere.

Key words: continental volcanism, hotspots, basalt, Snake River Plain

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INTRODUCTION

The Neogene Snake River Plain (SRP) comprises two distinct tectonic terranes with different crustal structure, stratigraphy, and volcanic history (Figure 1). One is the northeast-trending eastern SRP, a downwarped structural

depression with only minor fault control along its margins (Mabey, 1978, 1982; Malde, 1991; Zentner, 1989; Pierce and Morgan, 1992). This depression becomes progressively elevated towards the east, culminating in the Yellowstone Plateau, the current locus of volcanic activity (Christiansen, 1982; Malde, 1991). The eastern SRP trend is thought to mark the track of the Yellowstone plume from its mid-Miocene location beneath the Owyhee Plateau to its current place under Yellowstone (e.g., Pierce and Morgan, 1992; Malde, 1991; Smith and Braile, 1994), although this hypothesis has been challenged (Humphreys and others, 2000; Christiansen and others, 2002). Recent tomographic data suggest that the plume may actually rise to the west and be tilted eastward by counterflow in the mantle that results from the sinking Farallon slab (Smith and others, 2002; Steinberger and O'Connell, 2002).

The other terrane is the western SRP, a northwest-trending structural graben bounded by en echelon normal faults and filled with sediment up to 1.7 km thick (Malde, 1959, 1991; Malde and others, 1963; Mabey, 1976, 1982; Leeman, 1982). Sedimentary deposits in the western SRP range in age from Miocene through Quaternary and are known collectively as the Idaho Group (Malde and Powers, 1962, 1972; Malde and others, 1963). These deposits are dominantly lacustrine, with subordinate fluvial and phreatomagmatic deposits (Kimmel, 1982; Smith and others, 1982; Jenks and Bonnicksen, 1989; Malde 1991; Godchaux and others, 1992; Jenks and others, 1993). Sedimentation during this time was controlled by the presence of a large lake, Lake Idaho, which expanded or shrank in response to variations in climate and tectonics (Kimmel, 1982; Jenks and Bonnicksen, 1989).

Volcanic activity in the western SRP began about 11 million years ago with the eruption of rhyolite lavas from fissures that paralleled the range-front faults coeval with extension and graben formation (Ekren and others, 1982, 1984; Bonnicksen, 1982). These rhyolites form the local basement upon which subsequent sediments and basalts were deposited. Basaltic activity in the western SRP began about 9 million years ago, forming lavas that underlie sedimentary deposits of Lake Idaho and, later, local basalt horizons intercalated with these sediments (Malde and Powers, 1962, 1972; Amini and others, 1984; Malde, 1991; Jenks and Bonnicksen, 1989; Jenks and others, 1993).

In this paper we summarize the Neogene volcanic history of the western SRP in the area around Mountain Home, with particular emphasis on the basaltic volcanism and volcanic stratigraphy. Volcanic rocks less than 2.0 Ma are exposed as surface flows near Mountain Home,

forming a carapace over sediments of the Idaho Group and documenting an episode of volcanism that occurred some 8 million years after the Yellowstone plume passed this longitude. This area is critical to understanding intracontinental plume tracks because it lies near the intersection of the Yellowstone plume track and the western SRP graben—a tectonic enigma that does not conform to current models of plume-lithosphere interaction (Figure 1). We begin by reviewing first the stratigraphy of volcanic and sedimentary units, their structural deformation, and the geochemistry of the basalts in the Mountain Home area. We then discuss the implications of these data for the Neogene tectonic evolution of the western SRP and the relationship of the western SRP to the Yellowstone plume system.

GEOLOGIC SETTING

Mountain Home is located on the northeast margin of the western SRP, approximately 40 miles southeast of Boise and 70 miles northwest of Twin Falls (Figure 2). The area immediately surrounding Mountain Home is a volcanic plateau, which is underlain by basalt flows and lacustrine sediments of the Idaho Group, at an average

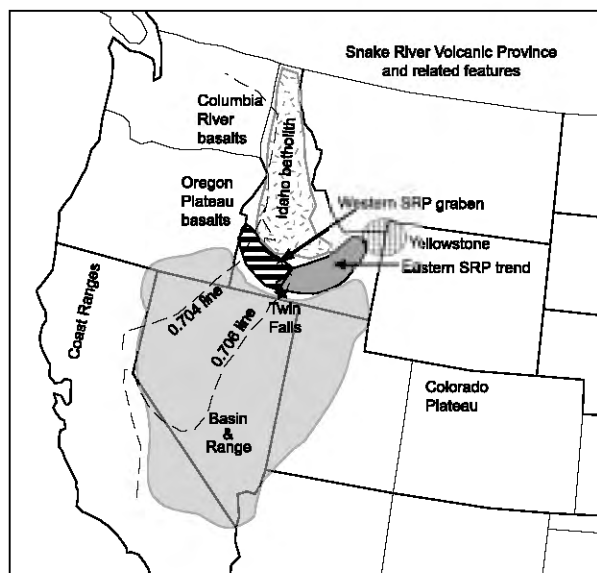


Figure 1. Overview of the northwestern U.S. showing the location of the Snake River Plain and adjacent physiographic regions including the western SRP (horizontal bars), the eastern SRP (dark gray), Columbia River basalt province, the Oregon Plateau basalt province, the Oregon Coast Ranges, the Owyhee Plateau, the Basin and Range Province (pale gray), the Idaho batholith (ticks), the Colorado Plateau, Yellowstone caldera, and the Sr “0.704” and “0.706” lines, which mark the western extent of Proterozoic and Archean crust.

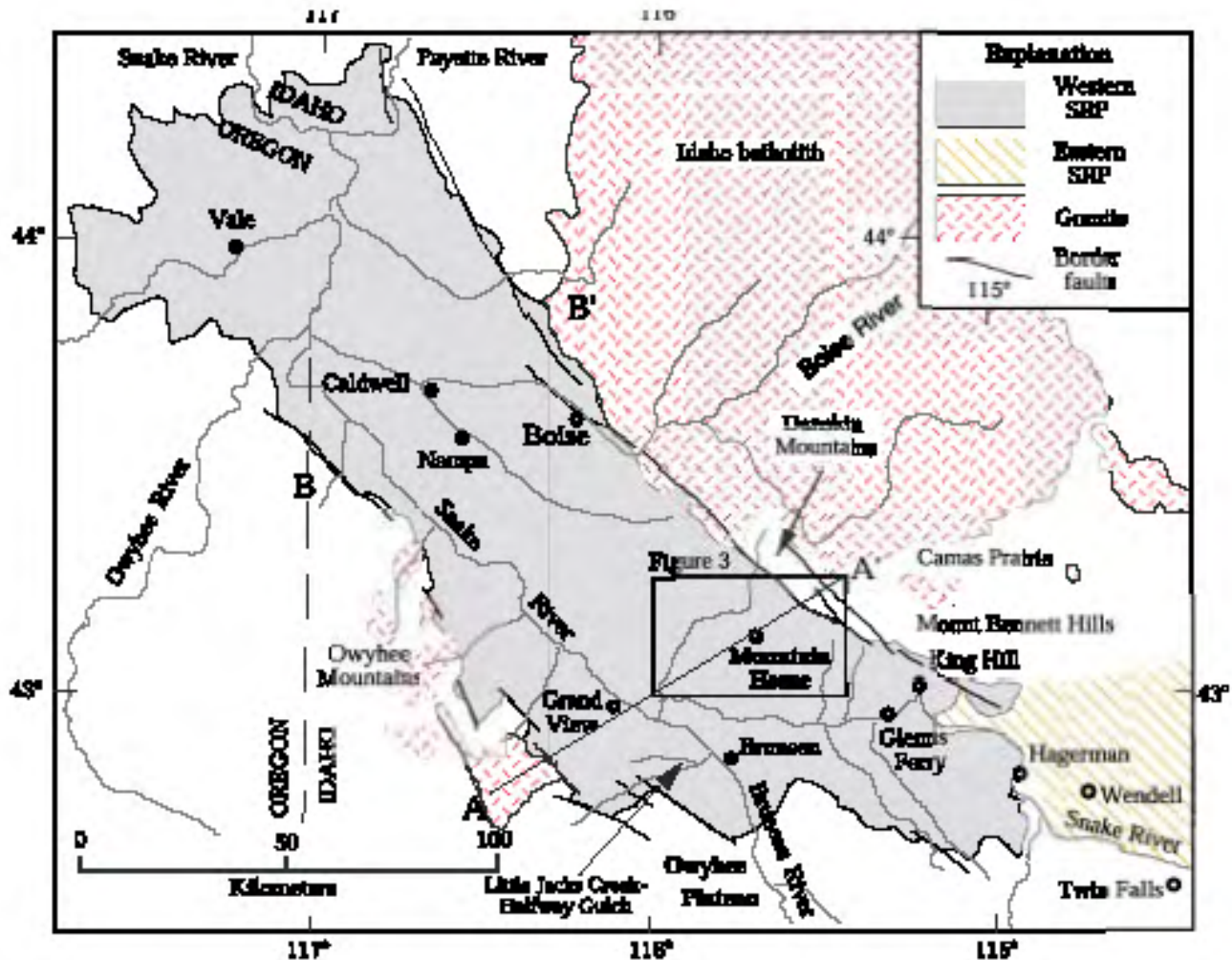


Figure 2. Index map showing southern Idaho and the western Snake River Plain region. Also shown are adjacent parts of the eastern SRP province and the Idaho batholith, and the location of cross sections A-A' (through Mountain Home) and B-B' (through Caldwell; see Figure 6). Unpatterned areas include both rhyolite volcanics and Neogene sediments. Location of the area mapped in Figure 3 is shown by black box.

elevation about 3,200 feet above sea level. The southern limit of this plateau is an escarpment overlooking the current drainage of the Snake River, just upstream from its confluence with the Bruneau River; the elevation at river level is about 2,800 feet. The plateau is truncated along its northern margin by the Danskin Mountains (to the north) and the Mount Bennett Hills (to the northeast). These mountains consist of rhyolite lava flows that have been uplifted along major down-to-the-southwest normal faults, creating a rugged topography with summit elevations from 5,500 to 7,000 feet.

Eight 7.5-minute quadrangles were mapped for this project: Mountain Home North, Mountain Home South, Crater Rings, Crater Rings SW, Crater Rings SE, Cinder Cone Butte, Teapot Dome, and Reverse (Figure 3). The resulting composite map spans 30 minutes of longitude (115°30'W. to 116°0'W.) and 15 minutes of latitude

(43°0'N. to 43°15'N.), encompassing about 450 square miles (1,170 square km). Rhyolite lavas of the Idavada Formation crop out in the northeast corner of the map area; lacustrine and fluvial-deltaic sediments of the Idaho Group crop out in embayments along the southern margin. The area between the rhyolitic Mount Bennett Hills and the southern escarpment is underlain largely by basalt flows covered by soil, windblown dust, and alluvial sediments (Figure 3).

There are fifteen identifiable basaltic vents in this area: two maarlike ring structures, three cinder cones, and nine shield volcanoes (Figure 3). One of the shield volcanoes (Crater Rings) has two spectacular pit craters on its summit, which we count as two separate vents. Most of the younger lava flows in this area can be correlated with one of these fifteen vents. There may be another vent near the northern margin of the plateau that has been ob-

scured by faulting. Vents for older flows exposed along the southern escarpment have been buried by sediments of the Idaho Group or by younger lava flows.

Mapping of the lava flows and their vents, coupled with flow direction indicators in the pillow lava deltas (dip of foreset beds), shows that lavas generally erupted from vents lying along the northeastern margin of the western SRP graben and flowed to the southwest toward the central axis of the western SRP graben. This pattern is mirrored on the southwest margin of the western SRP by vents which erupted lavas that flowed northeast toward the graben axis (e.g., Bonnicksen and Jenks, 1990; Jenks and Bonnicksen, 1990).

STRATIGRAPHY

The stratigraphic framework of the western SRP was first established by Cope (1883), who recognized evidence for a large, long-lived lake in the western SRP graben and named sediments associated with this lake the "Idaho formation." Malde and coworkers (e.g., Malde and Powers, 1962; Malde and others, 1963; Malde, 1991) discounted the importance of a widespread "Lake Idaho" depositional system, preferring a model in which a meandering river system (ancestral Snake River) coexisted with small, short-lived lakes. Malde and Powers (1962) elevated the Idaho formation to Group status and subdivided it into seven separate formations ranging in age from middle Miocene through Pleistocene (Poison Creek, Banbury Basalt, Chalk Hills, Glenss Ferry, Tuana Gravel, Bruneau, and Black Mesa Gravel).

More recent work has shown that the original concept of a large, long-lived lake is correct and that many of the sediments mapped by Malde and coworkers as fluvial flood-plain deposits are in fact nearshore lacustrine sediments or lacustrine deltaic deposits (Kimmel, 1982; Swirydzuk and others, 1979, 1980; Wood, 1984, 1994; Wood and Anderson, 1981; Jenks and Bonnicksen, 1989). Sediments in the main lacustrine units (Chalk Hills and Glenss Ferry formations) are nearly identical lithologically and can only be distinguished from one another based on paleontological assemblages and age (Chalk Hills = late Miocene, Glenss Ferry = Pliocene). An unconformity lies between the Chalk Hills and Glenss Ferry formations (Kimmel, 1982; Smith and others, 1982); the Glenss Ferry Formation is overlain locally by the Tenmile Gravel (= Tuana Gravel).

Quaternary units formerly in use include the Bruneau Formation (Idaho Group) and the Snake River Group; both units were defined to consist of intercalated sediments and basalt flows (Malde and Powers, 1962; Malde, 1991). Bonnicksen and coworkers have found that this

usage is inconsistent with field relations and that basalt flows may be assigned to one formation and their vents assigned to another (Jenks and Bonnicksen, 1989, 1990; Jenks and others, 1993).

In keeping with the practice of Bonnicksen and coworkers (Jenks and Bonnicksen, 1989, 1990; Jenks and others, 1993), we have abandoned the units "Bruneau formation" and "Snake River Group" and prefer instead to map individual basalt flows that in most places can be associated with specific vents and are stratigraphically distinct from other flows. On the southern margins of the map area, these flows are intercalated with lacustrine and fluvial-deltaic sediments deposited during the waning stages of Lake Idaho. Here, individual basalt flows can be mapped on the basis of their stratigraphic position in the sediments, their lateral continuity, and their elevation. We do not assign the sediments above and below these basalts to different formations, because the basalts are laterally finite and at other locations these sediments are contiguous. The basalt flows represent essentially instantaneous events during the slow accumulation of lacustrine sediment.

The mapping conventions followed here are the same as those currently used by the Idaho Geological Survey for mapping in the SRP, and our mapping in the Mountain Home area is tied stratigraphically to published maps of the Idaho Geological Survey along the southern and western margins of our map area (Bonnicksen and Jenks, 1990; Jenks and Bonnicksen, 1990; Jenks and others, 1993).

VOLCANIC UNITS

Volcanic activity in the Mountain Home area can be divided into six distinct phases, one rhyolitic and five basaltic. The phases comprise (from oldest to youngest) rhyolitic volcanism of the Danskin Mountains and Mount Bennett Hills ("Idavada volcanic series"), pre-Lake Idaho basaltic volcanism, late- to post-Lake Idaho plateau-forming basalts that underlie the uplands north of the Snake River drainage, maarlike vents that formed on top of the basaltic plateau, steep-sided shield vents that form the conspicuous hills around Mountain Home, and finally, cinder cone vents that represent the last phase of basaltic volcanism. Eruptive styles seem to be controlled in part by the presence of Lake Idaho and its water-saturated sediments through which many of the later basaltic units erupted.

Volcanic Basement: Idavada Volcanic Series

The oldest volcanic rocks exposed in the Mountain

Home area are rhyolite lava flows that form basement in the Danskin Mountains and the Mount Bennett Hills (northeast corner of map). These rhyolites have been correlated with the Idavada Volcanic Series, which ranges in age from around 9 Ma to 14 Ma (middle Miocene; Armstrong and others, 1975, 1980; Clemens and Wood, 1993).

Clemens and Wood (1993) mapped rhyolite in the area studied here as the Danskin Mountains Rhyolite and mapped rhyolite that crops out farther east as the Mount Bennett Rhyolite. They determined a K-Ar age of 10.0 ± 0.3 Ma for sanidine in a vitrophyre from the summit area on Teapot Dome (Danskin Mountains Rhyolite) and a K-Ar age of 11.0 ± 0.5 Ma for plagioclase in a rhyolite from near Mount Bennett. Possible correlative units on the south side of the western Snake River graben include the Sheep Creek Rhyolite (9.88 ± 0.46 Ma; Hart and Aronson, 1983), the rhyolite of Tigert Springs, the rhyolite of OX Prong, and the rhyolite of Rattlesnake Creek (Kauffman and Bonnicksen, 1990; Jenks and others, 1993). Rhyolite in the eastern Mount Bennett Hills ranges in age from 9.2 ± 0.13 Ma to 10.1 ± 0.3 Ma (Armstrong and others, 1980; Honjo, 1990).

The Danskin Mountains Rhyolite most commonly occurs as a vitrophyre with abundant phenocrysts of sanidine and quartz set in a red, gray-brown, or black volcanic glass. Flow banding appears as laminar variations in the color of the glass or in its crystallinity. The flow banding is commonly folded ptymatically, indicating rheomorphic mobilization of the rhyolite. Flow banding and axial foliation in the vitrophyre generally trend N. 50° W. to N. 60° W., and dip 15° - 45° NE. There are no indications that these rhyolites are rheomorphic ignimbrites; they appear to be rhyolite lavas erupted from fissures that were subparallel to the current range-front faults (B. Bonnicksen, oral commun., 1996, 1997).

Pre-Lake Idaho Basaltic Volcanism

Pre-Lake Idaho basaltic volcanism in the Mountain Home area is represented by core samples from the 4,403-foot Mountain Home Air Force Base (AFB) geothermal test well (Lewis and Stone, 1988) and by basalt horizons that rest directly on rhyolite in the Danskin Mountains and Mount Bennett Hills (Honjo, 1990; Clemens and Wood, 1993). Additional stratigraphic control comes from the 9,676-foot-deep Bostic 1A wildcat petroleum well (Arney and others, 1982, 1984).

The Mountain Home AFB test well was drilled in 1985 on Mountain Home Air Force Base, 10 miles southwest of Mountain Home (Figure 3). The hole was cored continuously from about 1,000 feet to total depth of 4,403

feet, with 60-70 percent recovery above 2,000 feet in the sediments and 90-100 percent recovery below 2,000 feet in the basalts (Lewis and Stone, 1988). Principal rock types are basalt with intercalated sediment (0-532 feet), silty sand and clay (532-1,900 feet), and basalt with minor intercalated hyaloclastites (1,900-4,403 feet). Temperature at the bottom of the hole approached 100°C (Lewis and Stone, 1988).

Basalts of the Mountain Home AFB drill core have not yet been studied in detail, but our preliminary petrographic and geochemical data indicate that they are dark gray to black, aphanitic aphyric to sparsely phyrlic (olivine or plagioclase plus olivine) ferrobasalts. These basalts are remarkably fresh and unaltered, except for a few horizons where the basalt appears to have flowed into water.

Basalts in the Danskin Mountains and Mount Bennett Hills that sit directly on rhyolite or are intercalated with lacustrine sediments that sit on rhyolite have been correlated with the Banbury Basalt of Malde and Powers (1962). They are generally altered olivine basalts, but there are little data that can be used to correlate these flows. Armstrong and others (1980) report a mean age of 9.4 Ma for the Banbury Basalt near Twin Falls, but it is unclear if this correlates with the unit referred to as "Banbury Basalt" in the Mount Bennett Hills (e.g., see Clemens and Wood, 1993, for a discussion of this problem).

Plateau-Forming Basalts: Late- to Post-Lake Idaho

Plateau-forming basalts crop out in the bluffs that overlook the current Snake River drainage, especially in the area north of C.J. Strike Reservoir (Figure 4). Younger plateau-forming basalts are also exposed on the tablelands above the bluffs, but the older plateau-forming units are seen only in cross section. Five plateau-forming basalt units are exposed in or near the area mapped (from oldest to youngest, Figure 3): the basalt of Goldsmith Road (Tgsr), the basalt of Canyon Creek (Tcan), the basalt of Simco Road (QTsim), the basalt of Strike Dam Road (QTstr), and the basalt of Rattlesnake Springs (QTrs). Only two units—the basalt of Rattlesnake Springs and the basalt of Strike Dam Road (Jenks and others, 1993)—can be associated with a specific volcanic vent. Vents for the other units have been buried by subsequent eruptive units, and their locations can only be guessed at using lateral variations in flow thickness.

These basalts typically form thin (8 to 35 feet thick), laterally extensive flows that rest directly on the youngest lacustrine or fluvial deltaic sediments of Lake Idaho or on older plateau-forming basalt units. The units tend



Figure 4. Plateau-forming basalts sitting on lacustrine sediments of the Idaho Group (Lake Idaho). Uppermost basalt is basalt of Rattlesnake Springs; lower unit is basalt of Simco Road. Note landslide deposits below main basalt ledge. View to East overlooking C.J. Strike Reservoir. North to left.

to thin near their margins, which allows us to estimate the relative positions of their buried vents or at least the topographic lows that controlled flow distribution.

The basalt of Goldsmith Road is exposed just south of our map area in a lower “plateau” adjacent to C.J. Strike Reservoir (Jenks and others, 1993). Based on its elevation, it appears to correlate with the deepest post-Lake Idaho basalts in the Mountain Home AFB drill core (about 500 feet below surface on the tableland above C.J. Strike Reservoir (Figure 3).

The basalt of Simco Road is commonly pillowed along its southern margin, suggesting a subaerial lava that flowed into standing water of Lake Idaho or its successors. The subaqueous part of the flow consists of hyaloclastite breccia forming foreset delta sequences with individual “rolled” pillows interspersed. The delta foresets dip to the southeast, indicating the direction the lava flowed when it entered the lake (Figure 5).

The basalt of Rattlesnake Springs is the youngest plateau-forming unit in this area. The vent for this unit is a low, topographically subdued shield volcano about 9 miles southwest of the town of Mountain Home (Figure 3). Despite its low topographic profile, this vent is actually a large structure covering all or large parts of five 7.5-

minute quadrangles. Lava flows from younger vents to the north, northwest, and northeast of this huge volcano flowed around it. The deflection of younger lava flows around the Rattlesnake Springs vent created a topographic “moat” along its northeast margin that filled with alluvial sediments and loess; this filled “moat” is the location of Mountain Home.

The basalt of Rattlesnake Springs rests directly on fluvial-deltaic sediments (sands, silts, gravels) that form the uppermost part of the Idaho Group. Current structures in these sediments show transport directions from north to south consistent with regional drainage of tributary streams into Lake Idaho from the Danskin Mountains.

Maarlike Vents: Fire Fountain Eruptions

These rather inconspicuous maarlike vents can only be seen clearly on large-scale topographic maps, where the low annular ridges that represent the original tuff rings are generally preserved by subsequent spatter deposition and the onlap of late-stage lavas from the central vents. Some of the older plateau-forming basalts may have erupted from maarlike vents also, but these vents have

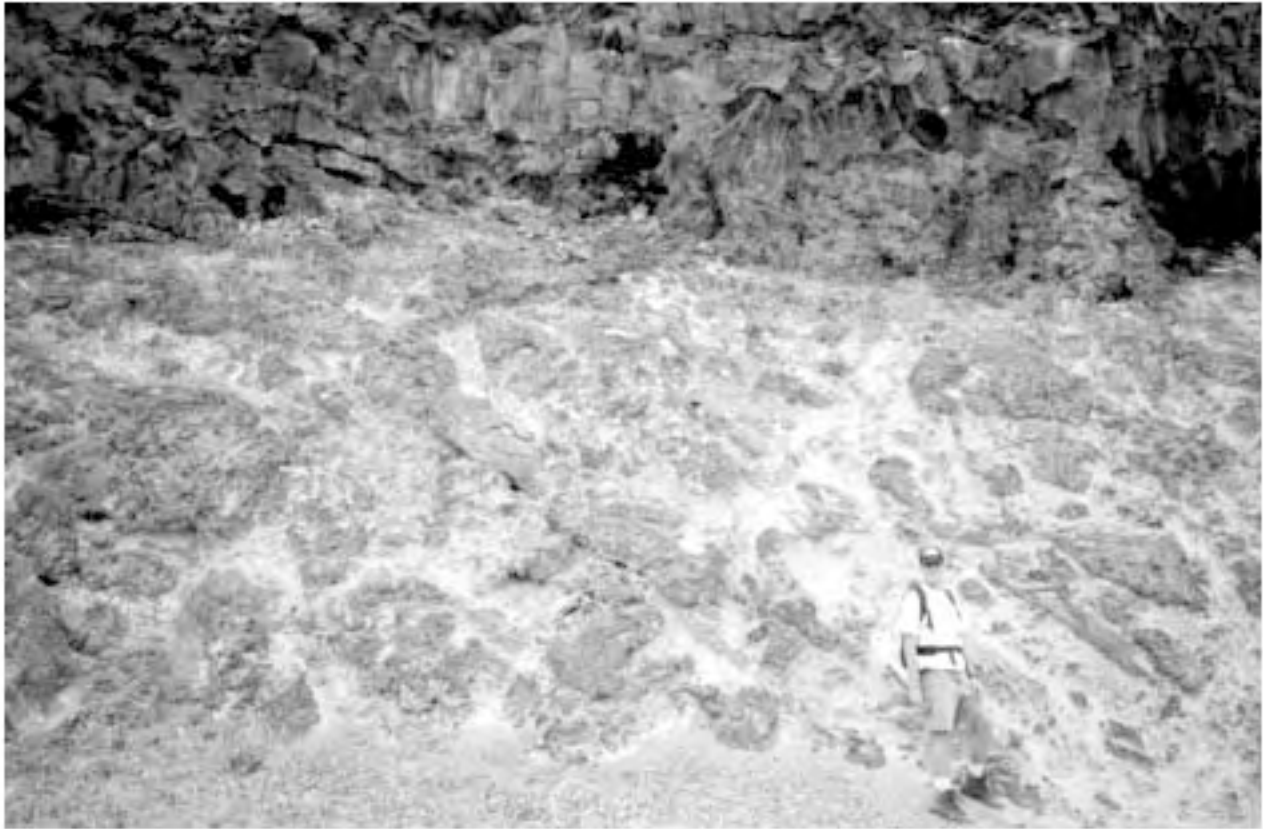


Figure 5. Foreset beds in hyaloclastite breccia + pillow lava delta at the base of the basalt of Strike Dam Road. Delta grades upward from dominantly glassy breccia to breccia + isolated pillows to subaerial basalt. Delta is underlain by lacustrine sediments (silty clay) of Idaho Group. Water depth was about 20 feet here. View to northeast.

been buried by younger flows. Bonnicksen (oral commun., 1996) suggests that these vents began as phreatomagmatic eruptions through water-saturated sediments, then shifted to fire fountain eruption style as the underlying sediments became dewatered. This model is difficult to evaluate, because the surface volcanic deposits cover evidence for the proposed earlier phreatomagmatic event. Nonetheless, an early phreatomagmatic eruptive style is consistent with the overall geometry of these vents.

There are two maarlike vents in the map area: the basalt of Brush (Qbr) and the basalt of Sheep (Qsh). Vents for both units consist of topographically low annular ridges that form ringlike structures about 2 to 3 miles (3 to 5 km) across. The ramparts of these ring structures are constructed largely of welded spatter, but cinder accumulations are found in places. Despite their maarlike structures, the dominant eruptive mode for these vents seems to have been fire fountain eruptions that formed abundant spatter and relatively fine-grained cinders (about 1 to 2 mm).

Shield Volcanoes

Shield volcanoes are the most common volcanic landforms in the Mountain Home area. These steep-sided volcanoes rise conspicuously above the tablelands formed by the plateau-forming basalts with 400 feet to 700 feet of relief (Figure 3). These vents are generally steeper than typical shield volcanoes and may represent magmas that are more viscous than typical Hawaiian tholeiites. These lavas rest on older plateau-forming basalts or on soil horizons developed on top of the older flows. The well-developed soil horizons, with extensive caliche layers, indicate that flows of different ages may be separated by several thousands of years.

Eight basalts are associated with shield volcano vents: the basalt of Teapot Basin (Qtb), the basalt of Rattlesnake Creek (Qrc), the basalt of Teapot South (Qts), the basalt of Teapot North (Qtn), the basalt of Rocky (Qrk), the basalt of Lockman Butte West (Qlbw), the basalt of Lockman Butte East (Qlbe), and the Crater Rings basalt (Qcr; Figure 2). It is not possible to discern the exact

order of eruption since not all of the vents have flows that overlap, but the list above represents their approximate stratigraphic order; the Crater Rings basalt appears to be the youngest unit of this series. In addition, other basalts in the uplands north of Mountain Home cannot be connected with a specific vent because of subsequent faulting. These units are mapped as undifferentiated basalt (Qbu).

The basalt of Lockman Butte West is a plagioclase-phyric ferrobasalt characterized by internal fractionation during flow (McGee and Shervais, 1997). Where well-exposed by a large roadcut along highway I-84, flow units of this basalt show flotation of plagioclase within covered lava tubes, and draining of very Fe-rich (about 16.5 weight percent total iron as FeO) ferrobasalt magma from the plagioclase cumulates into an aphyric bottom layer (McGee and Shervais, 1997). The plagioclase-rich flotation layers are characterized by diktytaxitic textures towards their tops (where exsolved gases have replaced the interstitial magma) and intergranular textures near their bases (where interstitial magma crystallized in place). Partially replaced magnesian olivine phenocrysts (Fo_{90}) suggest that the ferrobasalt was formed by extreme olivine fractionation of a primary picrite. The Fe-rich nature of these lavas is emphasized by the occurrence of Fe-rich K-feldspar, with about 5.5 weight percent Fe_2O_3 (McGee and Shervais, 1997).

The Crater Rings is a spectacular volcanic feature consisting of two large pit craters at the summit of a broad shield volcano about 5 miles west of Mountain Home (Figure 3). The smaller western crater is about 2,500 feet across and 300 feet deep; the larger eastern crater is about 3,000 feet across and 350 feet deep. The eastern crater is surmounted by spatter and agglutinate ramparts on its northern, eastern, and southern sides. Internally, the pit craters consist of welded spatter, agglutinate, and minor intercalated lava flows. The welded spatter and agglutinate are easily identified by their characteristic textures, oxidized coloration, and hollow ring when struck with a hammer.

The internal stratigraphy of the craters shows that they represent former lava lakes, similar to Halemaumau pit crater on the summit of Kilauea volcano and to the paired lava lakes of the 1972 Mauna Ulu eruption (Hawaii: Decker, 1987; Tilling and others, 1987). No fragmental horizons are exposed in the crater walls, which would suggest phreatomagmatic eruption. Fire fountains erupting through the lava lakes fed spatter to the rims, which were occasionally mantled by lava flows when the lava lakes overflowed their ramparts. The final eruptive phase was confined to the eastern vent, where fire fountains built ramparts on three sides of the vent that were not covered by subsequent lava flows, although lava from

the eastern vent may have flowed into the western vent during lava highstands at this time. A more recent but equally spectacular example of a double pit crater is Black Butte Crater, the source of the Shoshone flow, located 16 miles north of the town of Shoshone in central Idaho.

Cinder Cone Vents: Last Volcanic Phase

The youngest volcanic features found in the Mountain Home area are cinder cone vents with 150 feet to 300 feet of relief that erupted north of the Rattlesnake Springs shield volcano. The youngest of these is exceptionally well preserved and has no overlying soil in the vent area, consistent with an age of less than 300,000 years. These vents include the Cinder Cone Butte basalt, the Union basalt, and the basalt of Cinder Pit (Figure 2). The Union basalt and the basalt of Cinder Pit erupted from vents immediately north of the Rattlesnake Springs shield volcano, and flows from both of the younger vents were deflected around the older volcano.

SEDIMENTARY ROCKS

Idaho Group (Tida)

Lacustrine sediments and fluvial-deltaic deposits associated with Neogene Lake Idaho are found along the southern rim of the tablelands that underlie the Mountain Home area, much of which lies south of our map (Figure 3). Only 400–450 feet of Idaho Group sediment is exposed in the bluffs that overlook the current Snake River drainage (Figure 4), but drilling on the Mountain Home AFB demonstrates at least 1,400 feet of sediment beneath the deepest postlake basalt (Lewis and Stone, 1988). Farther to the east (about 20 miles east of the Mountain Home AFB core) the 9,676-foot-deep Bostic 1A well penetrated over 4,500 feet of lacustrine sediments with two basalt intercalations, each about 650 feet thick (Arney and others, 1982, 1984).

Generally, the sediments are fine-grained, calcareous, clay-rich muds and silts, with sandy silts higher in the section (Kimmel, 1982; Swirydzuk and others, 1979, 1980; Smith and others, 1982). Ash beds and ash-rich sediments are common (Swirydzuk and others, 1982). The sediments are white to pale green and have fine laminar bedding and rare current structures. The sandy layers may be graded, suggesting deposition from turbidity currents (Jenks and others, 1993). Oolitic limestone horizons are interpreted to represent shoreline facies (Swirydzuk and others, 1979, 1980). Other reefal limestone horizons represent algal or sponge reefs that formed

parallel to the shoreline (Straccia and others, 1990; Jenks and others, 1993).

Sediments intercalated with basalt in the bluffs above C.J. Strike Reservoir are commonly sandy, with both laminar and trough cross-bedding, indicating a fluvial-deltaic environment along the margins of the lake. This is supported by the observation that hyaloclastites and pillow deltas (Figure 5) are found only beneath the southernmost exposures of plateau-forming lavas; exposures farther north show little or no effects of basalt-water interaction. Cross-beds in the fluvial sands beneath the basalt of Rattlesnake Springs show currents moving from north to south, towards the axis of the western SRP graben.

No fossil data are available for this area, but the stratigraphic level of the exposed sediments and their location suggests correlation with sediments of the Pleistocene Bruneau Formation. Older sediments exposed in core or cuttings and lacustrine sediments exposed south of the Mountain Home area probably correlate with the Pliocene Glens Ferry Formation or Miocene Chalk Hills Formation of Malde and Powers (1962).

Surficial Deposits

Surficial deposits include the Melon Gravel (coarse, unsorted sand, gravel, and boulders deposited by the Bonneville Flood; Malde and Powers, 1962), intermittent lake deposits (clay- to silt-sized sediments transported largely as windblown loess and deposited into intermittent lakes that form in depressions on the surface of basalt flows; Jenks and others, 1993), talus and alluvial fan deposits that form along major range-front fault scarps, landslide deposits (produced by passage of the catastrophic Bonneville Flood, as discussed by Jenks and others, 1993), and alluvium (unconsolidated stream and valley deposits, including clay, silt, sand, and gravel).

STRUCTURE

Structural deformation of the Mountain Home area is restricted to high-angle faulting with two modes: (1) range-front faults that offset rhyolite and resulted in uplift of the Danskin Mountains and Mount Bennett Hills, and (2) younger faults that offset the surface of basalt flows or the alluvium. Tilting is evident in the rhyolite bedrock of the Mount Bennett Hills but is more difficult to establish elsewhere. Nonetheless, faulting clearly spans a range of ages (Neogene to Holocene) and has resulted in significant movement in the recent past.

RANGE-FRONT FAULTS

The range-front faults and related faults that offset

rhyolite of the Idavada Formation are responsible for uplift of the Danskin Mountains and Mount Bennett Hills and for faulting within these ranges (Malde, 1959). These faults trend approximately N. 55° W. and have near vertical to steep southwest dips (Figure 3). In general, throw is down to the southwest, so most of these faults are normal (Figure 6). Most actual range-front faults are concealed beneath talus or alluvial fan deposits. Malde (1991) estimates that the accumulated throw across these faults is about 9,000 feet (2,900 m), as shown by the elevation difference between the top of silicic volcanic rocks in the Bostic 1-A well (Arney and others, 1982, 1984) and the rhyolite lavas of the Mount Bennett Hills (Malde, 1959).

Interpretive cross sections of the western SRP show the arrangement of range-front faults, which control subsidence of the graben, and the distribution of volcanic and sedimentary fill within the graben (Figure 6). Cross section A-A' transects the western SRP through Mountain Home, whereas section B-B' (modified from Wood, 1994) depicts a transect through Caldwell (see Figure 3 for locations of cross sections). The Mountain Home section (based on surface maps, deep well logs and regional gravity anomalies) shows rhyolite basement overlain by Banbury Basalt, lacustrine sediments of Lake Idaho, and a thick wedge of early Pliocene basalt (Figure 6). This wedge pinches out to the southeast, as shown by well logs of the Bostic 1A well (Arney and others, 1982). The lacustrine sediments are capped by thin basalt flows intercalated with sediment on the uplands surrounding Mountain Home. The central basement high and the thick sections of basalt on each side of the basement high are required by the regional gravity anomaly (Arney and others, 1982). The Caldwell section (based on surface maps, deep well logs, and seismic reflection data) shows an acoustic basement of basalt overlain by up to 6,000 feet of lacustrine sediment (Wood, 1994). Wells in this region bottomed in basalt, so the depth to rhyolite basement (if present) is not known.

The Mount Bennett Hills block appears to be tilted to the south for most of its length, with north-facing normal faults along its northern margin with the Camas Prairie. The southern margin of the Mount Bennett Hills appears to be a flexural downwarp beneath lavas of the eastern SRP trend, with only minor normal faulting (Cluer and Cluer, 1986). The southwest-facing normal faults that bound the Mount Bennett Hills block in the Mountain Home area lift the western end of this block and accommodate an eastward plunge. These complex relationships reflect the position of the Mount Bennett Hills at the intersection of the western SRP structural graben with the eastern SRP downwarp.

The ages of the range-front faults are unknown but can be estimated as late Miocene to early Pliocene on the

basis of the middle Miocene age of the Mount Bennett rhyolite (about 10 Ma; Clemens and Wood, 1993) and the Pliocene age of Lake Idaho, which filled the western SRP graben that formed during uplift of the rhyolites. The occurrence of Lake Idaho sediments within the Mount Bennett Hills, sitting depositionally on rhyolite vitrophyre or older basalts (Vetter, oral commun., 1998), shows that uplift of the Mount Bennett Hills continued into the Pliocene.

QUATERNARY FAULTING

Recent tectonic activity related to extension of the western SRP graben is demonstrated by fault scarps, with 6 to 30 feet (2 to 9 m) of throw, that crosscut the shield

volcanoes and the basaltic flows associated with them. There are two dominant fault sets: one trends N. 85° W.; the other trends N. 60° W. (parallel to the range-front faults) and appears to truncate against the N. 85° W. set (Figure 3). All faults are vertical or high-angle normal faults that dip steeply to the south and are downthrown on the south or southwest side. Similar relationships are observed in the western Mount Bennett Hills where east-west trending faults offset N. 50° W. faults (Clemens and Wood, 1993).

Both sets of faults appear to have been active simultaneously, as shown by asymmetric escarpments in the N. 85° W. faults that have larger offsets at the east end than at the west end. This asymmetric movement on the N. 85° W. faults was accommodated by movement on the N. 60°

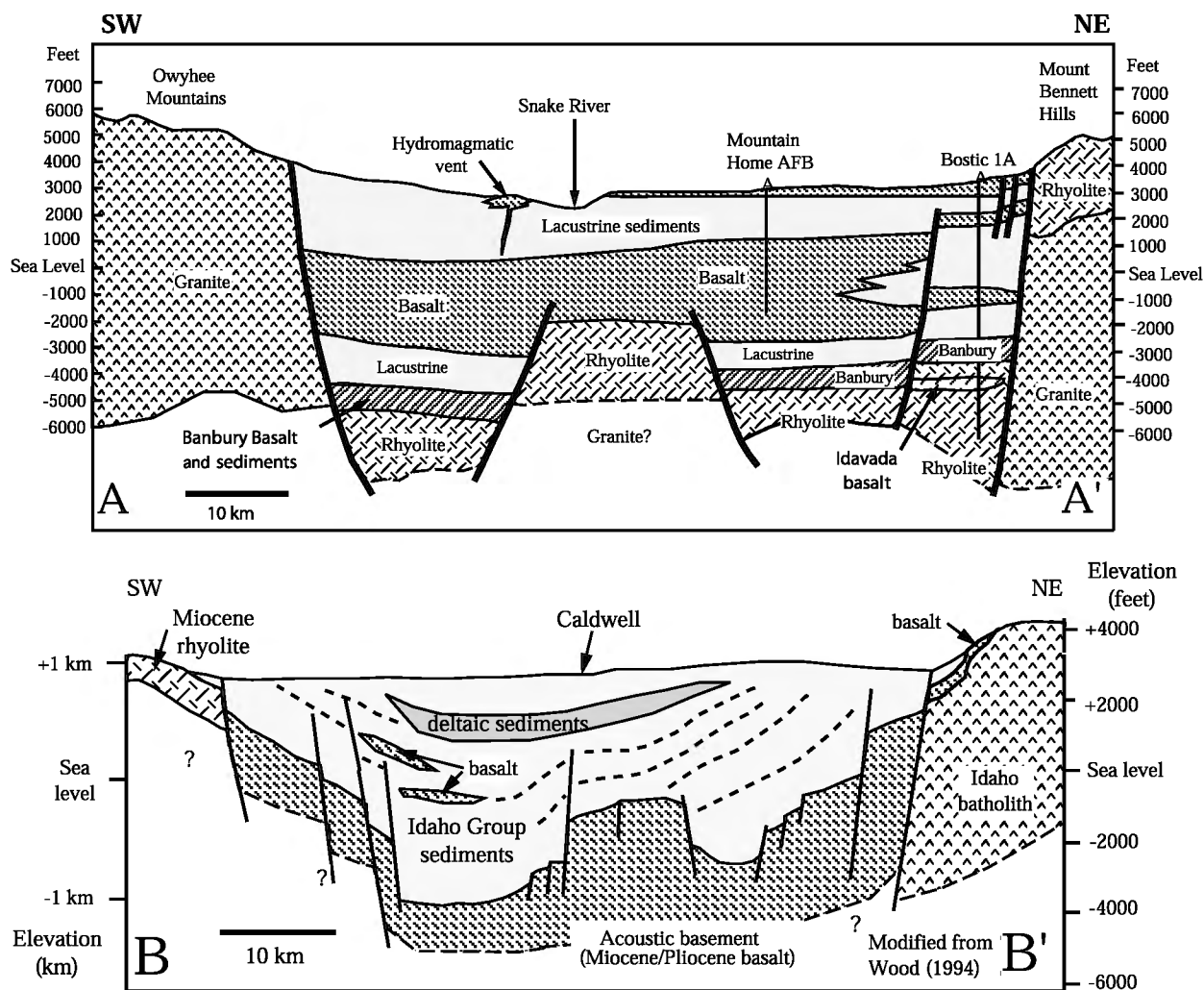


Figure 6. Interpretive cross sections of western SRP: section A-A' from Owyhee Plateau to Mountain Home area; section B-B' through Caldwell (see Figure 2 for location of sections). Section A-A' based on well logs of Mountain Home AFB core (Lewis and Stone, 1988), the Bostic 1A well (Arney and others, 1982, 1984), gravity profiles of the western SRP, and surface mapping (this study; Jenks and others, 1993). Section B-B' near Caldwell, modified from Wood (1994), is based on well logs and seismic reflection data.

W. faults, many of which also preserve asymmetric escarpments that have larger offsets on their north ends. The sense of motion here seems to be one in which trapezoid-shaped lozenges of crust accommodated northeast-southwest extension by rotating along pairs of south-dipping and southwest-dipping normal faults.

The age of faulting cannot be determined precisely at this time but must be younger than about 1 Ma, based on the age of the basalt units cut by the faults. In one location, basalt is faulted against alluvial gravel of Canyon Creek (Figure 3), suggesting a late Pleistocene or Holocene age. Beukelman (1997) has shown that similar scarps which offset alluvium in the Halfway Gulch-Little Jacks Creek area south of Mountain Home have ages of about 5,000 to 34,000 years, based on the degradation of scarp profiles. Trenching across one fault indicates five episodes of surface rupture over the last 26,000 years, based on caliche accumulation in the soils (Beukelman, 1997).

GEOCHEMISTRY

Geochemical studies of the volcanic rocks described here are still in progress, so it is not possible to discuss their chemical and petrologic evolution at this time. We can, however, make a general comparison between the older, pre-Lake Idaho lavas sampled by the Mountain Home AFB core and the surface lava flows (Table 1). We can also compare both of these groups to basaltic lavas from the eastern SRP trend (Shervais and others, 1994) and to flood basalts of the Columbia River Plateau province (Tolan and others, 1989; Reidel and others, 1989; Hooper, 1988).

In general, late Pliocene to Quaternary surface flows in the Mountain Home area are similar to basaltic lavas from the eastern SRP in their Fe, Ti, alkali, and silica content (Figure 7). Fe is at the high end of the range for this trend and is higher than typical eastern SRP basalts in many samples. In contrast, early Pliocene, pre-Lake Idaho basalts from the Mountain Home AFB core are much higher in Fe and Ti and lower in alkalis, silica, and phosphorus than typical basalts of the eastern SRP. This suggests a source for the older basalts that is depleted relative to the eastern SRP basalt source in large ion lithophile elements (LILE), but enriched in Fe and Ti, possibly as a result of Fe-Ti metasomatism (Shervais and Vetter, 1992).

When compared with basalts of the SRP province, flood basalts of the Columbia River Plateau (Tolan and others, 1989; Reidel and others, 1989) are much lower in Mg, Fe, Ti, and P and higher in Si and K (Figure 7). This suggests that, relative to basalts of the SRP province, the

Columbia River basalts have seen much more exchange with continental materials. This may reflect either assimilation of subcontinental lithosphere or partial melting and assimilation of continental crust (Carlson, 1984; Carlson and Hart, 1988; Carlson and others, 1981).

DISCUSSION

The history of basaltic volcanism in the western SRP is punctuated in the Pliocene by a prolonged hiatus of about 4 million years duration. This is clearly shown by the distribution of basalt and sediment in the Mountain Home AFB core samples, by the stratigraphy of sediments and basalts that crop out in the western SRP, and by seismic profiles of the western SRP (e.g., Wood, 1984, 1994; Wood and Anderson, 1981). The duration of this hiatus corresponds largely with sedimentation in Lake Idaho, but volcanism and sedimentation overlapped in time and space both near the beginning of sedimentation in the early Pliocene and near its end in the late Pleistocene. This overlap is greater farther to the west, near Boise and Caldwell, where phreatomagmatic vents demonstrate the eruption of large volcanos within standing water of the lake (Godchaux and others, 1992). The hiatus in basaltic volcanism shows that development of the western SRP occurred during two separate and possibly unrelated events. We examine each of these events below.

PRE-LAKE IDAHO TECTONICS AND VOLCANISM

Formation of the western SRP graben was preceded by the eruption of high-temperature rhyolites from northwest-trending fissures (Honjo and others, 1992; Bonnichsen, 1997). These rhyolites have anhydrous phenocryst assemblages and calculated eruption temperatures of around 850°C to 1,000°C (Honjo and others, 1992). Existing radiometric dates suggest an age progression of high-temperature rhyolites from northwest to southeast. Thus, rhyolites at the northwest end of the western SRP have ages around 11.2 Ma to 11.6 Ma; rhyolites in the Danskin Mountains have ages of 10.0 Ma to 11.0 Ma, and rhyolites in the western and central Mount Bennett Hills have ages of 9.2 Ma to 9.8 Ma (Armstrong and others, 1975, 1980; Honjo, 1990; Clemens and Wood, 1993).

Range-front faults in the western SRP are associated with the formation of the western SRP graben, which became the locus of deposition of Lake Idaho in the late Miocene through Pliocene (Figure 6). The formation of this graben predates Basin and Range extension, and its orientation (about N. 50° W.) is inconsistent with other

Table 1. Representative whole rock geochemistry for selected basaltic lavas from the Mountain Home area. Major elements by fused bead electron-probe analysis. Trace elements by x-ray fluorescence analysis. Latitude and longitude locations are in decimal degrees. Mountain Home AFB core location estimated from map location, with depth below surface in feet for each sample from driller's log.

Sample No.	96SRP-21-2	96SRP-58-2	96SRP-V40	96SRP-9	96SRP-27	96SRP-12	MH-2538	MH-3102	MH-4103
Unit/Vent	Borrow Pit/ 3245	Crater South Flow 3198	Lockman/ Lock 3624	Radio Tower/ Rocky 3649	Teapot North	Tuff Ring/ Brush 3291	Mtn. Home AFB Core	Mtn. Home AFB Core	Mtn. Home AFB Core
Quadrangle USGS 7.5'	Reverse	Cinder Cone Butte	Crater Rings	Mtn. Home North	Teapot Dome	Reverse	Crater Rings SE	Crater Rings SE	Crater Rings SE
Lat. North	43.078617	43.141500	43.201817	43.132450	43.186600	43.057400	43.057400	43.057400	43.057400
Long. West	115.597217	115.909933	115.765833	115.625117	115.605700	115.532433	115.839333	115.839333	115.839333
Depth (in feet)	NA	NA	NA	NA	NA	NA	2,538	3,102	4,103
SiO ₂	46.10	46.38	48.49	46.46	47.39	47.17	46.24	47.09	46.19
TiO ₂	3.03	3.35	2.17	3.17	3.24	2.58	4.06	3.49	4.48
Al ₂ O ₃	13.69	13.90	17.37	13.91	13.93	13.21	13.87	14.44	13.79
FeO	13.77	15.48	11.99	14.44	14.43	13.11	16.42	15.04	17.75
MnO	0.24	0.24	0.18	0.19	0.19	0.21	0.22	0.25	0.23
MgO	6.93	6.79	5.79	6.72	6.64	6.46	7.18	6.04	5.50
CaO	12.11	9.64	10.46	10.67	9.80	12.76	10.51	9.96	11.07
Na ₂ O	2.34	2.40	2.68	2.35	2.41	2.23	1.52	2.26	1.09
K ₂ O	0.60	0.57	0.43	0.58	0.64	0.70	0.26	0.66	0.07
P ₂ O ₅	0.58	0.63	0.74	0.68	0.53	0.51	0.11	0.66	0.14
Total	99.38	99.39	100.29	99.18	99.20	98.94	100.38	99.89	100.32
Nb	19	20	32		19	17	21	31	34
Zr	276	278	355		263	260	297	395	406
Y	43	42	48		42	39	54	61.5	70
Sr	316	315	338		325	320	302	289.5	300
Rb	14	7	2		11	13	4	15.5	3
Zn	136	145	147		144	134	178	161.5	175
Cu	46	31	42		52	48	50	38	49
Ni	62	61	72		80	74	93	76.5	67
Cr	182	181	196		209	199	209	154	134
Sc	36	33	33		30	33			
V	349	333	303		328	298			
Ba	470	441	501		454	514			

Basin and Range grabens (typically N. 20° W. to N. 10° E. in northern Nevada).

This graben appears to be older at its northwest-end and to become progressively younger to the southeast (e.g., Kimmel, 1982; Malde, 1991). This conclusion is based on the age progression of rhyolite lavas discussed above and the age of the oldest sediments filling the gra-

ben, which become progressively younger from northwest (late Miocene) to southeast (Pliocene) along the axis of the graben (Kimmel, 1982; Malde, 1991). While the western SRP graben at its northwest end (Oregon-Idaho border) is approximately coeval with the formation of the Bruneau-Jarvis eruptive center (10-12 Ma), the southeast end of the graben is younger, and structures

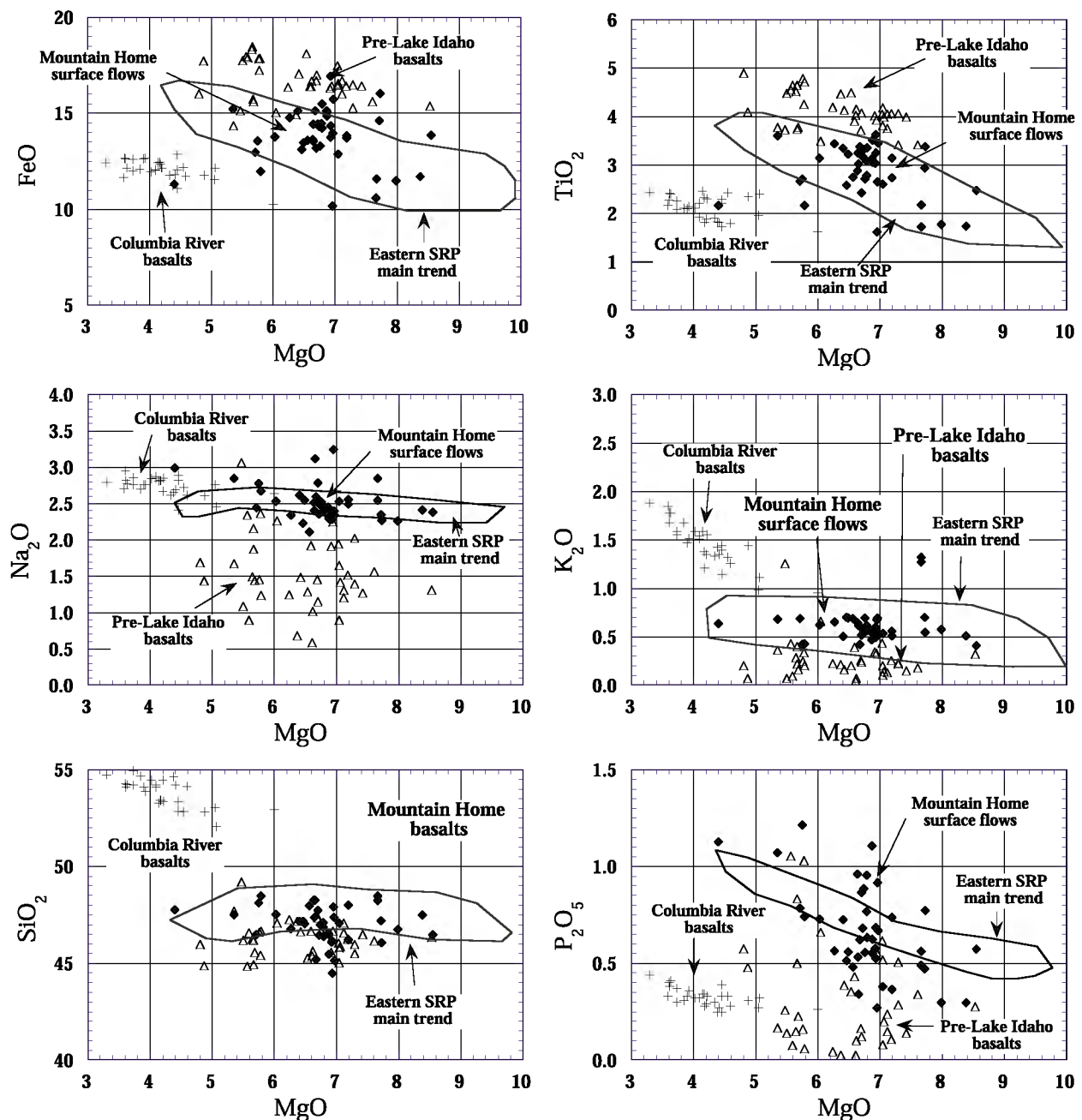


Figure 7. Summary of geochemical data for pre-Lake Idaho and post-Lake Idaho basalts from the Mountain Home region compared to basalts from the eastern Snake River Plain "main trend" and to flood basalts (basaltic andesites) of the Columbia River Plateau.

associated with the graben and its sedimentary fill cross-cut the margins of the Bruneau-Jarbridge eruptive center. The western SRP graben reached its maximum headward extent approximately 3 Ma, as shown by the age of the youngest Glens Ferry Formation at the southeast end of the Lake Idaho basin (Malde, 1991).

Pre-Lake Idaho basalts are characterized by low alkali contents and by extremely high Fe and Ti (Fe-Ti basalts). These basalts are coeval with plume-tail volcanism of the Bruneau-Jarbridge eruptive center (Bonnichsen, 1982), but they differ compositionally from basalts associated with this eruptive center (e.g., Vetter and others, 1997). They are also coeval with the Saddle Mountains Basalt—the final eruptive phase of the Columbia River flood basalt province (Reidel and others, 1989; Tolan and others, 1989).

The data discussed above suggest that the formation of the western SRP graben and its sedimentary fill is not related to passage of the Yellowstone plume tail from the Owyhee Plateau to the eastern SRP. The data do show a connection between the formation of the western SRP and the flood basalt volcanism of the Columbia River Plateau. To the extent that the Columbia River basalts can be related to the Yellowstone plume head, there is a connection between the western SRP and the Yellowstone plume (e.g., Glen and Ponce, 2002). If so, the plume head was deflected significantly to the north from its proper position in line with the track of the plume tail, as suggested by Geist and Richards (1993) and Camp (1995).

We suggest that the western SRP graben may be thought of as an aulocogenlike rift associated with thermal doming of the lithosphere beneath the Columbia River Plateau; the orientation of this rift was likely controlled by thermal softening of lithosphere by the plume tail, which at this time was located beneath the Bruneau-Jarbridge eruptive center, and by the orientation of large-scale fractures over the plume head beneath the Columbia River plateau (Glen and Ponce, 2002). If this model is correct, then pre-Lake Idaho basalts may be related to the flow of plume-source mantle along a sublithospheric conduit formed by extension of the western SRP. Since the graben is older in the northwest, the flow of this plume-source mantle was most likely from northwest to southeast, that is, from beneath the Columbia River Plateau toward Twin Falls. This implies that the pre-Lake Idaho basalts formed by pressure-release melting of both (1) the previously depleted plume-source mantle and (2) the overlying mantle lithosphere. This is also consistent with the occurrence of high-temperature rhyolites, which are thought to form by crustal anatexis in response to the intrusion of mafic magmas at depth.

This model is illustrated schematically in Figure 8. Between 17 Ma and 14 Ma, the Yellowstone plume head

was deflected northward by the Farallon plate (Geist and Richards, 1993) or by North American lithosphere (Camp, 1995), resulting in the eruption of flood basalts on the Columbia River and Oregon plateaus. Thermal tumescence over the plume head elevated eastern Oregon and Washington and initiated the formation of the western SRP graben as an “aulacogen” radial to the center of uplift (Figure 8a). During the period from 12 Ma to 6 Ma, the plume head was compressed and overridden by North America; the compressed plume material “escaped” to southeast along a sublithospheric conduit beneath the developing western SRP graben (Figure 8b). As the plume head cooled and relaxed thermally, the western SRP graben subsided and became the locus of Lake Idaho sedimentation (Figure 8c). At this same time, depleted plume head mantle underplated continental lithosphere beneath the western SRP. The final phase of its development (2 Ma to today) is discussed below.

POST-LAKE IDAHO TECTONICS AND VOLCANISM

Post-Lake Idaho basalts are all less than 2 Ma old and chemically similar to coeval basalts of the eastern SRP (although the common occurrence of ferrobalt is unique to the western SRP). In the eastern SRP, the youngest basalts are associated with north- to northwest-trending volcanic rift zones oriented perpendicular to the trend of the eastern SRP (Kuntz and others, 1982, 1988, 1992). Rodgers and others (1990) have shown that these volcanic rift zones, which parallel normal faults of the Basin and Range Province, accommodate aseismic extension of the eastern SRP in response to extension within the Basin and Range Province.

Young faults in the western SRP (i.e., those that offset post-Lake Idaho basalt flows or Holocene gravels) appear to reflect Basin and Range extension that has refracted to more westerly orientation to exploit preexisting range-front fault zones of the western SRP (Figure 8d). The occurrence of approximately east-west oriented faults of this age show that a component of north-south extension is also required. The distribution of post-Lake Idaho basalts along the northeast margin of the western SRP graben, and their association with Basin and Range extensional features, suggest that these basalts also formed in response to Basin and Range extension. The mechanism for the formation of the young eastern SRP basalts is still being debated, but there seems to be a consensus that they formed by pressure-release melting of plume-modified lithosphere (e.g., Leeman 1982, Vetter and Shervais, 1992).

The hiatus between the older pre-Lake Idaho basalts and the younger Basin and Range-related basalts prob-

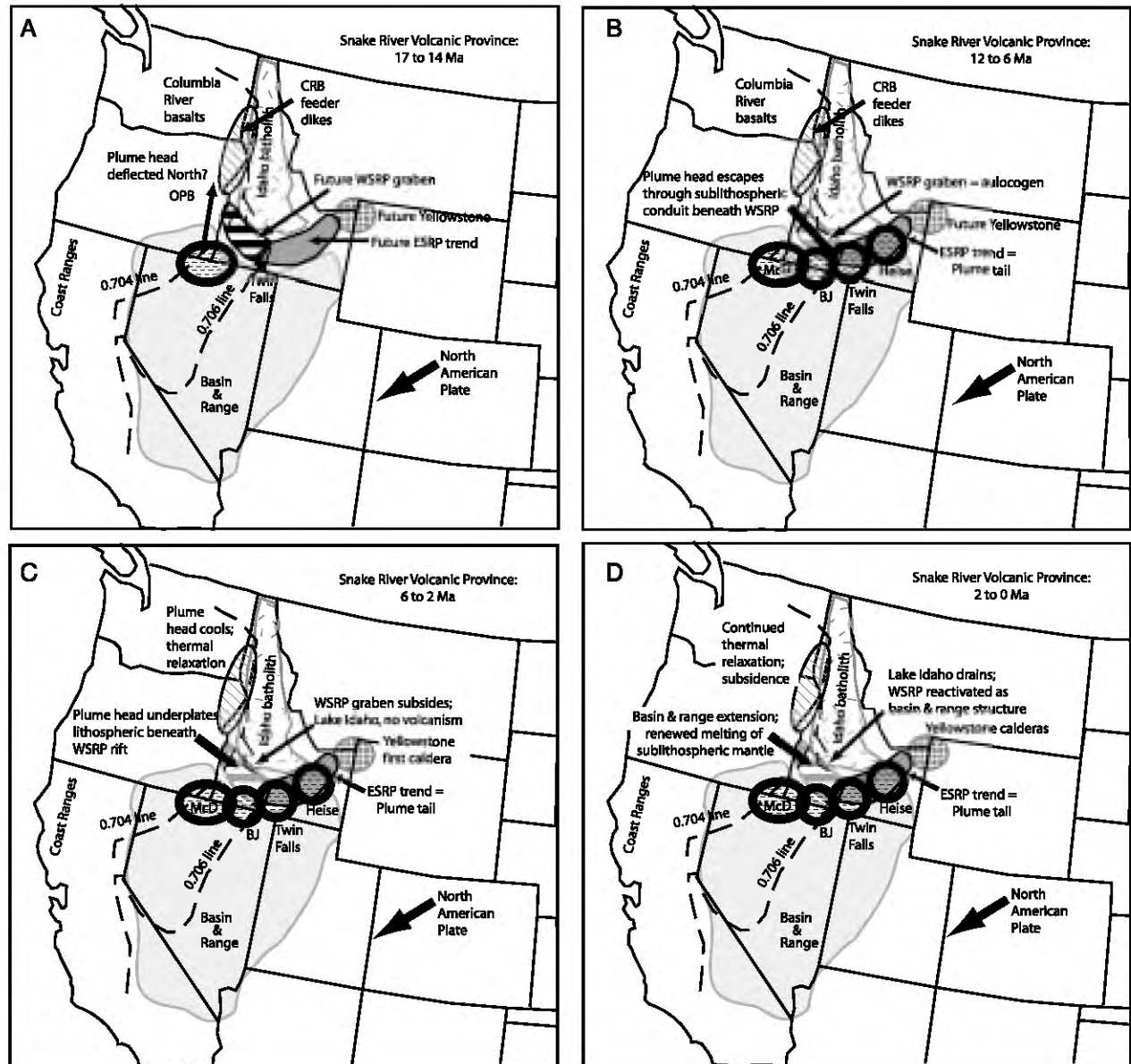


Figure 8. Cartoon depicting the evolution of the western SRP based on model presented here. (a) 17 Ma to 14 Ma: Yellowstone plume head deflected northward by Farallon plate or North American lithosphere; thermal tumescence of eastern Oregon and Washington. (b) 12 Ma to 6 Ma: Plume head compressed and overridden by North America, with continued thermal tumescence of lithosphere; western SRP graben develops as an “aulacogen” (sediment-filled rift) radial to the center of uplift; compressed plume material “escapes” to southeast along sublithospheric conduit beneath western SRP graben. (c) Plume head cools and relaxes, underplates western SRP; western SRP subsides and becomes locus of Lake Idaho sedimentation. (d) 2 Ma to today: Plume tail reaches Yellowstone, Lake Idaho drains, and western SRP reactivated as Basin and Range structure.

ably represents the recovery time of the lithosphere from thermal softening by the plume tail, which seems to have inhibited the propagation of Basin and Range-style extension northwards. The difference in the length of this hiatus in the western SRP (around 4 million years) and the eastern SRP (less than 1 million years?) may reflect differences in the nature, age, and composition of the lithosphere between these two locations (late Proterozoic to

Mesozoic in the west, Archean in the east).

CONCLUSIONS

Basaltic volcanism in the western SRP was active in two distinct phases separated by a hiatus of several million years. Lacustrine sediments of the Idaho Group were

deposited largely during this hiatus. Our work in the Mountain Home region of the western SRP, when combined with observations from other parts of the western SRP graben and from the eastern SRP, suggests that these volcanic episodes represent distinct, unrelated events.

The older volcanic episode formed in response to passage of the Yellowstone plume system and thermal tumescence of the Columbia River Plateau. This episode included the formation of the western SRP graben, the eruption of high-temperature rhyolite lavas, and the eruption of pre-Lake Idaho Fe-Ti basalts. The basaltic volcanism may be related to the flow of depleted plume source mantle along a sublithospheric conduit beneath the western SRP graben from the Columbia River Plateau. The basalts would form by pressure-release melting of this previously depleted material along with the overlying mantle lithosphere (Figure 8).

The younger volcanic episode apparently formed in response to Basin and Range extension in a fashion analogous to young basaltic volcanism in the eastern SRP. The source of these basalts is uncertain but may be plume-modified subcontinental lithosphere.

Finally, despite the progress made in the last few years, much remains to be done in understanding the origin and evolution of the SRP volcanic system. It is particularly important that detailed geochemical and isotopic studies, based on careful field studies and modern geologic maps, distinguish between events of different ages and locations. These age-location relationships are especially important in the western SRP, where major changes in tectonic regimes occurred during the Neogene.

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REFERENCES

Amini, M.H., H.H. Mehnert, and J.D. Obradovich, 1984, K-Ar ages of late Cenozoic basalts from the western Snake River Plain, Idaho: *Isochron West*, no. 41, p. 7-11.

Arney, B.H., J.N. Gardner, and S.G. Bellnami, 1984, Petrographic analysis and correlation of volcanic rocks in Bostic 1-A well near Mountain Home, Idaho: Los Alamos National Laboratory Report LA-9966-HDR, 29 p.

Arney, B.H., F. Goff, and Harding Lawson Associates, 1982, Evaluation of the hot dry rock geothermal potential of an area near Mountain Home Idaho: Los Alamos National Laboratory Report LA-9365-HDR, 65 p.

Armstrong, R.L., J.R. Harakal, and W.M. Neill, 1980, K-Ar dating of the Snake River Plain (Idaho) volcanic rocks—new results: *Isochron West*, no. 27, p. 5-10.

Armstrong, R.L., W.P. Leeman, and H.E. Malde, 1975, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho: *American Journal of Science*, v. 275, p. 225-251.

Bonnicksen, Bill, 1982, The Bruneau-Jarbridge eruptive center, southwestern Idaho, in Bill Bonnicksen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho*: Idaho Bureau of Mines and Geology Bulletin 26, p. 237-254.

———, 1997, Volcanism in the western Snake River Plain, southwestern Idaho: *Geological Society of America, Abstracts with Programs*, v. 29, no. 6, p. A296.

Bonnicksen, Bill, and D.F. Kauffman, 1987, Physical features of rhyolite lava flows in the Snake River Plain volcanic province, southwestern Idaho, in J. Fink, ed., *The Emplacement of Silicic Domes and Lava Flows*: Geological Society of America Special Paper 212, p. 119-145.

Bonnicksen, Bill, and M.D. Jenks, 1990, Geologic map of the Jarbridge River Wilderness Study Area, Owyhee County, Idaho: U.S. Geological Survey Map MF-2127, scale 1:50,000.

Beukelman, G.S., 1997, Evidence of active faulting in Halfway Gulch-Little Jacks Creek area of the western Snake River Plain, Idaho: Boise State University M.S. thesis, 148 p.

Camp, V.E., 1995, Mid-Miocene propagation of the Yellowstone mantle plume beneath the Columbia River basalt source region: *Geology*, v. 23, p. 435-438.

Carlson, R.W., 1984, Isotopic constraints on Columbia River flood basalt genesis and the nature of the subcontinental mantle: *Geochimica et Cosmochimica Acta*, v. 48, p. 2357-2372.

Carlson, R.W., and W.K. Hart, 1988, Flood basalt volcanism in the northwestern United States, in J.D. MacDougall, ed., *Continental Flood Basalts*: Kluwer Academic Publishers, p. 35-61.

Carlson, R.W., G.W. Lugmair, and J.D. MacDougall, 1981, Columbia River volcanism: The question of mantle heterogeneity or crustal contamination: *Geochimica et Cosmochimica Acta*, v. 45, p. 2483-2499.

Christiansen, R.L., 1982, Late Cenozoic volcanism of the Island Park area, eastern Idaho, in Bill Bonnicksen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho*: Idaho Bureau of Mines and Geology Bulletin 26, p. 345-368.

Christiansen, R.L., G.R. Foulger, and J.R. Evans, 2002, Upper-mantle origin of the Yellowstone hotspot: *Geological Society of America Bulletin*, v. 114, p. 1245-1256.

Clemens, D.M., and S.H. Wood, 1993, Late Cenozoic volcanic stratigraphy and geochronology of the Mount Bennett Hills, central Snake River Plain, Idaho: *Isochron West*, no. 60, p. 3-14.

Cluer, J.K., and B.L. Cluer, 1986, The late Cenozoic Camas Prairie rift, south-central Idaho: *Contributions to Geology*, University of Wyoming, v. 24, no. 1, p. 91-101.

Cope, E.D., 1883, A new Pliocene formation in the Snake River valley: *American Naturalist*, v. 17, p. 867-868.

Decker, R.W., 1987, Dynamics of Hawaiian volcanos: An overview, in R.W. Decker, T.L. Wright, P.H. Stauffer, eds., *Volcanism in Hawaii*: U.S. Geological Survey Professional Paper 1350, ch. 42, p. 997-1018.

- Ekren, E.B., D.H. McIntyre, E.H. Bennett, and R.F. Marvin, 1982, Cenozoic stratigraphy of western Owyhee County, Idaho, in Bill Bonnichsen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26*, p. 215-236.
- Geist, D.J., and M. Richards, 1993, Origin of the Columbia River Plateau and Snake River Plain: Deflection of the Yellowstone plume: *Geology*, v. 21, p. 789-792.
- Glen, J.M.G., and D.A. Ponce, 2002, Large-scale fractures related to inception of the Yellowstone hotspot: *Geology*, v. 30, p. 647-650.
- Godchaux, M.M., Bill Bonnichsen, and M.D. Jenks, 1992, Types of phreatomagmatic volcanoes in the western Snake River Plain, Idaho, USA: *Journal of Volcanology and Geothermal Resources*, v. 52, p. 1-25.
- Hackett, W.R., and R.P. Smith, 1992, Quaternary volcanism, tectonics, and sedimentation in the Idaho National Engineering Laboratory area, in J.R. Wilson, ed., *Field Guide to Geologic Excursions in Utah and Adjacent Areas of Nevada, Idaho, and Wyoming: Utah Geological Society, Miscellaneous Publications*, p. 92-93.
- Hart, W.K., and J.L. Aronson, 1983, K-Ar ages of rhyolites from the western Snake River Plain area, Oregon, Idaho, and Nevada: *Isochron West*, v. 36, p. 17-19.
- Honjo, Norio, 1990, *Geology and stratigraphy of the Mount Bennett Hills, and the origin of west-central Snake River Plain rhyolites: Rice University Ph.D. dissertation*, 259 p.
- Honjo, Norio, W.P. Leeman, and J.C. Stormer, 1992, Mineralogy and geothermometry of high-temperature rhyolites from the central and western Snake River Plain: *Bulletin of Volcanology*, v. 54, p. 220.
- Hooper, P.R., 1988, The Columbia River basalt, in J.D. MacDougall, ed., *Continental Flood Basalts: Kluwer Academic Publishers*, p. 1-33.
- Howard, K.A., and J.W. Shervais, 1973, *Geologic map of Smith Prairie, Elmore County, Idaho: U.S. Geological Survey Map I-818*.
- Howard, K.A., J.W. Shervais, and E.H. McKee, 1982, Canyon-filling lavas and lava dams on the Boise River, Idaho, and their significance for evaluating downcutting during the last two million years, in Bill Bonnichsen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26*, p. 629-641.
- Humphreys, E.D., K.G. Dueker, D.L. Schutt, and R.B. Smith, 2000, Beneath Yellowstone: Evaluating plume and nonplume models using teleseismic images of the upper mantle: *GSA Today*, v. 10, p. 1-7.
- Jenks, M.D., and Bill Bonnichsen, 1989, Subaqueous basalt eruptions into Pliocene Lake Idaho, Snake River Plain, Idaho, in V.E. Chamberlain, R.M. Breckenridge, and Bill Bonnichsen, eds., *Guidebook of the Geology of Northern and Western Idaho and Surrounding Areas: Idaho Geological Survey Bulletin 28*, p. 17-34.
- , 1990, *Geologic map of the Wild Horse Butte quadrangle, Ada and Owyhee counties, Idaho: Idaho Geological Survey Technical Report 90-8*, scale 1:24,000, 9 p.
- Jenks, M.D., Bill Bonnichsen, and M.M. Godchaux, 1993, *Geologic maps of the Grand View-Bruneau area, Owyhee County, Idaho: Idaho Geological Survey Technical Report 93-2*, scale 1:24,000, 21 p.
- Kimmel, P.G., 1982, Stratigraphy, age, and tectonic setting of the Miocene-Pliocene lacustrine sediments of the western Snake River Plain, Oregon and Idaho, in Bill Bonnichsen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26*, p. 559-558.
- Kuntz, M.A., D.E. Champion, R.H. Lefebvre, and H.R. Covington, 1988, *Geologic map of the Craters of the Moon, Kings Bowl, and Wapi lava fields and the Great Rift volcanic rift zone, south-central Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map I-1632*, scale 1:100,000.
- Kuntz, M.A., D.E. Champion, E.C. Spiker, R.H. Lefebvre, and L.A. McBroome, 1982, The Great Rift and the evolution of the Craters of the Moon lava field, Idaho, in Bill Bonnichsen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26*, p. 423-437.
- Kuntz, M.A., H.R. Covington, and L.J. Schorr, 1992, An overview of basaltic volcanism of the eastern Snake River Plain, Idaho, in P.K. Link, M.A. Kuntz, and L.B. Platt, eds., *Regional Geology of Eastern Idaho and Western Wyoming: Geological Society of America Memoir 179*, p. 227-267.
- Leeman, W.P., 1982, Development of the Snake River Plain-Yellowstone Plateau province, Idaho and Wyoming: An overview and petrologic model, in Bill Bonnichsen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26*, p. 155-177.
- Lewis, R.E., and M.A.J. Stone, 1988, Geohydrologic data from a 4403-foot geothermal test hole, Mountain Home Air Force Base, Elmore County, Idaho: *U.S. Geological Society Open-File Report 88-166*, 30 p.
- Mabey, D.R., 1976, Interpretation of a gravity profile across the western Snake River Plain, Idaho: *Geology*, v. 4, p. 53-55.
- , 1978, Regional gravity and magnetic anomalies in the eastern Snake River Plain, Idaho: *U.S. Geological Survey Journal of Research* 6, p. 553-562.
- , 1982, Geophysics and tectonics of the Snake River Plain, Idaho, in Bill Bonnichsen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26*, p. 139-153.
- Malde, H.E., 1959, Fault zone along northern boundary of western Snake River Plain, Idaho: *Science*, v. 130, p. 272.
- , 1991, Quaternary geologic and structural history of the Snake River Plain, Idaho and Oregon, in R.B. Morrison, ed., *Quaternary Non-Glacial Geology: Conterminous United States: Geological Society of America, Boulder, Colorado, The Decade of North American Geology, K2*, p. 251-281.
- Malde, H.E., and H.A. Powers, 1962, Upper Cenozoic stratigraphy of western Snake River Plain, Idaho: *Geological Society of America Bulletin* 73, p. 1197-1220.
- , 1972, *Geologic map of the Glens Ferry-Hagerman area, west-central Snake River Plain, Idaho: U.S. Geological Survey Miscellaneous Investigations Map I-696*, scale 1:48,000, 2 sheets.
- Malde, H.E., H.A. Powers, and C.H. Marshall, 1963, *Reconnaissance geologic map of west-central Snake River Plain, Idaho: U.S. Geological Survey Miscellaneous Investigations Map I-373*, scale 1:125,000.
- McGee, James, and John Shervais, 1997, Flotation cumulate in a Snake River Plain ferrobasalt: Petrologic study of a possible lunar analogue: *Geological Society of America, Abstracts with Programs*, v. 29, no. 6, P. A136.
- McIntyre, D.H., 1979, Preliminary description of Anschutz Federal No 1 drill hole, Owyhee County Idaho: *U.S. Geological Survey Open-File Report 79-651*, 15 p.
- Mitchell, V.E., D.J. Shivel, G.S. Hustedde, and E.H. Bennett, 1985, Isotopic age dates in Idaho, excluding carbon dates: *Idaho Geological Survey Information Circular* 38, 29 p.
- Othberg, K.L., and L.R. Stanford, 1992, *Geologic map of the Boise Valley and adjoining area, western Snake River Plain, Idaho: Idaho Geological Survey Geologic Map 18*, scale 1:100,000.
- Pierce, K.L., and L.A. Morgan, 1992, The track of the Yellowstone hot spot: Volcanism, faulting, and uplift, in P.K. Link, M.A. Kuntz, and L.B. Platt, eds., *Regional Geology of Eastern Idaho and Western Wyoming: Geological Society of America Memoir 179*, p. 1-53.

- Reid, M.R., 1995, Processes of mantle enrichment and magmatic differentiation in the eastern Snake River Plain: The isotopic evidence: *Earth Planetary Science Letters* 131, p. 239-254.
- Reidel, S.P., T.L. Tolan, P.R. Hooper, M.H. Beeson, K.R. Fecht, R.D. Bentley, and J.L. Anderson, 1989, The Grande Ronde Basalt, Columbia River Basalt Group: Stratigraphic descriptions and correlations in Washington, Oregon, and Idaho, *in* S.P. Reidel and P.R. Hooper, eds., *Volcanism and Tectonism in the Columbia River Flood Basalt Province: Geological Society of America Special Paper* 239, p. 21-53.
- Rodgers, D.W., W.R. Hackett, and H.T. Ore, 1990, Extension of the Yellowstone Plateau, eastern Snake River Plain, and Owyhee Plateau: *Geology*, v. 18, p. 1138-1141.
- Shervais, J.W., and S.K. Vetter, 1992, Young continental basalts of the Snake River Province: Fe-Ti metasomatism of continental lithosphere by an OIB plume component. *Eos, Transactions, American Geophysical Union*, v. 73, no. 14, p. 334.
- Shervais, J.W., S.K. Vetter, and W.R. Hackett, 1994, Chemical stratigraphy of basalts in coreholes NPR-E and WO-2, Idaho National Engineering Laboratory, Idaho: Implications for plume dynamics in the Snake River Plain: *Proceedings of the VIIth International Symposium on the Observation of Continental Crust Through Drilling*, Santa Fe, New Mexico, p. 93-96.
- Smith, G.R., Krystyna Swirydczuk, P.G. Kimmel, and B.H. Wilkinson, 1982, Fish biostratigraphy of late Miocene to Pleistocene sediments of the western Snake River Plain, Idaho, *in* Bill Bonnichsen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin* 26, p. 519-542.
- Smith, R.B., and L.W. Braile, 1994, The Yellowstone hot spot: *Journal of Volcanology and Geothermal Research*, v. 61, p. 121-187.
- Smith, R.B., E.D. Humphreys, P.J. Tackley, C.M. Meertens, K.G. Dueker, G. Waite, J. Crosswhite, D. Schutt, C. Puskas, and J.W. Hernlund, 2002, Geodynamics of the Yellowstone hotspot: Plume or not?: *Eos Transactions, American Geophysical Union*, v. 83, no. 47, Fall Meeting Supplement, Abstract S72C-04.
- Steinberger, B.M., and R.J. O'Connell, 2002, Hotspot motion and shape of plume conduits as inferred from global mantle flow models: *Eos Transactions, American Geophysical Union*, v. 83, no. 47, Fall Meeting Supplement, Abstract S71D-01.
- Swirydczuk, Krystyna, G.P. Larson, and G.R. Smith, 1982, Volcanic ash beds as stratigraphic markers in the Glens Ferry and Chalk Hills formations from Adrian, Oregon, to Bruneau, Idaho, *in* Bill Bonnichsen and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin* 26, p. 543-558.
- Swirydczuk, Krystyna, B.H. Wilkinson, and G.R. Smith, 1979, The Pliocene Glens Ferry oolite: Lake margin carbonate deposition in the southwestern Snake River Plain: *Journal of Sedimentary Petrology*, v. 49, p. 995-1004.
- , 1980, The Pliocene Glens Ferry oolite: Sedimentology of oolitic lacustrine terrace deposits: *Journal of Sedimentary Petrology*, v. 50, p. 1237-1248.
- Tilling, R.I., R.L. Christiansen, W.A. Duffield, E.T. Endo, R.T. Holcomb, R.Y. Koyanagi, D.W. Peterson, and J.D. Unger, 1987, The 1972-1974 Mauna Ulu eruption, Kilauea volcano: An example of quasi-steady-state magma transfer, *in* R.W. Decker, T.L. Wright, P.H. Stauffer, eds., *Volcanism in Hawaii: U.S. Geological Survey Professional Paper* 1350, ch. 16, p. 405-469.
- Tolan, T.L., S.P. Reidel, M.H. Beeson, J.L. Anderson, K.R. Fecht, and D.A. Swanson, 1989, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group, *in* S.P. Reidel and P.R. Hooper, eds., *Volcanism and Tectonism in the Columbia River Flood Basalt Province: Geological Society of America Special Paper* 239, p. 1-20.
- Vetter, S., S.H. Matthews, and J. Shervais, 1997, Basaltic volcanism of the Bruneau-Jarvis eruptive center, southwest, Idaho: *Geological Society of America, Abstracts with Programs*, v. 29, no. 6, p. A298.
- Vetter, S.K., and J.W. Shervais, 1992, Continental basalts of the Boise River Group near Smith Prairie, Idaho: *Journal of Geophysical Research* v. 97, no. B6, p. 9043-9061.
- Wood, Spencer, 1984, Review of late Cenozoic tectonics, volcanism, and subsurface geology of the western Snake River Plain, *in* P.C. Beaver, ed., *Geology, Tectonics, and Mineral Resources of Western and Southern Idaho: Tobacco Root Geological Society, Dillon, Montana*, p. 48-60.
- , 1989, Silicic volcanic rocks and structure of the western Mount Bennett Hills and adjacent Snake River Plain, Idaho: *SNAKE RIVER PLAIN-YELLOWSTONE VOLCANIC PROVINCE, 28th International Geologic Congress Field Trip Guide T305: American Geophysical Union, Washington, D.C.*, p. 69-77.
- , 1994, Seismic expression and geologic significance of a lacustrine delta in Neogene deposits of the western Snake River Plain, Idaho: *American Association of Petroleum Geologists Bulletin* 78, p. 102-121.
- Wood, S.H., and J.E. Anderson, 1981, Chapter 2, *Geology*, *in* J.C. Mitchell, ed., *Geothermal Investigations in Idaho, Part 11: Geological, Hydrological, Geochemical, and Geophysical Investigations of the Nampa-Caldwell and Adjacent Areas, Southwestern Idaho: Idaho Department of Water Resources, Water Information Bulletin* 30, p. 9-31.
- Zentner, N.C., 1989, Neogene normal faults related to the structural evolution of the eastern Snake River Plain, Idaho: *Idaho State University M.S. thesis*, 48 p.