

Origin of the Columbia Plateau and Snake River plain: Deflection of the Yellowstone plume

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ABSTRACT

Previous models relating the Snake River plain and Columbia River Basalt (northwest United States) to the Yellowstone plume have not taken into account the effects of the subducted Farallon and Juan de Fuca plates. Not only did subduction shield the surface from mantle plume activity, but it deflected the plume in the direction of plate motion. A variety of geophysical and geologic evidence suggests that the plume penetrated the subducted slab at ~17.5 Ma, causing eruption of the Columbia River Basalt. The plate boundary then migrated over the plume, and the Yellowstone plume has recovered to a more nearly vertical conduit, forming the Snake River plain and Yellowstone plateau.

INTRODUCTION

The Columbia Plateau and the Snake River plain constitute two enormous magmatic provinces, covering much of the inland northwest of the United States with a sequence of lava flows more than 1 km thick (Fig. 1). The tectonic origin of these Cenozoic magmatic provinces and their relation to each other have been the subjects of long-standing controversy. One hypothesis is that both were caused by the Yellowstone hot spot as the North American plate drifted southwest (Morgan, 1972; Suppe et al., 1975). This paper presents a model involving interaction of the Yellowstone plume with the subducting Farallon plate that explains some of the atypical features of these magmatic provinces.

Many lines of evidence support a mantle-plume origin for the Columbia River Basalt and the Snake River plain. First, the isotopic and trace element compositions of the Columbia River Basalt are strongly suggestive of a major plume component (Brandon and Goles, 1988; Hooper and Hawkesworth, 1993). Second, the voluminous Columbia River Basalt flows were erupted over a relatively short period of time (~66000 km³/10⁶ yr; Tolan et al., 1989), and a mantle plume is a reasonable mechanism for generating this volume of magma (e.g., Richards et al., 1989; White and McKenzie, 1989). It has been recognized that flood basalts from throughout geologic time may be related to hot spots (e.g., Morgan, 1981; Duncan and Richards, 1991), particularly hot-spot formation (Richards et al., 1989; Campbell and Griffiths, 1990). Third, volcanism in the eastern Snake River plain is time transgressive, and the orientation of the eastern plain coincides with the absolute motion of the North American plate (Armstrong et al., 1975). Fourth, seismic tomography has revealed a vertically oriented, deeply seated,

unusually slow region currently in the mantle beneath Yellowstone (Dueker and Humphreys, 1990). Seismic, neotectonic, and geomorphic features are consistent with a mantle-plume origin for the Snake River plain (Anders et al., 1989; Rodgers et al., 1990; Pierce and Morgan, 1992; Anders and Sleep, 1992).

The principal problem with the hot-spot model is that the Columbia River Basalt vents do not lie along the track of the Yellowstone hot spot, as predicted by the absolute motion of the North American plate (Fig. 1) (Engelbreton et al., 1984). A second problem with the model is the spatial and temporal gap between the vents for the Columbia River Basalt, which erupted mostly from near the Idaho-Oregon-Washington common border between 17.2 and 14.5 Ma, and the western Snake River plain and Owyhee plateau lavas, which began erupting 250 to 480 km to the south at ~16 Ma (Fig. 1). Third, there is no sign of anomalous magmatism in the Northwest prior to 17.2 Ma; thus, any older manifestation of the proposed hot spot is absent. Duncan (1982), however, proposed that some igneous rocks of the Coast Range of Oregon and Washington are accreted oceanic islands formed by the Yellowstone hot spot when it was below the Farallon-Kula divergent plate boundary during the early Tertiary. Other workers have recognized these problems and proposed that the absolute motion of the North American plate is actually aligned with the Columbia River Basalt vents and Yellowstone (azimuth of ~285°) (Brandon and Goles, 1988), or that the Yellowstone plume formed at ~16 Ma, creating the Owyhee plateau (Pierce and Morgan, 1992).

The most widely accepted alternative to the hot-spot model for the origin of the Columbia River Basalts attributes them to rift-

tiansen and McKee, 1978; Carlson and Hart, 1987) in a manner analogous to back-arc basins. Back-arc rifting is an unlikely setting for the Columbia River Basalt, because synmagmatic extensional structures are nearly absent from the Columbia Plateau (Hooper, 1990).

The tectonic origin of the Snake River plain is equally problematic because the plain lies at the boundary of several major tectonic provinces. One possibility is that it is the transform-like northern boundary of the Basin and Range province (e.g., Christiansen and McKee, 1978). The principal problem with this model is that the eastern Snake River plain clearly crosscuts extensional Basin and Range structures, some of which were extending prior to the arrival of the hot spot (Anders et al., 1989). In contrast, several lines of evidence indicate that the Snake River plain is the result of the passage of the North American plate over the Yellowstone hot spot (Morgan, 1972; Suppe et al., 1975; Leeman, 1982; Anders et al., 1989; Rodgers et al., 1990; Pierce and Morgan, 1992), but this hypothesis is also prob-

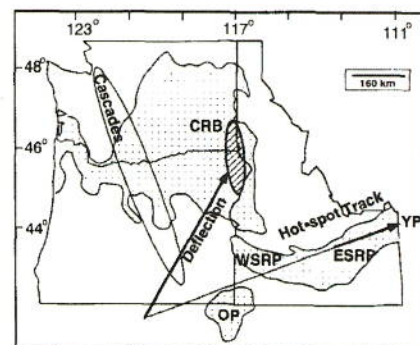


Figure 1. Location and tectonic setting of Columbia River Basalt (CRB) and western and eastern Snake River plain (WSRP and ESRP) provinces. Most vents for Columbia River Basalt lie within enclosed area centered at Idaho-Oregon-Washington common border. Hot-spot track vector indicates movement of North American plate over Yellowstone hot spot during past 17 m.y. by using absolute motions of Engelbreton et al. (1984). Vent swarm for Columbia River Basalt (CRB field) may have been deflected north-northeast by subducted Farallon plate by amount indicated by deflection vector. Location of Cascade Range is that at 17 Ma (Wells and Heller, 1988). OP—Owyhee plateau; YP—Yellowstone plateau.

lematic. In particular, there is no sign of the hot-spot track west of the Owyhee plateau and western Snake River plain. Furthermore, the ages of lavas indicate that volcanism has transgressed at a rate of 4.5 cm/yr (Armstrong et al., 1975; modified by Rodgers et al., 1990), which is at odds with the 1.1 cm/yr rate at which the North American plate has been drifting in the hot-spot reference frame (Engebretson et al., 1984). Post-Oligocene extension in the northern Basin and Range is estimated to be between <2% and 17% (M. H. Anders, 1993, personal commun.; Wells and Heller, 1988), which does not account for a significant part of the discrepancy.

The prominent change in direction between the eastern and western Snake River plain from southwest to northwest (Fig. 1) is another problem with the simple hot-spot model, because this change in direction is not explicable by changing motions of the North American plate. Instead, Miocene lavas of the Owyhee plateau are thought to be the western continuation of the eastern Snake River plain, and the western Snake River plain is thought of as an unrelated rift associated with Basin and Range extension (e.g., Mabey, 1982; Leeman, 1982; Bonnichsen and Kauffman, 1987; Rodgers et al., 1990; Pierce and Morgan, 1992).

Pierce and Morgan (1992) and Draper (1991) proposed that Miocene lavas of the Owyhee plateau resulted from the initial ascent of the Yellowstone mantle plume and melting of its head. The eastern Snake River plain then resulted from the passing of the North American plate over the plume's tail. The principal evidence for the plume-initiation model is the spatially widespread magmatism on the Owyhee plateau, the difference in the style of volcanism between the eastern Snake River plain and the Owyhee plateau, and the absence of time-transgressive volcanism west of the plateau (Pierce and Morgan, 1992). The dominance of rhyolitic volcanism on the plateau, however, suggests that it is not a typical plume-initiation province (Richards et al., 1989; Campbell and Griffiths, 1990; Hill et al., 1992).

GEOLOGIC AND GEOPHYSICAL CONSTRAINTS

Models relating the Columbia Plateau and Snake River plain to the Yellowstone hot spot have not always taken into account the history of subduction of the Farallon and Juan de Fuca plates and the movement of the Farallon-North American plate boundary relative to the hot spot. Several lines of evidence suggest a major perturbation to the subducting plate in the mid-Miocene. First, an angular unconformity in the

central Cascade Range has been determined to date from ~17 Ma (e.g., Priest, 1990; Beeson and Tolan, 1990). Moreover, there is a notable paucity of Cascade tephra in the interbeds of the main phase of the Columbia River Basalt. These two observations suggest that the mechanism for the subduction-related magmatism was interrupted leading up to the time of deposition of the Columbia River Basalt. Second, recent tomographic seismic inversions suggest that the ancient Farallon plate may no longer be connected to the actively subducting Juan de Fuca plate. P-wave velocity inversion shows that the subducted Juan de Fuca plate dips steeply at an angle of about 60° to 80° beneath western North America, and the subducted slab appears to end at ~300 km depth (Rasmussen and Humphreys, 1988). S-wave tomographic inversion suggests that the older Farallon plate is dipping shallowly beneath the central United States (Grand, 1987). A steep dip for the Juan de Fuca slab and a shallow dip for the Farallon slab imply that the two plates may not be continuous at depth. We suggest that the subducted slab segments separated at depth during the mid-Miocene, suspending arc magmatism in the Cascades and leading to generation of the Columbia River Basalt. This suggestion is not without precedent; teleseismic studies of the Pacific Northwest suggest that the Juan de Fuca slab is currently tearing along a north-propagating structure at ~150 km depth (Vandecar et al., 1991).

INTERACTION OF THE YELLOWSTONE HOT SPOT AND THE FARALLON-NORTH AMERICAN PLATE BOUNDARY

We suggest that both the Columbia Plateau and Snake River plain could be the result of the drift of the North American plate over the Yellowstone hot spot, with the complication of deflection and shielding of the mantle plume by the subducted Farallon plate, followed by the plate boundary crossing the hot spot. This hypothesis is motivated by recent models of the effect of large-scale mantle convection on the ascent of plumes (Richards and Griffiths, 1988, 1989; Griffiths and Richards, 1989). We propose that the subducted Farallon plate extended rapidly above the plume and ruptured at ~17.5 Ma. This would have opened a "window" for plume ascent (Fig. 2) and a temporary cessation, or slowing of the rate, of subduction and, presumably, related arc magmatism. The idea that the Yellowstone plume was affected by the subduction zone has been suggested previously (Leeman, 1982; Duncan, 1982; Draper, 1991; Hill et al., 1992; Hooper and Hawkesworth, 1993).

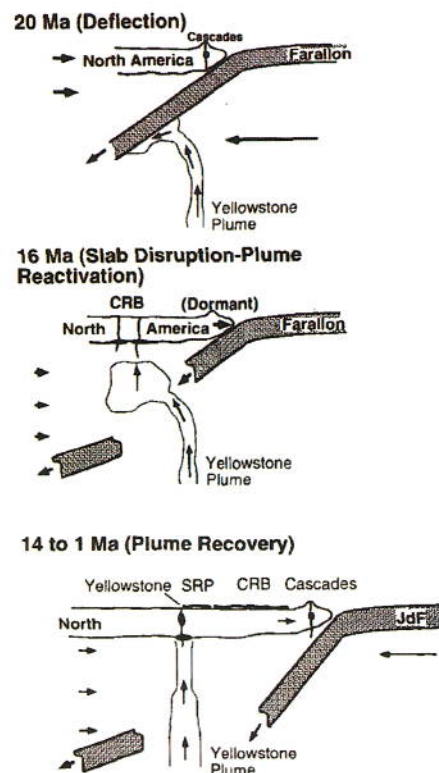


Figure 2. Schematic representation of proposed model as viewed in cross section from northwest. Top: At 20 Ma, Yellowstone plume was shielded from surface and deflected north-northeast by Farallon plate. Middle: At 16 Ma, Farallon plate allowed plume to pass through, and deflected part rose to create Columbia River Basalt. Bottom: Most recently, plume is only slightly deflected by slow (1 cm/yr) motion of North American plate. JdF—Juan de Fuca plate. Other abbreviations as in Figure 1.

Before ~17.5 Ma, the Yellowstone hot spot was beneath the subducted Farallon plate, which would have shielded the Yellowstone plume from shallow levels (where melting begins) or physically hindered the ascent of magmas. The hypothesis that plumes are shielded by subducted lithosphere is consistent with the observation of the excellent anticorrelation between the position of hot spots and the down-dip side of active subduction zones (e.g., Duncan and Richards, 1991).

In addition to shielding the Yellowstone plume, the subducted Farallon plate would have deflected it in the direction of absolute plate motion. The fluid dynamics experiments of Richards and Griffiths (1988) showed that plumes are bent by the upper mantle flowing with the lithospheric plates. The deflected plume is parabolic in cross-sectional shape, although changing directions of mantle flow and differences in viscosity with depth render the extent of

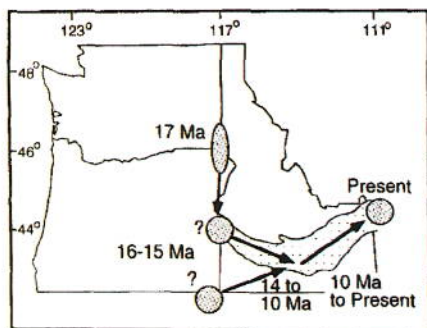


Figure 3. Plan view of proposed path of Yellowstone hot spot. At 17 Ma, plume was deflected to northeast, resulting in Columbia River Basalt. Plume partly recovered by 14 Ma, forming western Snake River plain. Arc in Snake River plain is caused by recovery of plume to its present steady-state position.

deflection uncertain. At ~20 Ma, the absolute motion of the Farallon plate, hence the direction of plume deflection, was 27° (Engbrechtsen et al., 1984).

When deflection of a plume ceases or changes direction, the bent part separates from the root of the plume and rises as an independent body, driven by its own Stokes buoyancy (Griffiths and Richards, 1989). The cessation of shielding and deflection by the Farallon plate at ~17.5 Ma would have allowed the rise of a large tilted buoyant mass that had built up beneath the sinking plate (Fig. 2), marking the reinitiation of the Yellowstone plume. This buoyant plume rose beneath the North American plate and resulted in the sudden eruption of the voluminous "Clarkston" phase (Hooper and Hawkesworth, 1993) of the Columbia River Basalt, which comprises the Imnaha, Grande Ronde, and Wanapum basalts (>97% of the Columbia River Basalt) near the Idaho-Oregon-Washington boundary.

The extent of deflection of the plume can be calculated by using the calibration of Richards and Griffiths (1988), but unfortunately it involves several unknown parameters, such as the viscosity and patterns of flow through the entire depth of the convecting mantle. An estimate that uses the velocity of the Farallon plate at 20 Ma (5 cm/yr) for the horizontal advective velocity and a 650-km-thick convecting layer indicates that the plume would have been deflected several hundred kilometres to the north-northeast relative to its vertical piercing point had the Farallon plate not interfered.

Deflection caused by a sinking slab may be much stronger than deflection beneath the interior of a surface plate. A variety of evidence suggests that the viscosity of the upper mantle increases by one or two orders

of magnitude in its upper 650 km (e.g., Davies and Richards, 1992). Because it penetrates into the higher viscosity region, a subducted slab would exert more traction on the plume than a moving plate at the surface, which is effectively lubricated by the uppermost, low-viscosity region (Whitehead, 1982; Richards and Griffiths, 1988). The radius of the Hawaii-Emperor bend indicates that the Hawaiian plume was deflected <200 km by the moving Pacific plate, in contrast to the nearly 500 km of deflection of the Yellowstone plume toward the Columbia River Basalt vent area suggested by our model. This difference may result from the sinking of the slab at depth, as described above. It may also result from the lesser buoyancy flux (or buoyancy cross section) of the Yellowstone plume relative to the Hawaiian plume (Sleep, 1990).

We suggest two possible consequences of plume recovery to a more nearly vertical conduit as the lower part of the subducted Farallon plate sank deeper toward the northeast (Fig. 2). These alternatives are not necessarily mutually exclusive, because the dynamics of plume recovery must be complicated. One possibility is that plume recovery resulted in the formation of the Owyhee plateau at ~16 Ma (cf. Pierce and Morgan, 1992). This hypothesis accounts for the rapid shift of the focus of magmatism to the south, from the Columbia River Basalt vents, and the 1 m.y. time lag between the start of Columbia River Basalt and Owyhee plateau magmatism (Fig. 3).

The second possibility is that the western and eastern parts of the Snake River plain constitute a continuous feature created by adjustment of the Yellowstone plume to changes in the flow of the uppermost mantle that accompanied the slab-penetrating event at 17.5 Ma. This change would have exposed the plume to a "mantle wind" that had different direction and velocity as the Farallon-North American plate boundary crossed over it. Adjustment of plumes to a new steady-state position occurs along a hyperbolic path (Griffiths and Richards, 1989), and a finite amount of time is necessary to adjust to a new steady-state position. Griffiths and Richards (1989) showed that the recovery distance after a change in plate motion is equivalent to the amount of deflection. If it is assumed that the eastern and western Snake River plain form a single hyperbolic hot-spot trace, its radius of curvature is ~350 km, which is only slightly less than the distance of deflection between the trace of the Yellowstone hot spot and eruptive sites of the Columbia River Basalt. This radius is greater than the 100 to 200 km radius of the Hawaiian-Emperor bend, suggesting that

the Yellowstone plume is not as buoyant as the Hawaiian plume (cf. Sleep, 1990), especially considering the much faster plate (and presumably upper mantle) flow velocities in the Pacific.

The observation that the eastern Snake River plain is aligned with the absolute motion of the North American plate suggests that the Yellowstone plume has recovered to a new steady-state position. The time for the plume to recover to steady state has been shown to be equal to the height of the convecting layer divided by the Stokes velocity of the plume (Richards and Griffiths, 1988). If deflection of the plume occurs in the upper (650 km) mantle, and the Yellowstone plume had just attained steady state (time = 17×10^6 yr), then the ascent rate of the plume is calculated to have been ~4 cm/yr, which is a reasonable figure. In addition, the apparent discrepancy between the transgression of volcanism along the Snake River plain and the velocity of the North American plate is a logical result of the plume's recovery to a new steady-state position.

SUMMARY

Complications imposed on the Yellowstone plume by subduction and the overriding of the plume by the convergent plate boundary provide a straightforward explanation for many of the discrepancies in the temporal and spatial distribution of magmatism in the inland Northwest. The progression from the Oregon Coast Range, Columbia River Basalt, and Snake River plain to Yellowstone provinces is a logical consequence of the changing plate-tectonic environment in the vicinity of the Yellowstone plume. During the Eocene, a divergent plate boundary lay above the plume, and the manifestation of this is the seamount province of the Oregon Coast Range (Duncan, 1982). During the late Eocene and early Miocene, the plume was shielded from the surface and deflected to the northeast by a subduction zone. This zone was reconfigured when an effective window opened in the subducted plate at ~17.5 Ma, and the plume burst forth, producing the Columbia River Basalt. The plume then readjusted to a more vertical orientation, producing a hot-spot track along the Snake River plain.

This model suggests that there is a common association of small-volume flood-basalt volcanism (the Columbia River Basalt is an order of magnitude less voluminous than other flood basalts; e.g., Richards et al., 1989) when a convergent plate margin crosses a hot spot. Although our model must surely be inadequate in detail, simple tectonic and fluid-dynamics considerations show that the Columbia River Basalt-Snake

River plain eruptions may be consistent with a Yellowstone plume origin. Furthermore, our hypothesis can be tested by several means, particularly by refined age determinations (e.g., Clemens and Wood, 1991), further geochemical study (e.g., Craig et al., 1992), and resolution of the geologic relations between the eastern and western Snake River plain and the Owyhee plateau.

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REFERENCES CITED

- Anders, M.H., and Sleep, N.H., 1992, Magmatism and extension: The thermal and mechanical effects of the Yellowstone hot spot: *Journal of Geophysical Research*, v. 97, p. 15,379–15,393.
- Anders, M.H., Geissman, J.W., Piety, L.A., and Sullivan, J.T., 1989, Parabolic distribution of circum-eastern Snake River plain seismicity and latest Quaternary faulting: Migratory pattern and association with the Yellowstone hot spot: *Journal of Geophysical Research*, v. 94, p. 1589–1621.
- Armstrong, R.L., Leeman, W.P., and Malde, H.E., 1975, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River plain, Idaho: *American Journal of Science*, v. 275, p. 225–251.
- Beeson, M.H., and Tolan, T.L., 1990, The Columbia River Basalt Group in the Cascade Range: A middle Miocene reference datum for structural analysis: *Journal of Geophysical Research*, v. 95, p. 19,547–19,560.
- Bonnicksen, B., and Kauffman, D.F., 1987, Physical features of rhyolite lava flows in the Snake River plain volcanic province, southwestern Idaho, in Fink, J.H., ed., The emplacement of silicic domes and lava flows: *Geological Society of America Special Paper* 212, p. 119–145.
- Brandon, A.D., and Gole, G.G., 1988, A Miocene subcontinental plume in the Pacific Northwest: Geochemical evidence: *Earth and Planetary Science Letters*, v. 88, p. 273–283.
- Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plumes for the evolution of flood basalts: *Earth and Planetary Science Letters*, v. 99, p. 79–93.
- Carlson, R.W., and Hart, W.K., 1987, Crustal genesis on the Oregon Plateau: *Journal of Geophysical Research*, v. 92, p. 6191–6206.
- Christiansen, R.L., and McKee, E.H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia intermontane regions, in Smith, R.B., and Eaton, G.P., eds., *Cenozoic tectonics and regional geophysics of the western Cordillera*: *Geological Society of America Memoir* 152, p. 283–311.
- Clemens, D.M., and Wood, S.H., 1991, Timing of volcanism and faulting in the northeastern margin of the western Snake River plain, southwestern Idaho—Preliminary results: *Eos (Transactions, American Geophysical Union)*, v. 72, p. 603.
- Craig, H., Scarsi, P., Cerling, T.E., and Leeman, W.P., 1992, High-helium 3 continental hot spots: Ethiopia, Yellowstone–Snake River Plain, and Erebus(?): *Eos (Transactions, American Geophysical Union)*, v. 73, p. 542.
- Davies, G.F., and Richards, M.A., 1992, Mantle convection: *Journal of Geology*, v. 100, p. 151–206.
- Draper, D.S., 1991, Late Cenozoic bimodal magmatism in the northern Basin and Range province of southeastern Oregon: *Journal of Volcanology and Geothermal Research*, v. 47, p. 299–328.
- Dueker, K., and Humphreys, G., 1990, Upper mantle velocity structure of the Great Basin: *Geophysical Research Letters*, v. 17, p. 1327–1330.
- Duncan, R.A., 1982, A captured island chain in the Coast Range of Oregon and Washington: *Journal of Geophysical Research*, v. 87, p. 10,827–10,837.
- Duncan, R.A., and Richards, M.A., 1991, Hot-spots, mantle plumes, flood basalts, and true polar wander: *Review of Geophysics*, v. 29, p. 31–50.
- Engelbreton, D.C., Cox, A., and Gordon, R.G., 1984, Relative motions between oceanic and continental plates in the Pacific basin: *Geological Society of America Special Paper* 206, 59 p.
- Grand, S.P., 1987, Tomographic inversion for shear velocity beneath the North American plate: *Journal of Geophysical Research*, v. 92, p. 14,065–14,090.
- Griffiths, R.W., and Richards, M.A., 1989, The adjustment of mantle plumes to changes in plate motion: *Geophysical Research Letters*, v. 16, p. 437–440.
- Hill, R.L., Campbell, I.H., Davies, G.F., and Griffiths, R.W., 1992, Mantle plumes and continental tectonics: *Science*, v. 256, p. 186–193.
- Hooper, P.R., 1990, The timing of crustal extension and the eruption of continental flood basalts: *Nature*, v. 345, p. 246–249.
- Hooper, P.R., and Hawkesworth, C.J., 1993, Isotopic and geochemical constraints on the origin and evolution of the Columbia River Basalt: *Journal of Petrology* (in press).
- Leeman, W.P., 1982, Development of the Snake River plain—Yellowstone Plateau province, Idaho and Wyoming: An overview and petrologic model, in Bonnicksen, B., and Breckenridge, R., eds., *Cenozoic geology of Idaho*: *Idaho Geological Survey Bulletin*, v. 26, p. 155–178.
- Mabey, D.R., 1982, Geophysics and tectonics of the Snake River plain, Idaho, in Bonnicksen, B., and Breckenridge, R., eds., *Cenozoic geology of Idaho*: *Idaho Geological Survey Bulletin*, v. 26, p. 139–154.
- Morgan, W.J., 1972, Plate motions and deep mantle convection, in Shagam, R., et al., eds., *Studies in earth and space sciences*: *Geological Society of America Memoir* 132, p. 7–22.
- Morgan, W.J., 1981, Hotspot tracks and the opening of the Atlantic and Indian oceans, in Emiliani, C., ed., *The sea*, Volume 7: New York, Wiley Interscience, p. 443–475.
- Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hotspot: Volcanism, faulting, and uplift, in Link, P.K., et al., eds., *Regional geology of eastern Idaho and western Wyoming*: *Geological Society of America Memoir* 179, p. 1–53.
- Priest, G.R., 1990, Volcanic and tectonic evolution of the Cascade volcanic arc, central Oregon: *Journal of Geophysical Research*, v. 95, p. 19,583–19,600.
- Rasmussen, J., and Humphreys, E., 1988, Tomographic image of the Juan de Fuca plate beneath Washington and western Oregon using teleseismic P-wave travel times: *Geophysical Research Letters*, v. 15, p. 1417–1420.
- Richards, M.A., and Griffiths, R.W., 1988, Deflection of plumes by mantle shear flow: Experimental results and a simple theory: *Geophysical Journal*, v. 94, p. 367–376.
- Richards, M.A., and Griffiths, R.W., 1989, Thermal entrainment by deflected mantle plumes: *Nature*, v. 342, p. 900–902.
- Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot-spot tracks: Plume head and tails: *Science*, v. 246, p. 103–107.
- Rodgers, D.W., Hackett, W.R., and Ore, T.H., 1990, Extension of the Yellowstone Plateau, eastern Snake River plain, and Owyhee plateau: *Geology*, v. 18, p. 1138–1141.
- Sleep, N.H., 1990, Hot spots and mantle plumes: Some phenomenology: *Journal of Geophysical Research*, v. 95, p. 6715–6736.
- Suppe, J., Powell, C., and Berry, R., 1975, Regional topography, seismicity, Quaternary volcanism, and the present day tectonics of the western United States: *American Journal of Science*, v. 275A, p. 397–417.
- Tolan, T.L., Reidel, S.P., Beeson, M.H., Anderson, J.L., Fecht, K.R., and Swanson, D.A., 1989, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group, in Reidel, S.P., and Hooper, P.R., eds., *Volcanism and tectonism in the Columbia River flood-basalt province*: *Geological Society of America Special Paper* 239, p. 1–20.
- Vandecar, J.C., Crosson, R.S., and Creager, K.C., 1991, Tectonic inferences from the three-dimensional upper-mantle velocity structure of the Cascadia subduction zone: *Eos (Transactions, American Geophysical Union)*, v. 72, p. 326.
- Wells, R.E., and Heller, P.L., 1988, The relative contribution of accretion, shear, and extension to Cenozoic rotation in the Pacific Northwest: *Geological Society of America Bulletin*, v. 100, p. 325–338.
- White, R.S., and McKenzie, D.P., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: *Journal of Geophysical Research*, v. 94, p. 7685–7730.
- Whitehead, J.A., 1982, Instabilities of fluid conduits in a flowing earth—Are plates lubricated by the asthenosphere?: *Royal Astronomical Society Geophysical Journal*, v. 70, p. 415–433.

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