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Notes

Mid-Miocene propagation of the Yellowstone mantle plume head beneath the Columbia River basalt source region

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ABSTRACT

Columbia River flood-basalt volcanism is the product of mid-Miocene distortion of the Yellowstone mantle plume head against the Precambrian margin of North America. The overall migration pattern of Columbia River basalt vents reflects northward propagation of the plume head beneath the west-southwest-migrating North American plate. Thermal uplift mimics the vent migration. Over the 1.5 m.y. of Grande Ronde basalt extrusion, the projected crest of the plume head migrated 105 km (7 cm/yr), from the Chief Joseph dike swarm east-northeast into the Clearwater embayment, where uplift occurred over the same period at a rate of 0.67 mm/yr. Chemical variations reflect progressive melting of the plume and mantle lithosphere, followed by the mixing of these components with an enriched source from the overriding craton. Rapid thickening of the plume head against the cratonic margin led to decompressional melting and magma rise beneath a thin oceanic lithosphere of accreted terranes.

INTRODUCTION

The Nevada-Oregon rift zone (Fig. 1), a 1000-km-long, north-south belt extending through western Idaho and adjacent Washington, Oregon, and Nevada, records a dynamic period of volcanism, largely restricted to a narrow time interval between 17 and 14 Ma (Zoback and Thompson, 1978; Pierce and Morgan, 1992). The zone is delineated to the south by bimodal, basalt-dominated dikes and lava-filled grabens of the north-northwest-trending northern Nevada rift (Zoback et al., 1994), and to the north by similarly trending feeder dikes of the Columbia River and Oregon Plateau basalts (Swanson et al., 1981; Carlson and Hart, 1987). Zoback and Thompson (1978) noted that the central part of the Nevada-Oregon rift zone marks the location of the Yellowstone mantle plume at ~16 Ma, delineated by the McDermitt caldera, which is the first in a succession of calderas lying along the Yellowstone hotspot track (Pierce and Morgan, 1992).

The absence of an obvious hotspot trend west of the McDermitt caldera led Draper (1991) and Pierce and Morgan (1992) to conclude that the Yellowstone plume was generated near the Oregon-Idaho-Nevada trisect area at ~17–18 Ma. Geist and Richards (1993), however, argued for an alternative model (Duncan, 1982), in which the surface was shielded from the plume by the subducting Farallon plate until the plume reemerged to the east at ~17.5 Ma.

Whereas slab deflection or plume generation can account for the plume's arrival beneath the McDermitt caldera, neither model in itself adequately explains the linearity of magmatism along the Nevada-Oregon rift zone. Models calling for a plume origin for the belt, or for segments of the

belt, suggest that surface volcanism must be influenced by magma rise beneath a heterogeneous lithosphere (Zoback and Thompson, 1978; Brandon and Goles, 1988; Draper, 1991; Pierce and Morgan, 1992; Hooper and Hawkesworth, 1993; Parsons et al., 1994). I concur, and I suggest here that the north-south alignment of magmatism reflects distortion and propagation of the plume head against the Precambrian margin of North America. I examine the proposed northward propagation of the plume head

as reflected in stratigraphic, structural, and petrologic relations in the Columbia River basalt lava sequence.

DISTORTION OF THE MANTLE PLUME HEAD

Thompson and Gibson (1991) showed that the circular shapes common to oceanic plume heads that spread laterally beneath horizontal lithosphere (White and McKenzie, 1989) are unlikely to be maintained beneath heterogeneous, regionally deformed continental lithosphere. Such structural and compositional heterogeneity is evident across the Precambrian continental margin of North America, which lies parallel to, and is partly coincident with, the Nevada-Oregon rift zone. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ isopleth lines of Armstrong et al. (1977) and Kistler and Peterman (1978) (Fig. 1) delineate Precambrian continental crust east of the 0.706 line and accreted Mesozoic oceanic terranes west of the 0.704 line; the region between these two isopleths is likely to be crust of transitional character (Pierce and Morgan, 1992).

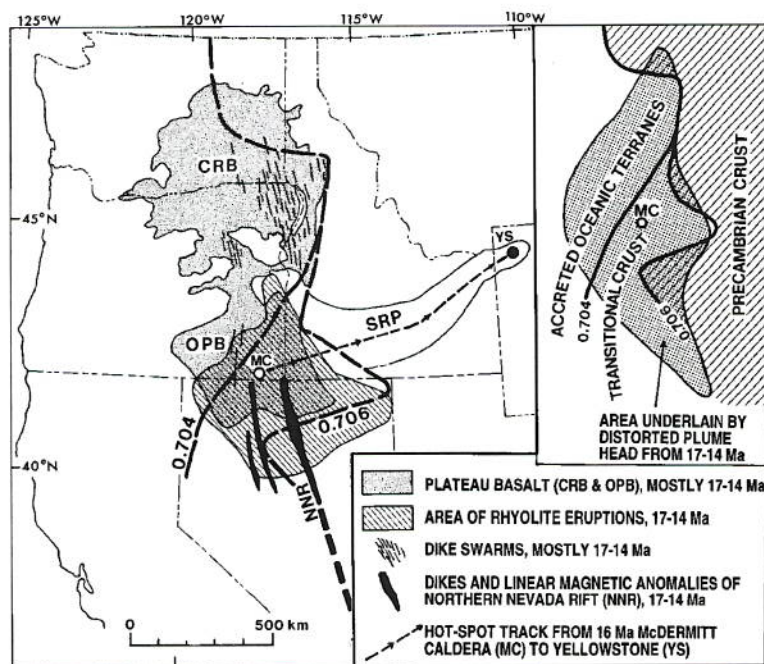


Figure 1. Distribution of volcanic rocks erupted from 17 to 14 Ma along Nevada-Oregon rift zone, modified after Pierce and Morgan (1992). CRB—Columbia River basalt; OPB—Oregon Plateau basalt; SRP—Snake River Plain; MC—McDermitt caldera. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ isopleth lines from Armstrong et al. (1977) and Kistler and Peterman (1978).

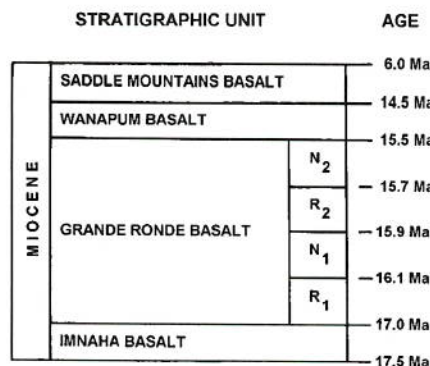


Figure 2. Formations of Columbia River basalt group exposed in eastern Columbia plateau. Ages from Baksi (1989) and Tolan et al. (1989).

South of the 0.704 and 0.706 lines, the small-volume, mildly alkaline lavas of the northern Nevada rift reflect surficial magmatism on a relatively small scale above an extended crust of transitional to continental character (Zoback et al., 1994). North of the 0.704 line, the Columbia River and Oregon Plateau tholeiitic flood basalts were generated by large-scale melting and rapid ascent through relatively thin, dense crust of oceanic character (Hooper and Hawkesworth, 1993). The center part of the Nevada-Oregon rift zone, between the 0.704 and 0.706 lines, is the only segment characterized by significant eruptions of peralkaline rhyolite (e.g., the McDermitt caldera), suggesting a greater degree of thermal erosion and crustal anatexis above the central, hotter part of the distorted mantle plume (Pierce and Morgan, 1992). The Precambrian margin, therefore, appears to be a controlling factor in the distribution of volcanism, as well as in the style, volume, and composition of volcanism along the Nevada-Oregon rift zone trend.

The elongation of activity away from the predicted center of the plume suggests that the eastern flank of the plume head may

have been distorted as its lateral flow was impeded by the relatively thick, southwest-moving continental margin of the North American craton. Compression of the plume head resulted in a north-south protraction of mantle flow, the surface expression of which is the Nevada-Oregon rift zone.

Propagation of the plume head north and south of the McDermitt caldera should be reflected in the history of uplift, rifting, and magmatism along the axis of the Nevada-Oregon rift zone. A well-established pattern of activity to the south is hampered by the lack of a conformable sequence of 17 to 14 Ma lava flows. To the north, however, the Columbia River basalt province provides a thick, generally conformable sequence of well-studied lava flows that record the history of uplift and magmatism above the supposed northward-propagating head of the mantle plume.

The Columbia River basalt eruption rate was greatest in the early stages; extrusions of Imnaha, Grande Ronde, and Wanapum basalts were essentially continuous from 17.5 to 14.5 Ma and were followed by sporadic extrusions of the relatively small volume Saddle Mountains basalts from about 14 to 6 Ma (Fig. 2) (Tolan et al., 1989).

SOURCE MIGRATION

The source region of Columbia River basalt volcanism lies in the southeastern part of the Columbia Plateau, where numerous dikes are concentrated in the Chief Joseph dike swarm (Fig. 3). Flood-basalt volcanism here, 500 km north of the supposed center of the mantle plume, is attributed to a thin, dense oceanic lithosphere that has undergone at least one previous period of Tertiary extension (Hooper and Hawkesworth, 1993). Thompson and Gibson (1991) described this region as a "thinspot" susceptible to massive, plume-generated volcanism. The oceanic lithosphere is confined by the

older craton to the east and also to the north, where the cratonic margin (the 0.706 line) makes an abrupt westward bend immediately north of the Chief Joseph dike swarm (Fig. 1). The scarcity of dikes to the north suggests that this bend might have acted as a bulwark against plume flow.

Within the Chief Joseph swarm, the greatest density of dikes occurs in two en echelon zones—the Cornucopia and Grande Ronde swarms (Fig. 2). Although both are dominated by Grande Ronde basalt, the more southern swarm (Cornucopia) has a greater percentage of Imnaha basalt dikes, suggesting a northward advance of activity (Hooper and Conrey, 1989). This apparent migration is repeated in the flow-distribution pattern. The oldest recognized Columbia River basalt flows (Imnaha magnetostratigraphic unit R₀) are found only along the southern part of the Chief Joseph swarm, whereas progressively younger Grande Ronde magnetostratigraphic units (R₁–N₂, Fig. 2) are found progressively farther to the north (Fig. 4) (Camp and Hooper, 1981; Swanson et al., 1981).

The dike migration pattern for the younger Wanapum and Saddle Mountains basalts is more complex. The lack of Wanapum and Saddle Mountains basalt dikes in the southern part of the Chief Joseph swarm is consistent with the above pattern of northward migration; however, rather than being confined to the northern part of the dike swarm, they extend over a broad area of the southeastern plateau. The east-west width of the Columbia River basalt source region thus appears to become greater with advancing time (Fig. 3). Although partly a function of the greater exposure of the younger dikes, the main cause is here attributed to two contemporaneous events: (1) an eastward migration of eruptive activity as the crest of the plume head is overridden by the North American plate, and (2) a broad-

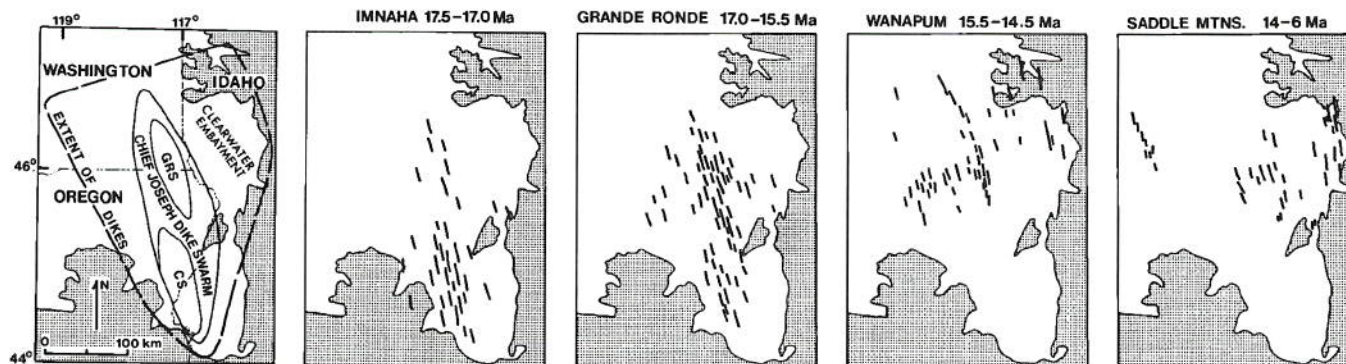


Figure 3. Age distribution of Columbia River basalt dikes in southeastern Columbia Plateau based on mapped localities (e.g., Swanson et al., 1981), known but unmapped localities, and localities inferred from stratigraphic relations. GRS—Grande Ronde dike swarm; CS—Cornucopia dike swarm.

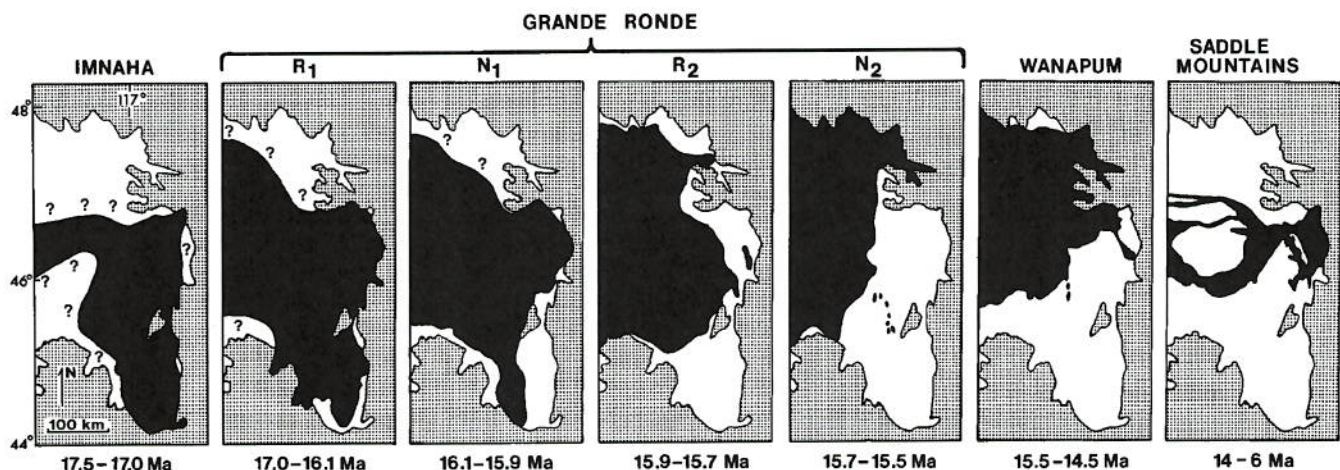


Figure 4. Distribution of Columbia River basalt units with advancing age, from Swanson et al. (1981), Camp (1981), Camp and Hooper (1981), and Tolan et al. (1989).

ening of activity to the west as the plume head is sheared and extended over time in the direction of plate movement by convective flow, lithospheric drag, and a variety of other potential mechanisms described, for example, by Epp (1984).

The effect of plate migration is seen in a progressive shift in the eastern margin of the source region. From the Cornucopia swarm it shifts eastward to the somewhat younger Grande Ronde swarm and still farther eastward into the Clearwater embayment during Wanapum and Saddle Mountains time (Fig. 3). Wanapum extrusion is marked by a clear eastward shift in its progressively younger Frenchman Springs, Roza, and Priest Rapids Members (Tolan et al., 1989). Although the Saddle Mountains source locations are the most diffuse, nine of its 14 members have their sources in the Clearwater embayment (Camp, 1981).

Progressive widening of the source region has partly disguised an overall vent pattern of northward and eastward migration, a pattern consistent with the superposition of two related phenomena: (1) northward propagation of the mantle plume head and (2) overriding of the plume head by the westward-moving North American plate.

PLUME-GENERATED UPLIFT

Evidence for a Miocene period of plume-generated uplift along the southern segment of the Nevada-Oregon rift zone comes from the recognition of a large low-density anomaly in the mantle, interpreted by Parsons et al. (1994) as the Miocene remnant of the Yellowstone starting plume head. Miocene uplift is also evident along the northern segment of the rift zone, although there it is preserved in the basalt stratigraphy of the southeast Columbia Plateau. Uplift appears to mimic the dike migration pattern, as dem-

onstrated by the offlap of age-progressive units (Fig. 4), reflecting the gradual development of a northwest-dipping paleoslope (Hooper and Camp, 1981). Uplift began in the south, after extrusion of Imnaha basalt, and migrated to the north with time. As the North American plate migrated to the west, above the advancing plume head, the eastern plateau rose at an accelerated rate, as shown by the progressive offlap of Grande Ronde magnetostratigraphic units west of the Clearwater embayment after N_1 time (Fig. 4). Later, Wanapum and Saddle Mountains basalts were extruded on the uplifted Clearwater embayment as the eastern margin of the source region migrated to the east, toward the site of plume-generated uplift.

Eocene through Miocene uplift east of the Columbia River basalt source area was interpreted by Hooper and Camp (1981) to reflect isostatic rise of granitic terrains to the east, contemporaneous with relative subsidence of the Pasco basin to the west. In this model, the west-dipping basalt paleoslope is merely a snapshot of a prolonged period of steady Tertiary uplift. As shown below, however, uplift during basalt extrusion must have occurred at an accelerated rate.

From about 17 to 15.5 Ma, Grande Ronde basalt accumulated to a thickness of about 1000 m in southeast Washington near the northern axis of the Chief Joseph dike swarm. During this time, south of the dike swarm, the center conduit (tail) of the mantle plume was migrating from the McDermitt caldera (~16 Ma) to the Owyhee-Humboldt volcanic field (~14 Ma) to the east-northeast, at a rate of 7 cm/yr (Pierce and Morgan, 1992). At that rate, the northern edge of the plume head would have migrated from the Chief Joseph dike swarm 105 km to the east-northeast over the 1.5

m.y. interval of Grande Ronde extrusion. This would place it near the northeast margin of the Clearwater embayment, close to the linear dike system of the Wanapum Priest Rapids Member (14.5 Ma) (Camp and Hooper, 1981). Northeast of the dike system, near Dent, Idaho, the Priest Rapids is directly above Imnaha basalt. There, the entire 1000-m-thick Grande Ronde sequence has pinched out across the 105 km distance. From these data, the relative rate of uplift as the eastern margin of the plume head migrated from the Chief Joseph dike swarm to Dent, Idaho, was ~0.67 mm/yr.

PLUME-GENERATED MELTING

Hooper and Hawkesworth (1993), on the basis of recent isotopic and trace-element data, described a variety of mantle sources for the Columbia River basalt magmas. They showed that Imnaha and Grande Ronde basalts (90% of the Columbia River basalt volume) are chemically and isotopically similar to oceanic-island basalt and plume-related tholeiites, like those of Hawaii. Plume-generated magmas of Imnaha composition were increasingly modified by a high-silica component, probably derived from subcontinental lithospheric mantle, to produce the voluminous basaltic andesites of Grande Ronde basalt (Hooper and Hawkesworth, 1993). It appears that the bulk of Columbia River basalt magmas were derived beneath the Chief Joseph dike swarm from (1) partial melting of the northward-propagating plume head (Imnaha basalt) accompanied by (2) increasing amounts of thermal erosion and mixing of the subcontinental lithospheric mantle source above the propagating head (Grande Ronde basalt).

By Wanapum basalt time, volcanism began to incorporate a third component, which appears to be associated with the >2000 Ma

subcontinental lithospheric mantle beneath the North American plate (Hooper and Hawkesworth, 1993), consistent with the calculations above, which place the arrival of the plume head at the cratonic margin at the beginning of Wanapum time. The plume head was overridden by the craton in Saddle Mountains time, resulting in sporadic, less voluminous extrusions concentrated in the Clearwater embayment of the eastern plateau. Predictably, the primary source for these Saddle Mountains basalts was the enriched subcontinental lithospheric mantle beneath the ancient craton (Hooper and Hawkesworth, 1993).

TECTONOMAGMATIC MODEL

White and McKenzie (1989) described flood-basalt volcanism as the passive response to lithospheric rifting above the head of a mantle plume. Richards et al. (1989), however, suggested that rifting is not necessary because the plume itself is the driving force of the eruption. A rift-related model for Columbia River basalt volcanism is incompatible with field evidence for minor extension during eruption, estimated by Taubeneck (1970) to be <1%. In the absence of rifting, the high Columbia River basalt eruption rate cannot be attributed to passive mantle upwelling beneath an extending crust. The alternative explanation presented here calls for active mantle upwelling driven by rapid thickening of the plume head as it was compressed and distorted against the southwest-migrating Precambrian craton. As the thickened plume head rose adiabatically beneath the adjacent, relatively thin oceanic lithosphere, the release of pressure resulted in voluminous melting. The sequence of melting reflects an upward progression of thermal erosion, from an initial plume-head component (Imnaha basalt), to increasing amounts of an oceanic lithospheric component (Grande Ronde), to partial melting of the ancient continental lithosphere of the overriding plate (Saddle Mountains) (Hooper and Hawkesworth, 1993).

From 17 to 14 Ma, the high eruption rate of the early lavas may have been facilitated by rapid ascent of magma along weak boundaries in the accreted collage, and by the thin, dense nature of the oceanic crust. At ~14 Ma, the Precambrian margin began to override the distorted crest of the plume head; simultaneously, as the central tail of the plume began to breach the craton, the main site of volcanism shifted to the south. Generation of the Snake River Plain hot-spot track was thus contemporaneous with a rapid decline in the Columbia River basalt eruption rate to the north and a cessation of

magmatism along the northern Nevada rift to the south. The smaller volume Columbia River basaltic melts produced after ~14 Ma were diverted west of the craton and extruded sporadically as Saddle Mountains basalt flows until their cessation at ~6 Ma.

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REFERENCES CITED

- Armstrong, R. L., Taubeneck, W. P., and Hales, P. O., 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington, and Idaho: Geological Society of America Bulletin, v. 88, p. 397–411.
- Baksi, A. K., 1989, Reevaluation of the timing of extrusion of Imnaha, Picture Gorge, and Grande Ronde Basalts, 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. 105–112.
- Brandon, A. D., and Goles, G. G., 1988, A Miocene subcontinental plume in the Pacific Northwest: Geochemical evidence: Earth and Planetary Science Letters, v. 99, p. 79–93.
- Camp, V. E., 1981, Geologic studies of the Columbia Plateau: Part II. Upper Miocene basalt distribution, reflecting source locations, tectonism, and drainage history in the Clearwater embayment, Idaho: Geological Society of America Bulletin, v. 92, p. 669–678.
- Camp, V. E., and Hooper, P. R., 1981, Geologic studies of the Columbia Plateau: Part I. Late Cenozoic evolution of the southeast part of the Columbia River Basalt Province: Geological Society of America Bulletin, v. 92, p. 659–668.
- Carlson, R. W., and Hart, W. K., 1987, Crustal genesis on the Oregon Plateau: Journal of Geophysical Research, v. 92, p. 6191–6206.
- 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.
- Duncan, R. A., 1982, A captured island chain in the Coast Range of Oregon and Washington: Journal of Geophysical Research, v. 87, p. 827–837.
- Epp, D., 1984, Possible perturbations to hotspot traces and implications for the origin and structure of the Line Islands: Journal of Geophysical Research, v. 89, p. 11,273–11,286.
- Geist, D., and Richards, M. A., 1993, Origin of the Columbia Plateau and Snake River Plain: Deflection of the Yellowstone plume: Geology, v. 21, p. 789–792.
- Hooper, P. R., and Camp, V. E., 1981, Deformation of the south-east part of the Columbia Plateau: Geology, v. 9, p. 323–328.
- Hooper, P. R., and Conrey, R. M., 1989, A model for the tectonic setting of the Columbia River basalt eruption, 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. 293–306.
- 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, v. 34, p. 1203–1246.
- Kistler, R. W., and Peterman, Z. E., 1978, Reconstruction of crustal blocks of California on the basis of initial strontium isotopic compositions of Mesozoic granitic rocks: U.S. Geological Survey Professional Paper 1071, 17 p.
- Parsons, T., Thompson, G. A., and Sleep, N. H., 1994, Mantle plume influence on the Neogene uplift and extension of the U.S. western Cordillera?: Geology, v. 22, p. 83–86.
- 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.
- Richards, M. A., Duncan, R. A., and Courtillot, V. E., 1989, Flood basalts and hot-spot tracks: Plume heads and tails: Science, v. 23, p. 103–107.
- Swanson, D. A., Anderson, J. L., Camp, V. E., Hooper, P. R., Taubeneck, W. H., and Wright, T. L., 1981, Reconnaissance geologic map of the Columbia River Basalt Group, northern Oregon and western Idaho: U.S. Geological Survey Open-File Report 81-797, scale 1:250,000.
- Taubeneck, W. H., 1970, Dikes of the Columbia River Basalt in northeastern Oregon, western Idaho, and southeastern Washington, in Gilmour, E. H., and Stradling, D., eds., Proceedings, Columbia River Basalt Symposium, 2nd: Cheney, Eastern Washington State College Press, p. 73–96.
- Thompson, R. N., and Gibson, S. A., 1991, Subcontinental mantle plumes, hotspots, and pre-existing thinspots: Geological Society of London Journal, v. 148, p. 973–977.
- 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.
- White, R., and McKenzie, D., 1989, Magmatism at rift zones: Generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729.
- Zoback, M. L., and Thompson, G. A., 1978, Basin and Range rifting in northern Nevada: Clues from a mid-Miocene rift and its subsequent offsets: Geology, v. 6, p. 111–116.
- Zoback, M. L., McKee, E. H., Blakely, R. J., and Thompson, G. A., 1994, The northern Nevada rift: Regional tectono-magmatic relations and middle Miocene stress direction: Geological Society of America Bulletin, v. 106, p. 371–382.

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