



Great ellipse



Great elliptical basin, western United States: Evidence for top-down control of the Yellowstone hot spot and Columbia River Basalt Group

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Abstract

The Middle Miocene outbreak point of the Yellowstone hot spot (YHS) and Columbia River Basalt Group (CRBG) occupies the exact center of a surprisingly symmetrical, ~900,000 km² elliptical basin, where the western United States lithosphere is attenuated. The ellipse includes the Great Basin and adjacent parts of the Columbia and Missouri River basins and encloses concentric rings of grabens and horsts. Middle Miocene grabens and dikes radiate outward for hundreds of kilometers from the center of the ellipse. The grabens filled with Middle Miocene and younger lake beds, river sediments, and volcanics above angular unconformities that were eroded on volcanic and sedimentary rocks as young as late Lower Miocene.

The ellipse evidently formed in response to dextral torsion between the North American and Pacific plates, between the Walker Lane of Nevada and the Lewis and Clark line of Montana and Idaho. Attenuation within this elliptical region may have driven decompression melting in the Paleogene arc region of the Cordillera. Magma then migrated toward the center of the ellipse and erupted as the Columbia River Basalt Group (CRBG). Depletion of the magma from the margins of the ellipse collapsed the ring-grabens, rather like a mega-caldera. The ellipse continues to extend. Its widening minor axis parallels North American plate motion.

The geometric and temporal linkage of the elliptical basin to plate boundaries, shear zones, and tectonic domains supports top-down, lithospheric control for the CRBG and YHS, rather than the eruption of a randomly arisen deep-mantle plume.

Introduction

Geologists debate the origins of hot spots and associated large igneous provinces. *Morgan* (1972), *Richards et al.* (1989), and *Ernst & Buchan* (2001) think that hot spots and large igneous provinces represent outbreaks of deep mantle plumes. In contrast, *Anderson* (1994) and authors in *Foulger et al.* (2005) and *Foulger & Jurdy* (2007) propose that these features may form where lithospheric attenuation triggers decompression melting.

Pierce & Morgan (1992) and *Hooper et al.* (2007) interpret the Yellowstone hot spot (YHS) and its companion, the Columbia River Basalt Group (CRBG) of the western United States as having erupted from a Middle Miocene mantle plume. Conversely, *Eaton* (1984), *Hart & Carlson* (1987), *Smith* (1992), *Christiansen et al.* (2002), *Hales et al.* (2005), and *Hamilton* (2007) propose an upper mantle origin. *Humphreys et al.* (2000) and *Yuan & Dueker* (2005) show that the tomographic anomaly that may represent the feeder channel for the active YHS volcano does not extend below the upper mantle.

Pierce & Morgan (1992) and Hooper et al. (2007) locate the outbreak region of the YHS/CRBG at the common borders of Idaho, Oregon, and Nevada, the sites of the oldest CRBG flows and the oldest and hottest silicic volcanic fields of the YHS track.

Here I show that the outbreak region occupies the exact center of a surprisingly elliptical structural basin that embraces much of the Great Basin, Columbia River Basin, and upper Missouri River Basin (Figure 1). The track of the YHS curves from the center of the ellipse to its NE side. The elliptical basin is a first-order tectonic element of the Cordilleran lithosphere that began to form during leadup to the outbreak of the YHS/CRBG, and continues to widen today.

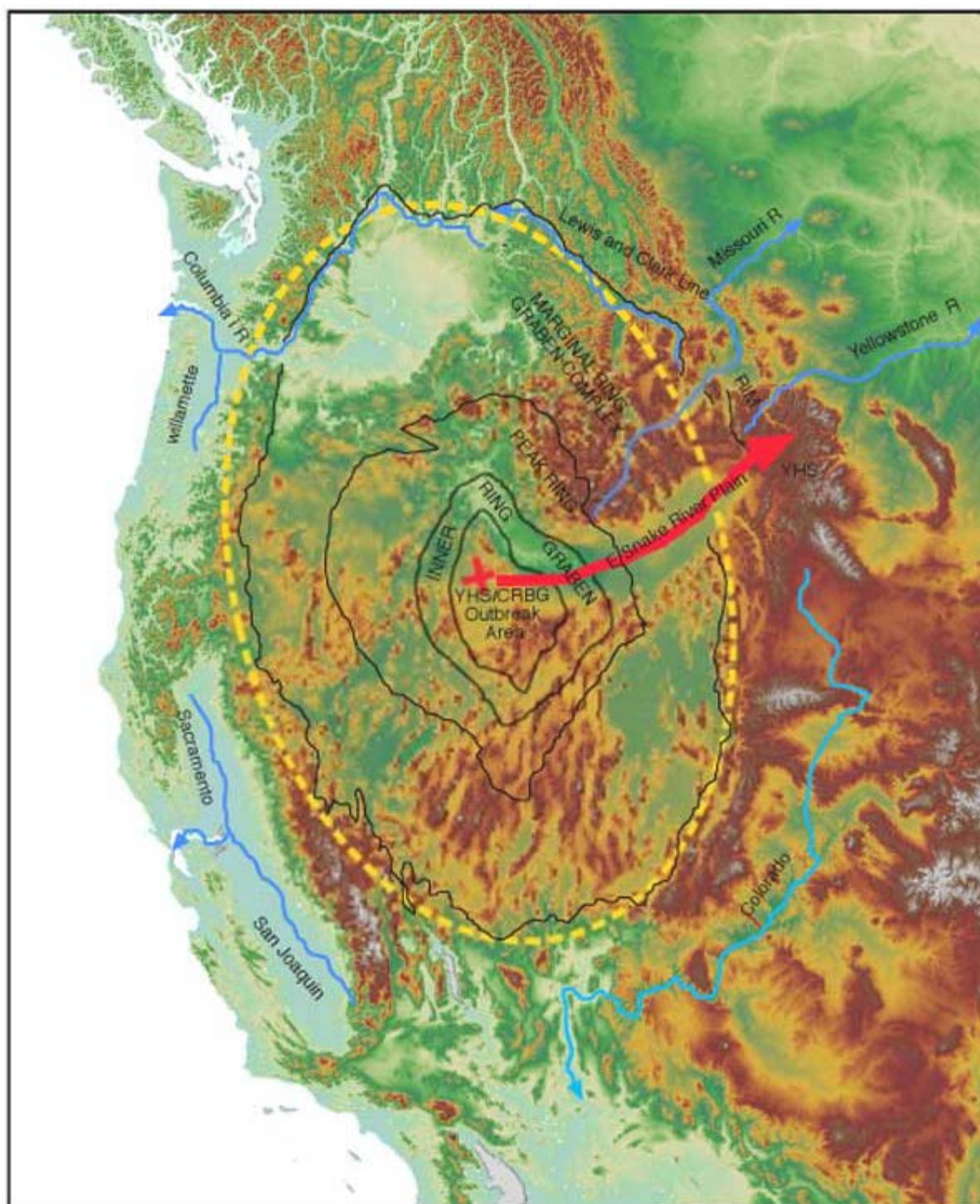


Figure 1: Great elliptical structure of the western United States (yellow dashed ellipse). Black lines—edge and internal divisions of elliptical structure shown in Figures 2 and 3. Blue lines—major rivers of the western United States influenced by the elliptical structure. Red arrow—path of the Yellowstone hot spot. Red (+)—geometric center of the ellipse and outbreak point of the Yellowstone hot spot and Columbia River Basalt

Group.

The bulk of the CRBG erupted between 17.5 and 15.5 Ma (Tolan *et al.*, 1989). Figure 2 shows dike swarms and fractures that radiated from the outbreak point during this time span. These include the Monument, Joseph, and Cornucopia dike swarms, northern Nevada rift, grabens in Idaho, Montana, Wyoming, Utah, Colorado, Arizona, Nevada, and Oregon, and the Olympic-Wallowa lineament (Sears, 1995; Sears & Thomas, 2007; Hooper *et al.*, 2007; Sears *et al.*, 2009).

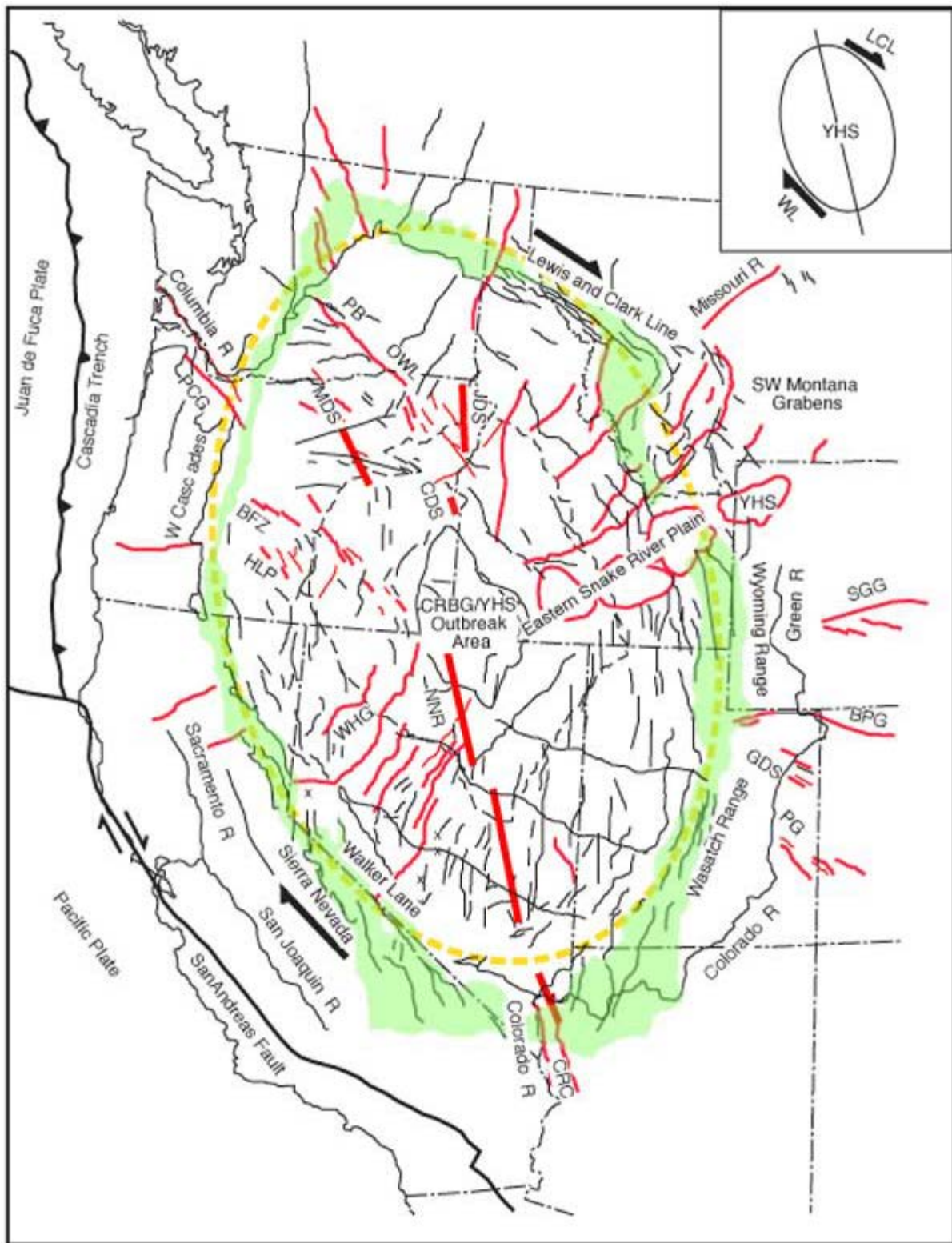


Figure 2: Middle and Late Miocene structural features of the western USA that define the great elliptical structure (red dashed line) centered on the outbreak area of the CRBG/YHS (central area). Green—uplifted rim. Heavy red lines—mafic dike swarms. Medium red lines—radial faults. Heavy arrows—dextral shear couple

between Lewis and Clark line and Walker lane. Red ellipses—YHS silicic volcanic centers of the eastern Snake River Plain, after Pierce & Morgan (1972). Abbreviations, clockwise from north: JDS—Joseph dike swarm; YHS Yellowstone hot spot; SGG—Sweetwater-Granite graben; BPG—Browns Park graben; GDS—Gibsonite dikes; PG—Paradox grabens; CRC—Colorado River corridor; NNR—Northern Nevada rift; WHG—West Humboldt graben; HLP—High Lava Plains; BFZ—Brothers fault zone; PCG—Portland Hills-Clackamas graben; MDS—Monument dike swarm; PB—Pasco basin; OWL—Olympic-Wallowa lineament; CDS—Cornucopia dike swarm. Base map from Reed et al. (2004). Inset: simplified map showing how the major axis of the ellipse links into the tips of the Lewis and Clark line (LCL) and the Walker lane (WL). Shear couple widens the ellipse.

The disturbance coincided with an unusually wet climatic period in the region (Thompson et al., 1982) and the elliptical basin and associated radial fractures captured deep lakes and channeled the Missouri and Columbia rivers.

The great elliptical basin

The elliptical basin is elongate to the NNW and encloses an area of ~900,000 km². Its major and minor axes measure ~1200 km and ~900 km. The ellipse overlies a tectonically complex region that includes parts of the ancient North American craton, Cordilleran fold and thrust belt, accreted oceanic terranes, and magmatic arcs (e.g., Burchfiel et al., 1992). It mostly occupies the region of the Paleogene Cordilleran magmatic arc, characterized by relatively thin, hot, volatile-rich, weak crust and lithosphere (Dickenson, 1998; Hyndman et al., 2005; Marone & Romanowicz, 2007; Thatcher & Pollitz, 2008; Sine et al., 2008). The crust thins from 40-50 km under parts of the rim to 20-30 km under parts of the interior.

Some of the highest mountains in the western USA lie on the elliptical rim. These include the Wasatch Range, Sierra Nevada, and Northern Cascades. Normal fault scarps that had Middle Miocene activity outline most of the rim of the ellipse. Many of these activated older structures that had appropriate orientations to accommodate the disturbance—individual fault zones tend to have complex histories but experienced a Middle Miocene crescendo. The rim faults exhibit 3-5 km of throw and Middle Miocene sediments or volcanics overlapped rim faults that displaced rocks as young as Oligocene and Early Miocene. (Christiansen & McKee, 1978). An early Paleogene erosional surface descends outward from the ellipse rim across broad, gently-sloping mountain blocks. Major rivers flow in concentric troughs along the lower edges of these tilted blocks. NW-trending, dextral-extensional fault zones bound the ellipse on the NE (the Lewis and Clark line), and on the SW (the Walker lane). Several NW-trending shear zones segment the interior of the ellipse (Stewart, 1998).

The distributions of Middle and Upper Miocene grabens, lake beds, and volcanics within the ellipse define a succession of nested elliptical rings, including a marginal ring-graben complex, a peak-ring, and an inner ring-graben (Figure 3). The ellipse-bounding faults remain active. Figure 4 maps seismic risk along the east and west rims of the ellipse (Smith & Arabasz, 1991; USGS, 2008).

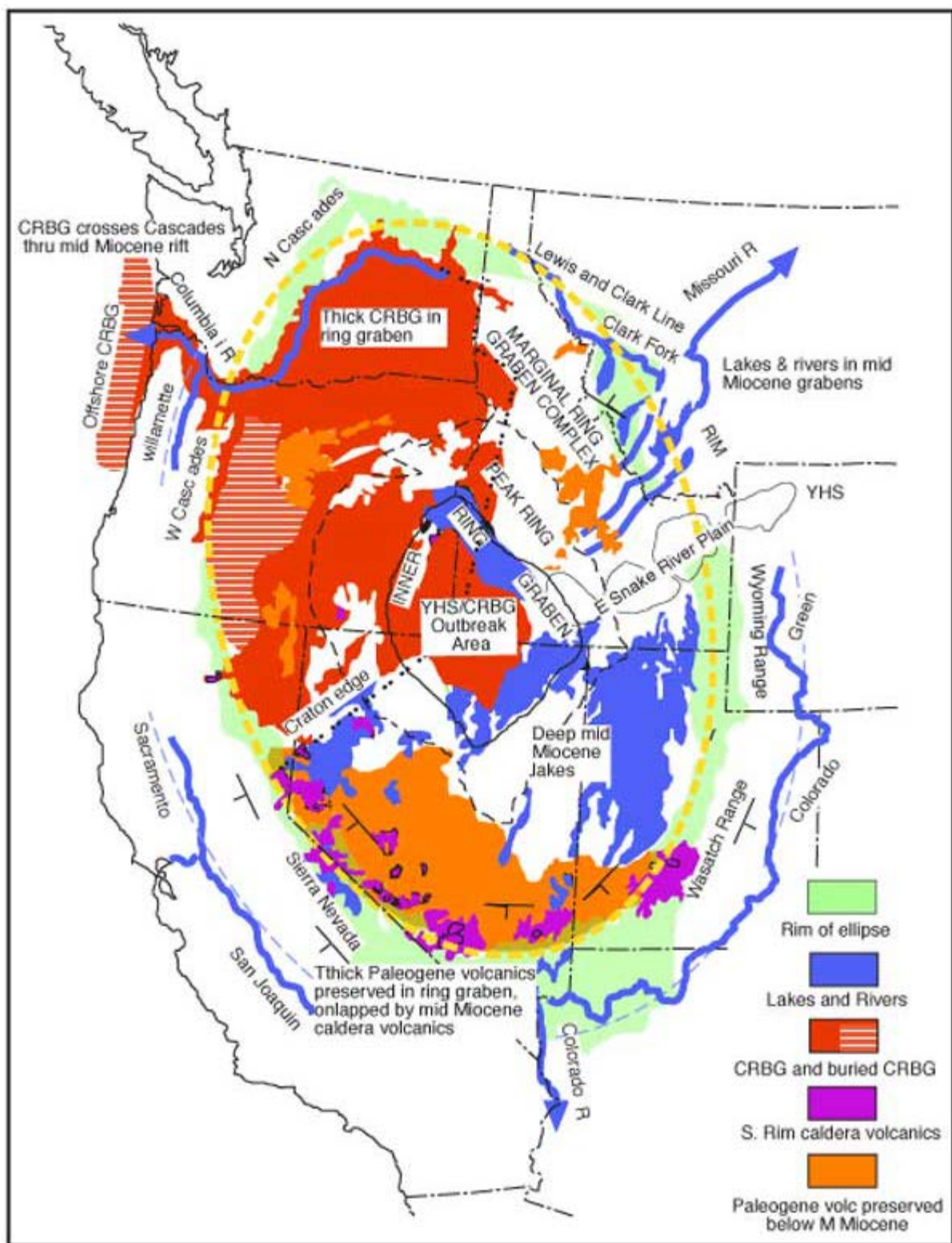


Figure 3: Geologic units that define Middle Miocene nested elliptical rings centered on the outbreak area of the CRBG/YHS. Yellow dashed line—best fit ellipse centered on the CRBG/YHS outbreak area. Dotted line—western edge of the Precambrian basement of North America. Most of the CRBG lies west of this edge. Blue—Middle Miocene lakes and rivers; orange—CRBG; orange hatched—CRBG covered by Pleistocene Cascade volcanics and offshore; brown—Paleogene and Early Miocene volcanics preserved below the Middle Miocene unconformity; purple—Middle Miocene caldera volcanics; green—elliptical rim. Dashed black line—inner edge of Paleogene rocks below the Middle Miocene unconformity. Dashed light blue curves—structural troughs at edges of rim with major rivers. Lakes and flood basalts are ponded in ring grabens. Missouri and Columbia Rivers flow out of the ellipse via radial fractures. Green, middle Colorado, San Joaquin, Sacramento, and Willamette Rivers follow structural troughs along outer edges of the elliptical rim. The lower Colorado River follows the radial Colorado River extensional corridor. The Columbia River shifted

its course eastward upon uplift of the Yakima fold belt (not shown).

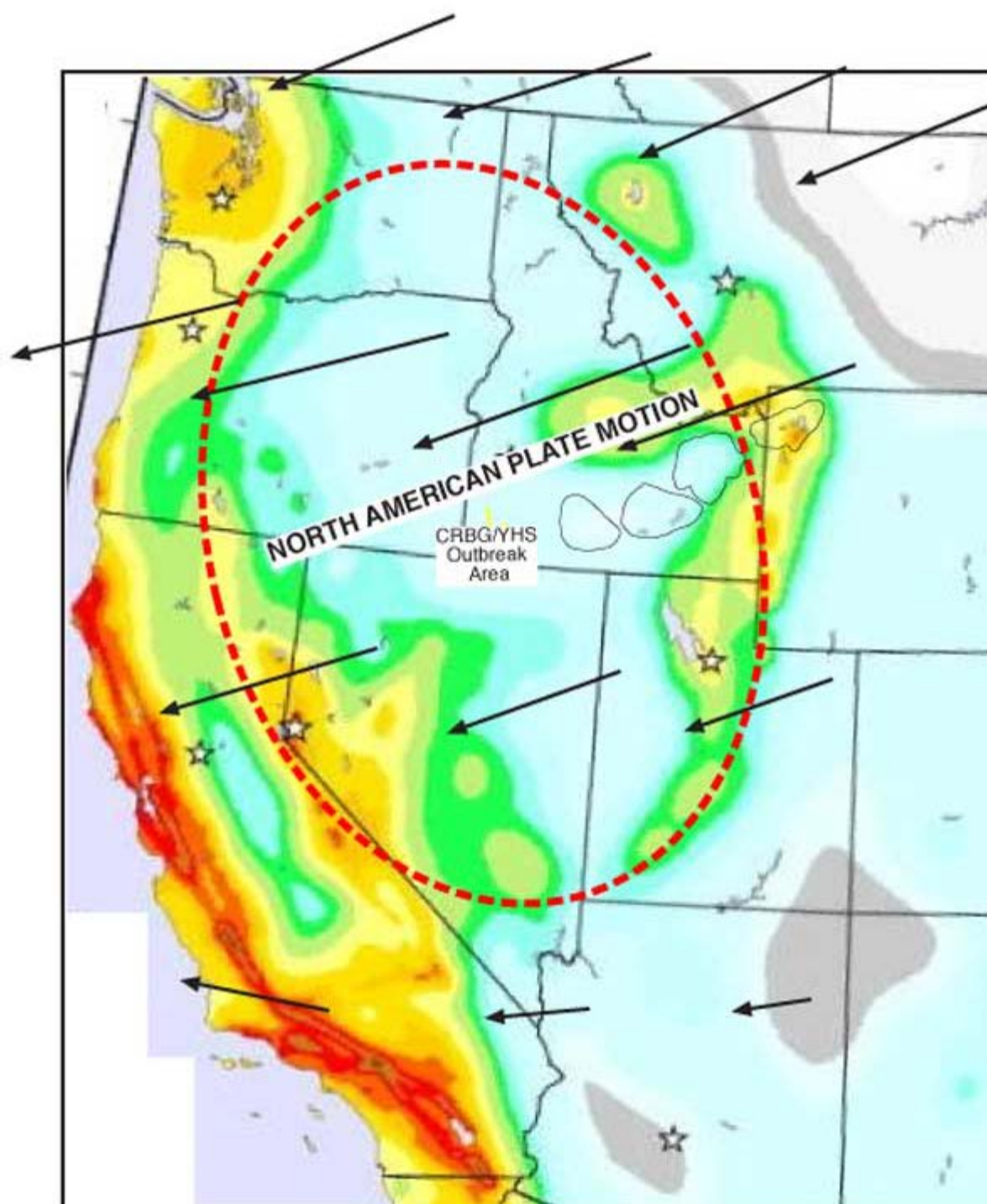


Figure 4: The short axis of the great ellipse parallels North American plate motion (arrows), as shown by olivine anisotropy in sublithospheric mantle (Marone & Romanowicz, 2007). The ellipse widens in this direction, suggesting tensional pull of North American plate, as advocated by Hamilton (2007). Color patterns show seismic risk, from USGS National Seismic Hazard Maps. Warm colors indicate higher seismic risk.

The following sections highlight specific geological observations that correlate initiation of the elliptical structure with the main phases of YHS and CRBG eruption.

NE sector

The Lewis and Clark line (LCL) bounds the ellipse in northern Idaho and western Montana (Figure 2). This structure originated as a Mesoproterozoic rift zone (Sears, 2007a). It experienced dextral extension during

the Middle Miocene disturbance that initiated the ellipse (Sears & Hendrix, 2004; Wallace *et al.*, 1990), accumulating 26 km of dextral slip in northern Idaho (Harrison *et al.*, 1974). Commonly, as much as 5 km of vertical throw, SW-side down, occurs between uplifted rim segments and adjacent grabens. Middle Miocene fluvial and alluvial sediments and CRBG basalts fill canyons along the LCL and unconformably overlie tilted strata as young as late Lower Miocene, bracketing the disturbance to 20-17 Ma (Fields *et al.*, 1985; Smiley, 1989). Massive debris flows descended inward from the rim and aggraded alluvial fans in the grabens (Sears, 2007b).

NE-trending grabens radiated from the YHS/CRBG outbreak region and intersected NW-trending ring-grabens to form a complex interference pattern near the rim of the ellipse (Pardee, 1950). Deep rift lakes were ponded at the intersections (McLeod, 1987; Sears & Ryan, 2003; Smith *et al.*, 1989). Provenance of some Middle and Upper Miocene river cobbles indicate that rivers flowed NE from the uplifted peak-ring region (Sears & Ryan, 2003; Sears *et al.*, 2009). The Miocene Clark Fork River was diverted into the ring-grabens across NW Montana (Figure 3). The Miocene Missouri River exited the ellipse to the NE via radial fractures that broke across the Lewis and Clark line.

The eastern Snake River Plain separates the NE and SE sectors of the elliptical basin. Armstrong *et al.* (1975), Pierce & Morgan (1992), Smith & Braille (1993), Perkins & Nash (2002), and others show that the ages of silicic volcanic fields young systematically toward the NE along the eastern Snake River Plain, from 16.5 Ma in the SW to the active Yellowstone volcano in the NE. The age progression approximates the direction of movement of the North American plate over a fixed mantle reference, and the plain is usually interpreted as the track of the Yellowstone hot spot (Anders *et al.*, 1989; Beranek *et al.*, 2006; Hackett & Morgan, 1988).

Hamilton (2007) and others, however, interpret the plain as a propagating fracture with Yellowstone at its tip. The older parts of the track were extended with the Basin and Range province. Therefore, the length of the eastern Snake River Plain, restored for extension, may be significantly shorter than the correlative displacement of North American plate. If so, the YHS would not be fixed in the mantle reference frame.

SE sector

The Wasatch and Wyoming Ranges, on the eastern edge of the Great Basin, define the rim of the ellipse in eastern Utah, SE Idaho, and SW Wyoming. Much of the edge in this sector follows the Wasatch line, a Neoproterozoic rift (Link, 1993). Zoback (1983) summarizes the structure of this region of the Great Basin. An exhumed Paleogene erosional surface was faulted down into a dozen north-trending, east-tilted blocks in the ring graben. The faults have 3-5 km of throw and were active during deposition of the Middle and Late Miocene Salt Lake Formation, a thick lacustrine deposit (Piety *et al.*, 1992). Four kilometers of late Cenozoic sediments accumulated in the ring-graben zone (Zoback, 1983).

Radial features include the Sweetwater Pass-Granite Mountains grabens of central Wyoming (Love, 1970), Browns Park graben of western Colorado and NE Utah (Hansen, 1965), a gibsonite dike swarm (Verbeek & Grout, 1993), and the Paradox and other grabens.

The Wasatch rim slopes gently eastward to the Green River and middle course of the Colorado River. These rivers flow in an arc that is concentric to the ellipse rim. Uplift of the elliptical rim may have reversed the regional westward slope off the Continental Divide and diverted runoff from the Colorado Plateau and western Wyoming into the resulting structural trough. Middle and Late Miocene faulting along the ellipse rim and Colorado River extensional corridor may have instigated headward erosion into the western Colorado Plateau to trigger incision of the Grand Canyon (Longwell, 1960; Fedo & Miller, 1992; Young, 2008; Karlstrom *et al.*, 2008).

SW sector

Oligocene and Lower Miocene volcanics as thick as 6 km (Stuckless & O'Leary, 2007) dip gently south in the ring-graben zone and abut fault zones that define the ellipse rim (Ekron *et al.*, 1968). Middle Miocene volcanics overlie these thick volcanics within the ellipse, but lap on to pre-Cenozoic bedrock to the SW, showing that the ring-graben faults were active in early Middle Miocene. A 500-km arc of Middle Miocene calderas closely follows the southern boundary of the ellipse, from SW Utah to western Nevada. Middle Miocene lake and river beds overlapped the caldera volcanics (Bonham & Garside, 1979). The 17 Ma northern Nevada rift (Zoback *et al.*, 1994) forms a major radial basaltic trend across this sector. The Middle Miocene rocks are broken by numerous younger Neogene extensional faults that widened the ellipse.

In eastern California, the Sierra Nevada elevates segments of the ellipse rim (*Wernicke & Snow, 1998*). Easterly-sourced Miocene volcanics bracket initiation of uplift of the northern Sierra Nevada to 20-17 Ma. The Miocene volcanics abruptly thin from 4 km within the ring-graben zone of the ellipse, near Reno, Nevada, to less than 400 m in the northern Sierra Nevada, indicating ~ 4 km of Middle Miocene structural relief (*Slemmons, 1966; Bonham, 1969*). The rim of the ellipse slopes gently down the SW flank of the Sierra Nevada on an exhumed Paleogene erosional surface – the mirror image of the Wasatch Range. The Sacramento and San Joaquin rivers follow the base of this slope, mimicking the Colorado and Green rivers. *Unruh (1991)* showed that much of the tilting occurred in the late Neogene. *Phillips (2008)* summarized the extensional history as beginning at ca. 16 Ma and migrating westward. The tectonically active Walker lane along the NE side of the Sierra Nevada has dextral slip (*Billingsley & Locke, 1939; Wernicke, 1992; Henry et al., 2007*) and lies on the opposite boundary of the ellipse from the LCL of Montana. Together they comprise a simple shear couple that widens the ellipse (Figure 2, inset).

NW sector

The High Cascade volcanic chain follows the rim of the ellipse from northern California to southern Washington. Greenschist-facies volcanic and plutonic rocks of the Oligocene-Early Miocene western Cascades magmatic arc form the uplifted rim of the ellipse (*Evarts & Swanson, 1994*). At 17 Ma, the magmatic arc abruptly extinguished and the arc rocks were faulted up by 3 km. Meanwhile, the CRBG flowed across the subsiding Columbia Plateau and overlapped the rim (*Evarts & Swanson, 1994*). The Columbia River hugged the NW edge of the elliptical depression during the 16.5-15.6 Ma Grande Ronde eruption, so that river gravels with sources in quartzite terranes of the eastern Cordillera were interlayered with basalts (*Smith, 1988*). The Pasco basin, a structure radial to the outbreak point of the YHS/CRBG, sank during eruption and filled with some 5 km of CRBG (*Hooper et al., 2007*).

The Columbia River Gorge crosses the Cascades along a rift (*Beeson et al., 1989*) that is radial to the CRBG outbreak point. The rift cross-cut the Paleogene rocks of the Cascades, and was flooded by Middle Miocene CRBG that flowed through the gorge to the Pacific Ocean.

CRBG occurs along a ~200 km length of the Oregon-Washington coast. Seismic reflection profiles across the Oregon shelf reveal CRBG reflectors dipping seaward for at least 15 km offshore (*McNeill et al., 2000*). An unknown volume of CRBG flowed onto the Juan de Fuca plate only to be subducted or accreted into the Cascadia trench wall. The oldest remaining sea floor on the plate is 10 Ma, whereas the bulk of the CRB erupted from 17-15 Ma (*Tolan et al., 1989*).

The peak-ring

An irregular peak-ring rises inward from the marginal ring-graben zone. Middle Miocene volcanics and lake beds lap downward from Paleogene volcanics to pre-Eocene bedrock on the peak-ring. A rough elliptical line marks the truncated inner edge of Paleogene volcanics beneath the middle Miocene unconformity (Figure 3). The peak-ring includes some of the higher topography of the interior of the elliptical depression, including numerous 3-km peaks. The peak-ring faces into the inner ring-graben and central volcanic region.

The inner ring-graben and central volcanic region

The inner ring-graben defines an ellipse with rectilinear margins (Figure 3). It encloses the central volcanic region (YHS/CRBG outbreak area). The segments of the inner ring-graben are about 50 km wide. Some collected as much as 3 km of Middle and Upper Miocene lake beds (*Swirydczuk et al., 1982*). The NW side faulted 16.6 Ma flows of the CRBG and filled with sediments and volcanics beginning at 15.5 Ma (*Cummings et al., 1994*). The 12 Ma Bruneau-Jarbridge volcanic center of the YHS track cross-cuts the ring-graben. The inner ring-graben thus formed after 16.6 Ma and before 12 Ma. It may represent a mega-caldera for the 16.5 Ma Idavada felsic volcanic field.

The central volcanic region marks the outbreak site of the YHS/CRBG. *Honjo et al. (1992)* document the enormous and vigorous nature of high temperature silicic eruptions from the central volcanic region during birth of the YHS.

Discussion

Several authors, beginning with *Billingsley & Locke (1939)* and *Locke et al. (1940)*, propose that dextral torsion between the Walker lane and Lewis and Clark line extended the Great Basin. *Atwater (1970)* shows from plate tectonic circuits that impingement of the Pacific plate against the North American plate initiated

dextral torsion at about 20 Ma. *Dickenson* (1997) proposes that torsion thinned the lithosphere in the region, and triggered CRBG eruption by destabilizing the sublithospheric mantle, which had been charged with melt-enhancing volatiles during its long history above the Pacific rim subduction zone. *Hyndman et al.* (2005) propose that thin, hot, wet lithosphere in this region is extremely weak and susceptible to variations in tectonic stresses, and that high elevations are supported by small convection cells in volatile-rich asthenosphere. Recent work by *Sine et al.* (2008) confirms small-scale convection along the SE edge of the ellipse.

I suggest that the ellipse specifically defines a lithospheric domain that stretched in the soft plate boundary zone between the Walker lane and Lewis and Clark line, beginning at 20 - 17 Ma, and continuing today. The major axis of the ellipse links the NW tip of the Lewis and Clark line with the SE tip of the Walker lane (Figure 1, inset). The ellipse may have initiated somewhat like a tension gash between the dextral faults. It then broadened and thinned as the margins collapsed on inward-dipping listric normal faults.

Absolute motion of the North American plate determined by olivine anisotropy in the sublithospheric mantle (*Marone & Romanowicz*, 2007) parallels the widening minor axis of the ellipse (Figure 4). The margins of the ellipse remain seismically active (Figure 4).

Interpretation & summary

I suggest the following interrelated events and features:

1. Upon impingement of the Pacific and North American plates, dextral torsion between the LCL and Walker lane attenuated the Cordilleran lithosphere in the region of the ellipse beginning at 20 Ma.
2. As the lithosphere thinned, decompression of underlying hot, volatile-rich asthenosphere generated basaltic magma within the elliptical region.
3. The basaltic magma expanded the asthenosphere, forming a broad elliptical dome in overlying, thinning lithosphere.
4. Radial grabens plunged down the lithospheric dome and captured runoff from the center of the ellipse during the 20-17 Ma erosional episode. *Rainbird & Ernst* (2001) document similar radial erosion patterns for other hot spot-large igneous province outbreaks. Runoff escaped via ring-grabens where radial fractures cut across the rim. Two main escape points channeled the Missouri and Columbia rivers.
5. Once sufficient basalt had melted to achieve melt phase connectivity, it migrated upward toward the center of the elliptical dome.
6. Migration of magma toward the center of the dome further uplifted the peak-ring, while sapping of magma from the marginal ring-grabens produced a pattern resembling a mega-caldera.
7. As it accumulated in the center of the ellipse, CRBG magma melted the overlying crust, leading to voluminous, superheated silicic eruptions that heralded the birth of the YHS.
8. The CRBG erupted from radial fissures and filled the especially low NW quartile of the elliptical basin, west of the old craton edge (dotted line in Figure 3). Eruption of CRBG magma caused the inner ring-graben to collapse as the center of the ellipse drained.
9. The CRBG overlapped the rim of the ellipse, showing that the ellipse had gained its essential form before CRBG eruption. The Columbia Plateau has a smoother physiography than Great Basin, perhaps because the CRBG buried earlier structures associated with initial extension of the ellipse.
10. An unknown volume of basalt escaped the ellipse through the radial graben along the Columbia River Gorge and flowed onto the Juan de Fuca plate. It was later subducted or accreted into the subduction wedge. Previous volume estimates of the CRBG are therefore minimums.
11. Eruptions coincided with an unusually wet climatic period in the region, and immense, deep lakes and large rivers established new drainage patterns across the tectonically disturbed land.
12. Ongoing extension broadens the ellipse in the direction of North American plate drift and Late Cenozoic faults break the volcanic and sedimentary rocks that record initiation of the YHS/CRBG.
13. The YHS hot spot track may follow an older radial fracture of the ellipse that parallels North American plate motion, exploited by lingering ascent of magma from the asthenospheric site of the original outbreak (e.g., *Christiansen et al.*, 2002).

The geometric and temporal linkages between the YHS/CRBG outbreak and the inception of the great elliptical basin imply that, rather than impingement of a random deep-mantle plume, lithospheric thinning induced by dextral torsion between the Pacific and North American plates triggered the outbreak of YHS/CRBG volcanism.

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References

- Anders, M. H., Geissman, J. Wm., 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, *J. Geophys. Res.*, **94**, 1589-1621.
- Armstrong, R.L., Leeman, W., and Malde, H.E., 1975, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho, *Am. J. Sci.*, **275**, 225-251.
- Anderson, D.L., 1994, The sublithospheric mantle as the source of continental flood basalts; the case against the continental lithosphere and plume head reservoirs, *Earth Planet. Sci. Lett.*, **123**, 269-280.
- Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, *Geol. Soc. Am. Bull.*, **81**, 3513-3563.
- Beeson, M.H., Tolan, T.L., and Anderson, J.L., 1989, The Columbia River Basalt Group in western Oregon; geologic structures and other factors that controlled flow emplacement patterns, in Reidel, S., and Hooper, R., eds., *Volcanism and tectonism in the Columbia River Flood-Basalt Province*, *Geol. Soc. Am. Spec. Pap.*, **239**, 233-246.
- Beranek, L. C. Link, K. and Fanning, C. M., 2006, Miocene to Holocene landscape evolution of the western Snake River Plain region, Idaho: Using the SHRIMP detrital zircon provenance record to track eastward migration of the Yellowstone hot spot, *Geol. Soc. Am. Bull.*, **118**, 1027-1050, DOI: 10.1130/B25896.1
- Billingsley, and Locke, A., 1939, Structure of ore districts in the continental framework, *Am. Inst. Min. Met. Eng.*, New York, 51 pp.
- Bohannon, R.G., 1983, Mesozoic and Cenozoic tectonic development of the Muddy, North Muddy, and northern Black Mountains, Clark County Nevada, in Miller, D.M., and Howard, K.A., eds., *Tectonic and stratigraphic studies in the eastern Great Basin*, *Geol. Soc. Am. Mem.*, **157**, 125-148.
- Bonham, H.F., 1969, Geology and mineral deposits of Washoe and Storey Counties, Nevada, *Nevada Bureau of Mines, Bull.*, **70**, 140 pp.
- Bonham, H.F., and Garside, L.J., 1979, Geology of the Tonopah, Lone Mountain, Klondike, and Northern Mud Lake Quadrangles, Nevada, *Nevada Bureau of Mines, Bull.*, **92**, 142 pp.
- Burchfiel, B.C., Cowan, D.S., and Davis, G.A., 1992, Tectonic overview of the Cordilleran orogen in the western United States, in Burchfiel, B.C., Lipman, W., and Zoback, M.L., eds., *The Cordilleran Orogen: Conterminous US: Boulder, Colorado*, *Geol. Soc. Am.*, G-3, 407-478.
- Christiansen, R.L., Foulger, G.R., and Evans, J.R., 2002, Upper mantle origin of the Yellowstone hot spot, *Geol. Soc. Am. Bull.*, **114**, 1245-1256.
- Christiansen, R. L., and McKee, E. H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia intermontane regions, *Geol. Soc. Am. Mem.* **152**, 388 pp.
- Cummings, M.L., Evans, J.G., and Ferns, M.L., 1994, Stratigraphic and structural evolution of the Middle Miocene Oregon-Idaho graben, Malheur County, Oregon, in Swanson, D.A., and Haugerud, R.S., eds., *Geologic field trips in the Pacific Northwest, 1*, Dept Geological Sciences, University of Washington, Seattle, Washington., 1G 1-20.
- Dickenson, W.R., 1997, Tectonic implications of Cenozoic volcanism in coastal California, *GA Bull.*, **109**, 936-954.
- Eaton, G., 1984, The Miocene Great Basin of western North America as an extended back-arc region, *Tectonophysics*, **1102**, 275-295.
- Ekren, E.B., Rogers, C.L., Anderson, R.E., and Orkild, 1968, Age of Basin and Range normal faults in Nevada Test Site and Nellis Air Force range, Nevada, in Ekren, E.B., ed., *Nevada Test Site*, *Geol. Soc. Am. Mem.*, **110**, 247-262.
- Ernst, R.E., and Buchan, K.L., 2001, Large mafic magmatic events through time and links to mantle plume-heads, in Ernst, R.E. and Buchan, K.L., eds., *Mantle Plumes: Their identification through time*, *Geol. Soc. Am. Spec. Pap.*, **352**, 483-575.
- Evarts, R.C., and Swanson, D.A., 1994, Geologic transect across the Tertiary Cascade Range, southern Washington, in Swanson, D.A., and Haugerud, R.S., eds., *Geologic field trips in the Pacific Northwest, 2*, Dept Geological Sciences, University of Washington, Seattle, Washington, 2H1-31.

- Fedo, C.M, and Miller, J.M.G., 1992, Evolution of a Miocene half-graben basin, Colorado River extensional corridor, southeastern California, *Geol. Soc. Am. Bull.*, **104**, 481-493.
- Fields, R. W., Rasmussen, D. L., Nichols, R., and Tabrum, A. R., 1985, Cenozoic rocks of the intermontane basins of western Montana and eastern Idaho, in, Flores, R. M. and Kaplan, S. S., eds., *Cenozoic paleogeography of the west-central United States*, Rocky Mountain Section of the Society of Economic Paleontologists and Mineralogists, 9-36.
- Foulger, G.R., and Jurdy, eds., 2007. *Plates, plumes, and planetary processes*, *Geol. Soc. Am. Spec. Pap.*, **430**, 997 pp.
- Foulger, G.R., J.H. Natland, D.C. Presnall and D.L. Anderson, Eds., 2005, *Plates, Plumes, and Paradigms*, *Geol. Soc. Am. Spec. Pap.*, **388**, 881 pp.
- Friedmann, S.J., Davis, G.A., and Fowler, T.K., 1996, Geometry, paleodrainage, and geologic rates from the Miocene Shadow Valley supradetachment basin, eastern Mojave Desert, California. In: Beratan, K. K, ed., *Reconstructing the History of Basin and Range Extension Using Sedimentology and Stratigraphy*, *Geol. Soc. Am. Spec. Pap.*, **303**, 85-106.
- Hackett, W. R., and Morgan, L. A., 1988, Explosive basaltic and rhyolitic volcanism of the eastern Snake River Plain, Idaho, in, Link, K., and Hackett, W. R., eds., *Guidebook to the geology of central Idaho*, Idaho Geol. Surv. Bull., **27**, 283-301.
- Hales, T.C., Abt, D.L., Humphreys, E.D., and Roering, J.J., 2005, Delamination origin for the Columbia River flood basalts and Wallowa uplift in NE Oregon, USA, *Nature*, **110**, 1038.
- Hamilton, W.B., 2007, Driving mechanism and 3-D circulation of plate tectonics, in, Sears, J.W., Harms, T.A., and Evenchick, C.A., eds., *Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price*, *Geol. Soc. Am. Spec. Pap.*, **433**, 1-26.
- Hansen, W.R., 1965, *Geology of the Flaming Gorge area, Utah-Colorado-Wyoming*, U.S. Geol. Surv. Prof. Pap. **490**, 196 pp.
- Harrison, J.E., Griggs, A.B., and Wells, J.D., 1974, *Tectonic features of the Precambrian Belt basin and their influence on post-Belt structures*, U.S. Geol. Surv. Prof. Pap. **866**, 15 pp.
- Hart, W.K., and Carlson, R.W., 1987, Tectonic controls on magma genesis and evolution in the northwestern United States, *J. Volc. Geotherm. Res.*, **32**, 119-135.
- Henry, C.D., Faulds, J.E., and dePolo, C.M., 2007, Geometry and timing of strike-slip and normal faults in the northern Walker lane, northwestern Nevada and northeastern California: Strain partitioning or sequential extension and strike-slip deformation? in, Till, A.B., Roeske, S.M., Sample, J.C., and Foster, D.A., eds., *Exhumation associated with continental strike-slip systems*: *Geol. Soc. Am. Spec. Pap.*, **434**, 59-79.
- Honjo, N., Bonnichsen, B., Leeman, W., and Stormer, J.C., Jr., 1992, Mineralogy and geothermometry of high-temperature rhyolites from the central and western Snake River Plain, *Bull. Volc.*, **54**, 220-237.
- Hooper, R., Camp, V.E., Reidel, S., and Ross, M.E., 2007, The origin of the Columbia River flood basalt province: Plume versus nonplume models, in, Foulger, G.R., and Jurdy, D.M., eds., *Plates, Plumes, and Planetary Processes*, *Geol. Soc. Am. Spec. Pap.*, **430**, 997 pp.
- Humphreys, E.D., Dueker, D.L., Schutt, D.L., and Smith, R.B., 2000, Beneath Yellowstone: Evaluating plume and non-plume models using teleseismic images of the upper mantle, *GSA Today*, **10**, 1-6.
- Hyndman, R D; Currie, C A; Mazzotti, S , 2005, Subduction zone backarcs, mobile belts, and orogenic heat, *GSA Today*, **15**, 4-10.
- Karlstrom, K.E., Crow, R., Crossey, L.J., Coblenz, D., and Van Wijk, J.W., 2008, Model for tectonically driven incision of the younger than 6 Ma Grand Canyon: *Geology*, **36**, 835-838.
- Link, K., ed., 1993, Middle and Late Proterozoic stratified rocks of western US Cordillera, Colorado Plateau, Basin and Range province, in, Reed, J. C., et al., eds. *Precambrian: Continental U.S., Boulder, Colorado*, *Geol. Soc. Am.*, *Geology of North America*, C-2, 463-595.
- Locke, A., Billingsley, R., and Mayo, E.B., 1940, Sierra Nevada tectonic patterns, *GSA Bull.*, **51**, 513-539.
- Longwell, C.R., 1960, Possible explanation of diverse structural pattern in southern Nevada, *Am. J. Sci.*, Bradley Volume, **58-A**, 192-203.
- Love, J.D., 1970, Cenozoic geology of the Granite Mountains area, Central Wyoming: *U.S. Geol. Surv. Prof. Pap.*, 495-C, 154 pp.
- Marone, F., and Romanowicz, B., 2007, The depth distribution of aximuthal anisotropy in the continental upper mantle, *Nature*, **447**, 198-201.
- McLeod, J., 1987, *The depositional history of the Deer Lodge basin, western Montana*, M.S. thesis, University of Montana, Missoula, 61 pp.
- McNeill, L.C., Goldfinger, C., Kulm, L.D., and Yeats, R.S., 2000, Tectonics of the Neogene Cascadia

- paleoarc basin: Investigations of a deformed late Miocene unconformity:
- Geol. Soc. Am. Bull.*
- ,
- 112**
- , 1209-1224.
- Morgan, W.J., 1972, plate motions and deep mantle convection, *Geol. Soc. Am. Mem.*, **132**, 7-22.
 - Pardee, J.T., 1950, Late Cenozoic block faulting in western Montana, *Geol. Soc. Am. Bull.*, **61**, 359-406.
 - Perkins, M.E., and Nash, B.P., 2002, Explosive silicic volcanism of the Yellowstone hot spot: The ash fall record, *Geol. Soc. Am. Bull.*, **114**, 367-381.
 - Phillips, F.M., 2008, Geological and hydrological history of the paleo-Owens River drainage since the late Miocene, in Reheis, M.C., Hershler, R., and Miller, D.M., Late Cenozoic drainage history of the southwestern Great basin and lower Colorado River region: Geologic and biologic perspectives: *Geol. Soc. Am. Spec. Pap.* **439**, 115-150.
 - Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone Hot spot: Volcanism, faulting, and uplift, in Link, K., Kuntz, M.A., and Platt, L.B., eds., *Regional geology of eastern Idaho and western Wyoming*, *Geol. Soc. Am. Mem.*, **179**, 1-54.
 - Piety, L.A., Sullivan, J.T., and Anders, M.H., 1992, Segmentation and paleoseismicity of the Grand Valley Fault, southeastern Idaho and western Wyoming, in Link, K., Kuntz, M.A., and Platt, L.B., eds., *Regional geology of eastern Idaho and western Wyoming*, *Geol. Soc. Am. Mem.*, **179**, 155-182.
 - Rainbird, R.H., and Ernst, R.E., 2001, [The sedimentary record of mantle-plume uplift](#), *Geol. Soc. Am. Spec. Pap.*, **352**, 227-245.
 - Reed, J. C., Jr., Wheeler, J.O., and Tucholke, B.E., 2005, *Geologic Map of North America*, *Geol. Soc. Am.*, DNAG Continent-Scale Map 001, scale: 1:5,000,000.
 - Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot-spot tracks: plume heads and tails, *Science*, **246**, 103-107.
 - Sears, J.W., 2007a, Belt-Purcell basin: Keystone of the Rocky Mountain fold-and-thrust belt, United States and Canada, in Sears, J.W., Harms, T.A., and Evenchick, C.A., eds., *Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price*, *Geol. Soc. Am. Spec. Pap.*, **433**, 147-166.
 - Sears, J.W., 2007b, Middle Miocene karst and debris flows and neotectonic faults near Clark Canyon Reservoir, Southwest Montana, *Northwest Geology*, **36**, 251-260.
 - Sears, J.W., 1995, Middle Miocene rift system in SW Montana: Implications for the initial outbreak of the Yellowstone hot spot, *Northwest Geology*, **25**, 43-46.
 - Sears, J.W., and Thomas, R.C., 2007, Extraordinary Middle Miocene crustal disturbance in southwestern Montana: Birth of the Yellowstone hot spot?, *Northwest Geology*, **36**, 133-142.
 - Sears, J.W., and Fritz, W.J., 1998, Cenozoic tilt-domains in southwest Montana: Interference among three generations of extensional fault systems, in Faulds, J.E., and Stewart, J.H., eds., *Accommodation zones and transfer zones: The regional segmentation of the Basin and Range province*, *Geol. Soc. Am. Spec. Pap.*, **323**, 241-248.
 - Sears, J.W., and Hendrix, M., 2004, Lewis and Clark line and the rotational origin of the Alberta and Helena salients, North American Cordillera, in Sussman, A., and Weil, A., eds., *Orogenic curvature*, *Geol. Soc. Am. Spec. Pap.*, **383**, 173-186.
 - Sears, J.W., and Ryan, 2003, Cenozoic evolution of the Montana Cordillera: Evidence from paleovalleys, in Reynolds, R., and Flores, J., eds., *Cenozoic Paleogeography of western US, Denver, CO, Rocky Mountain Section, Soc. Expl. Paleont. Min.*, 289-301.
 - Sears, J.W., Hendrix, M.S., Thomas, R.C., and Fritz, W.J., 2009, Stratigraphic record of the Yellowstone hot spot track, Neogene Sixmile Creek Formation, SW Montana, *J. Volc. Geotherm. Res.*, in press.
 - Sine, C.R., Wilson, D., Gao, W., Grand, S.P., Aster, R., Ni, J., and Baldrige, W.S., 2008, Mantle structure beneath the western edge of the Colorado Plateau: Geophysical Research Letters, **35**, L10303, doi:10.1029/2008GL033391.
 - Slemmons, D.B., 1966, Cenozoic volcanism of the central Sierra Nevada, California, in Bailey, E.H., ed., *Geology of Northern California, Calif. Div. Mines and Geol., Bull.*, **190**, 199-208.
 - Smiley, C.J., 1989, The Miocene Clarkia fossil area of northern Idaho, in Chamberlain, V.E., Breckenridge, R.M., and Bonnicksen, B., eds., *Guidebook to the geology of northern and western Idaho and surrounding area: Idaho Geological Survey, Bull.*, **28**, 35-48.
 - Smith, A.D., 1992, Back-arc convection model for Columbia River basalt genesis, *Tectonophysics*, **207**, 269-285.
 - Smith, G.A., 1988, Neogene syn-volcanic and syn-tectonic sedimentation in Washington, *Geol. Soc. Am. Bull.*, **100**, 1479-1492.
 - Smith, G.A., Bjornstad, B.N., and Fetch, K.R., 1989, Neogene terrestrial sedimentation on and adjacent to the Columbia Plateau; Washington, Oregon, and Idaho, in Reidel, S.P and Hooper, R.,

- eds. *Volcanism and tectonism in the Columbia River flood-basalt province*, *Geol. Soc. Am. Spec. Pap.*, **239**, 187-198.
- Smith, R.B., and Arabasz, W.J., 1991, Seismicity of the Intermountain seismic belt, in Slemmons, D.B., Engdahl, E.R., Zoback, M.D., and Blackwell, D.D., eds., *Neotectonics of North America*, Boulder, Colo., Geol. Soc. Am., Decade Map Volume to Accompany the Neotectonic Maps, Part of the Continent-Scale Maps of North America, 185-228.
 - Smith, R.B., and Braile, L.W., 1993, Topographic signature, space-time evolution, and physical properties of the Yellowstone-Snake River Plain volcanic system: the Yellowstone hot spot, in Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., *Geology of Wyoming*, Volume 5, Laramie, WY, Geol. Surv. Wyoming Mem., 694-754.
 - Stewart, J.H., 1998, Regional characteristics, tilt domains, and extensional history of the late Cenozoic Basin and Range province, western North America, in Faulds J.E., and Stewart, J.H., eds., *Accommodation zones and transfer zones: the regional segmentation of the Basin and Range Province*, *Geol. Soc. Am. Spec. Pap.*, **323**, 47-74.
 - Stuckless, J.S., and O'Leary, D.W., 2007, Geology of the Yucca Mountain region, in *Geology and climatology of Yucca Mountain and vicinity, southern Nevada and California*, *Geol. Soc. Am. Mem.*, **199**, 9-52.
 - Swirydczuk, K., Larson, G.P., and Smith, G.R., 1982, Volcanic ash beds as stratigraphic markers in the Glens Ferry and Chalk Hills formations from Adrian, Oregon, to Bruneau, Idaho, in Bonnicksen, B., and Breckenridge, R.M., eds., *Cenozoic Geology of Idaho*, Idaho Bureau of Mines and Geology, Bull., **26**, p 543-558.
 - Thatcher, W., and Pollitz, F.F., 2008, Temporal evolution of continental lithospheric strength in actively deforming areas, *GSA Today*, **18**, 4-11.
 - Thompson, G. R., Fields, R. W., and Alt, D., 1982, Land-based evidence for Tertiary climatic variations: Northern Rockies, *Geology*, **10**, 413-417.
 - Tolan, T.L., Reidel, S., Beeson, M.B., Anderson, J.L., Fecht, K.R., and Swanson, D.A., 1989, Revisions to estimates of the areal extent and volume of the Columbia River Basalt Group, *Geol. Soc. Am. Spec. Pap.*, **239**, 1-20.
 - Unruh, J.R., 1991, The uplift of the Sierra Nevada and implications for late Cenozoic epeirogeny in the western Cordillera: *Geol. Soc. Am. Bull.*, **103**, 1395-1404.
 - USGS, 2008, [Earthquake hazards program. Intermountain west region.](#)
 - Verbeek, E.R., and Grout, M.A., 1993, Geometry and structural evolution of gilsonite dikes in the eastern Uinta Basin, Utah, *U.S. Geol. Surv. Bull.*, 1787-HH, 42 pp.
 - Wallace, C.A., Lidke, D.J., and Schmidt, R.G., 1990, Faults of the Lewis and Clark line and fragmentation of the Late Cretaceous foreland basin in west-central Montana, *Geol. Soc. Am. Bull.*, **102**, 1021-1037.
 - Wernicke, Brian, 1992, Cenozoic extensional tectonics of the U.S. Cordillera, in Burchfiel, B.C., Lipman, W., and Zoback, M.L., eds., *The Cordilleran Orogen: Conterminous U.S.*, Boulder, Colo., *Geol. Soc. Am.*, The Geology of North America, G-3, 553-581.
 - Wernicke, B., and Snow, J.K., 1998, [Cenozoic tectonism in the central Basin and Range: motion of the Sierran-Great Valley Block](#), *Int. Geol. Rev.*, **40**, 403-410.
 - Yuan, H., and K. Dueker, 2005, Teleseismic P-wave tomogram of the Yellowstone plume, *Geophys. Res. Lett.*, **32**, L07304, doi:10.1029/2004GL022056.
 - Young, R.A., 2008, Pre-Colorado River drainage in western Grand Canyon: Potential influence on Miocene stratigraphy in Grand Wash trough, in Reheis, M.C., Hershler, R., and Miller, D.M., *Late Cenozoic drainage history of the southwestern Great basin and lower Colorado River region: Geologic and biologic perspectives*: *Geol. Soc. Am. Spec. Pap.*, **439**, 319-333.
 - Zoback, M.L., 1983, Structure and Cenozoic tectonism along the Wasatch fault zone, Utah, in Miller, D.M., and Howard, K.A., eds., *Tectonic and stratigraphic studies in the eastern Great Basin*, *Geol. Soc. Am. Mem.*, **157**, 3-28.
 - 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, *Geol. Soc. Am. Bull.*, **106**, 371-382.

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