Large-scale fractures related to inception of the Yellowstone hotspot

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ABSTRACT

During middle Miocene time, western North America was subject to flood-basalt volcanism, dike-swarm injection, and broad-scale fracturing and folding of the crust. We propose a simple model to account for these events and for a regional pattern of geologic and geophysical features. Aeromagnetic maps reveal some of the most important elements of this pattern, which are several narrow, arcuate anomalies, here referred to as the Northern Nevada rifts. These rifts extend hundreds of kilometers across Nevada and are likely caused by highly magnetic, middle Miocene mafic dikes. With the aid of filtering techniques, the anomalies can be traced into Oregon. Together with other geologic features, such as fold axes, dike swarms, and faults, they produce a spoke-like pattern fanning over 220° of arc that converges toward a point near the Oregon-Idaho border (lat ~44°N). A possible cause for this pattern is a point source of stress at the base of the crust related to the formation of the Yellowstone hotspot. The spoke-like pattern, however, does not persist at large distances from the emerging hotspot; several hundred kilometers to the south, the Northern Nevada rifts deviate significantly (>30°) from a radial trend. We show that a simple model—imposing a point source of stress at the base of the crust and a regional stress field aligned with the presumed middle Miocene stress direction—fits the observed fracture pattern. It thus accounts for both the radial pattern present near the nascent hotspot and the far-field pattern due to regional stresses.

Keywords: Yellowstone hotspot, Northern Nevada rifts, Snake River Plain, dike swarm, flood basalts, Columbia River Plateau.

INTRODUCTION

Among the most striking geophysical features of western North America (Figs. 1 and 2) are long and narrow positive magnetic anomalies (collectively referred to here as the Northern Nevada rifts) trending north-northwest across northern Nevada. Although best defined by their magnetic signatures, these features are also partly expressed in gravity anomalies and play an important role in controlling the location of epithermal gold deposits (Ponce and Glen, 2002). The most conspicuous, the eastern rift, is caused by strongly magnetic mafic dikes and lavas that were emplaced in the middle Miocene roughly synchronous with the onset of Steens Mountain and Columbia River flood-basalt eruptions.

Several other subparallel, slightly arcuate magnetic anomalies (e.g., the central and western Northern Nevada rifts, Fig. 1) have similar geophysical expressions, though little is known of their origin. On or near these anomalies, we have sampled numerous north-northwest–trending mafic dikes that might represent the anomalies' source rocks. Although the dikes are not radioisotopically constrained in age, their paleomagnetic poles, when compared with the apparent polar wander path for North America, are consistent with the dikes having formed in the middle Miocene, contemporaneously with the eastern Northern Nevada rift (Glen and Ponce, 2000).

Some have speculated that emplacement of the eastern rift and the Columbia River flood basalts resulted from emergence of a mantle plume associated with the Yellowstone hotspot (e.g., Zoback et al., 1994; Hooper, 1997; Pierce et al., 2000). Others, however, have argued that a ''Yellowstone plume'' resided offshore tens of millions of years before the Columbia River flood-basalt eruptions, forming an oceanic volcanic plateau later obducted onto the continental margin (e.g., Duncan, 1982; Johnston et al., 1996; Oppliger et al., 1997; Murphy et al., 1998).

Still others question a plume origin for the hotspot because of the apparent lack of a plume tail, a curved hotspot track, and other features like a westward-migrating magmatic trend mirroring the Yellowstone track (Matthews and Anderson, 1973; Christiansen and McKee, 1978; Alt et al., 1988; Hamilton, 1989; Beucher et al., 1999; Humphreys et al., 2000).

Regardless of whether the hotspot originated in the deep mantle or was caused by a shallow-melting phenomenon, it is unclear where the hotspot first appeared and how fracturing of the crust (e.g., associated with the Northern Nevada rifts) and flood-basalt eruptions relate to hotspot stresses. Some have suggested that the eastern Northern Nevada rift originated near the McDermitt caldera along the Nevada-Oregon border (Fig. 1; Zoback, 1978; Camp, 1995; Ernst and Buchan, 1997; Pierce et al., 2000). Others (Zoback et al., 1994; Cummings et al., 1996; Pierce et al., 2000) have further proposed that the eastern Northern Nevada rift and the Chief Joseph dike swarm in eastern Washington and Oregon formed along a single linear rift in response to the hotspot's emergence near McDermitt. However, this seems unlikely, because the trace of the eastern rift is clearly east of the caldera. In addition, the Northern Nevada rifts appear to extend well north of McDermitt (discussed subsequently), suggesting that the source of stress is also north of McDermitt.

Zoback (1978) further suggested that the eastern Northern Nevada rift, although forming in response to hotspot stresses, reflected, in its trend, the middle Miocene regional stress direction for western North America. This interpretation is somewhat complicated because (1) the trace of the rift coincides with a deep-crustal discontinuity that may predate, and may have influenced, emplacement of the eastern rift rocks (Glen and Ponce, 2000; Ponce and Glen, 2000; John et al., 2000), and (2) the anomaly curves significantly eastward as it projects into Oregon.

Although the deep-crustal discontinuity could indicate an ancient structure reactivated in middle Tertiary time, we demonstrate that a simple model combining hotspot and regional stress fields can alone account for both the curved fracture pattern and the general alignment of the eastern Northern Nevada rift with the presumed middle Miocene stress direction in central Nevada.

PROPAGATING FRACTURE

Paleomagnetic studies applied to both intrusive and extrusive igneous rocks associated with the Northern Nevada rifts may help resolve their origin and the timing of magmatism. The key to understanding how comes from a stack of mafic lavas erupted ca. 15.5 Ma over the eastern Northern Nevada rift in the southeastern Sheep Creek Range (Fig. 1). The flows, which were probably fed by dikes related to the eastern rift (John et al., 2000), record a reverse-to-normal polarity transition (Bogue et al., 2000).

It is not surprising, therefore, that the dikes

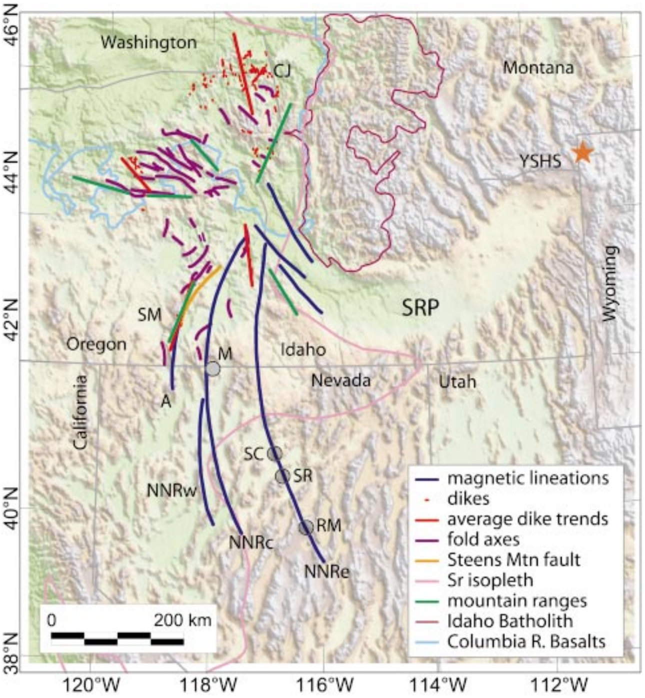

Figure 1. Topographic index map of western United States showing physiographic, geologic, and geophysical features discussed in text. SRP—Snake River Plain, M—McDermitt Caldera, SC—Sheep Creek Range, SR—Shoshone Range, RM—Roberts Mountains, CJ—Chief Joseph dikes, SM—Steens Mountain dikes, YSHS—Yellowstone hotspot, A—magnetic lineation, NNRw, NNRc, NNRe—western, central, and eastern Northern Nevada rifts, respectively.

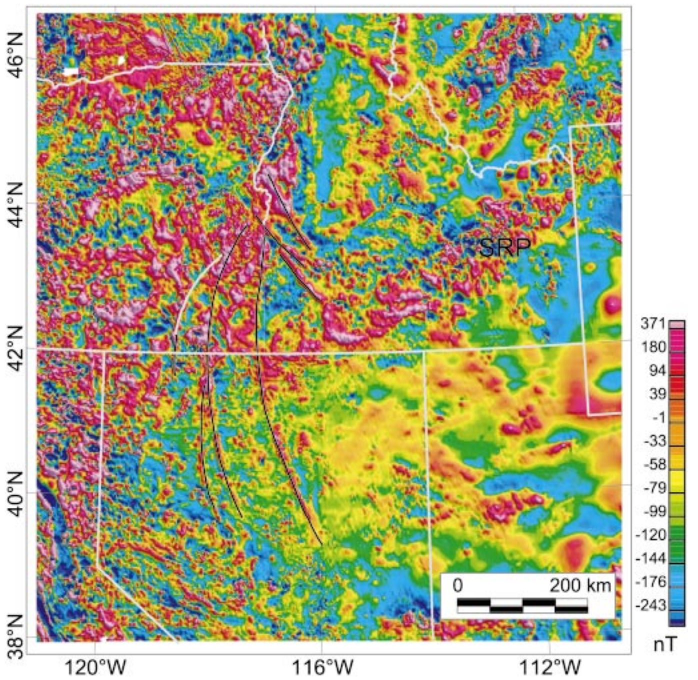

Figure 2. Aeromagnetic map of northern Great Basin with magnetic lineations (black lines) discussed in text. SRP—Snake River Plain.

along the eastern rift also record both normal and reverse directions (Zoback, 1978; Li et al., 1990; Glen and Ponce, 2000). What is apparently unexpected, however, is the arrangement of intrusive rock magnetizations: dikes along the anomaly in northern Nevada (i.e., south of the Sheep Creek Range, Fig. 1) generally have magnetizations of reverse polarity, whereas those farther south have normal polarity. At central locations, dikes yield normal, reverse, and transitional polarities. Although not conclusive, this pattern suggests that the polarity reversal present in the Sheep Creek Range lavas was also recorded laterally along the length of the eastern Northern Nevada rift (Zoback et al., 1994). If so, the sense of the reversal in the Sheep Creek lavas (reverse to normal) implies (1) that magmatism propagated from north to south along a time-transgressive rift and (2) that the source of stress leading to fracturing related to the Northern Nevada rifts must have originated north of the Nevada-Oregon border. Although a compilation (John et al., 2000) of $^{40}Ar/^{39}Ar$ ages for lavas along the eastern rift does not show a north to south progression, the few existing ages on dikes do (D.A. John, 2001, personal commun.): older ages are found to the north in the northern Shoshone Range, and younger ages are found to the south in the Roberts Mountains.

RADIATING FRACTURES

The eastern Northern Nevada rift is more than 500 km long, extending from the Nevada-Oregon border into southern Nevada (Blakely and Jachens, 1991; Zoback et al., 1994). Its northern extent, however, is difficult to define owing to widespread, strongly magnetic volcanic rocks, the anomalies of which mask the subtle expressions of the deeper intrusive rocks of the Northern Nevada rifts. Although the rifts' source rocks may extend into Oregon, it is difficult to distinguish their magnetic expression in unfiltered magnetic data.

We applied a match-filtering technique (Syberg, 1972) to enhance the expression of the Northern Nevada rifts' anomalies in Oregon. The method, which models the spectrum of the observed anomalies originating from horizontal layers of varying depth, was used to separate short-wavelength magnetic anomalies (like those arising from the near-surface volcanic rocks) from longer wavelength anomalies generally due to deeper bodies (such as the rift-related dikes). Maps of the longer wavelength anomalies (Fig. 3) can be interpreted to show that the rifts' anomalies curve to the east as they project northward into Oregon. The rifts converge on a point midway along the Oregon-Idaho border, suggesting that they have a common origin. Our interpretation that the rifts verge eastward is strengthened by the observation that one of the lineations (feature A, Fig. 1) merges with the Steens Mountain frontal fault, which clearly bends to the east. The correspondence is likely not a coincidence because a prominent dike swarm, having the same trend as the frontal fault, occurs within Steens Mountain adjacent to the fault and in line with the magnetic lineation (Fig. 1).

A number of other linear or arcuate geologic features throughout western North America may relate to the same causative stress field that produced the structures imaged by the magnetic data. In eastern Washington and Oregon there are several dike swarms, such as the Chief Joseph dikes (feeders for the Columbia River flood-basalt lavas, Fig. 1), Steens Mountain dikes (Fig. 1), and possibly the Cascade dikes (not shown here; Ernst and Buchan, 1997). The ages of these dikes all appear to be contemporaneous, having formed ca. 16 Ma.

Between the Chief Joseph dike swarm and Northern Nevada rifts is a series of folds that fan out across eastern Oregon. Although the folds clearly postdate the flood basalts, several apparently formed along structures that were active prior to and during the early stages of flood-basalt volcanism (Robyn and Hoover, 1982; Walker and Robinson, 1990). It is per-

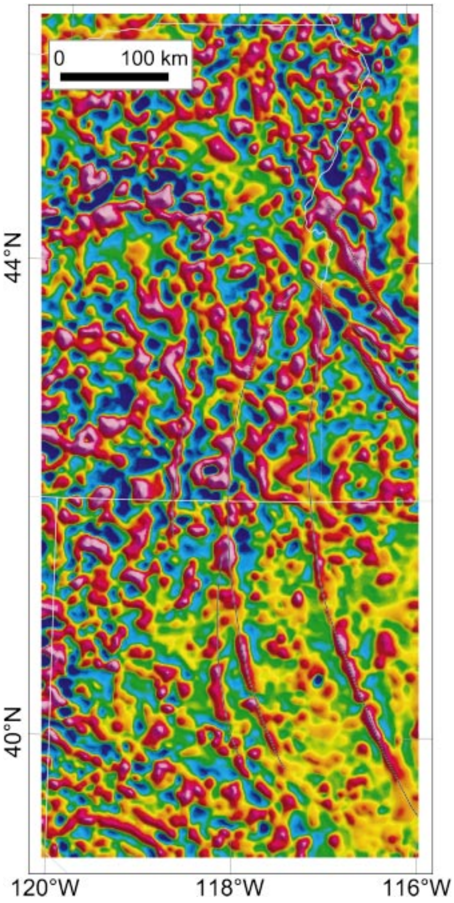

Figure 3. Match-filtered aeromagnetic map highlighting expression of anomalies arising from mid-crustal sources. Magnetic lineations shown in black.

missible, therefore, that the structures originated from stresses induced by the hotspot.

Numerous mountain chains and canyons (including, clockwise from the southeast, Owyhee, Steens, Ochoco, and Strawberry Mountains, Elkhorn Ridge, Hells Canyon, and Seven Devils Mountains) and several major fault traces (including the Steens frontal fault and graben-bounding faults in the western Snake River Plain) combine with the dike swarms, fold axes, and magnetic lineations to form a radiating pattern extending over 220° in arc. This fan of lineations converges on a common point at the northwestern end of the western Snake River Plain (Figs. 1 and 4). The lack of fractures to the northeast corresponds to the location of the Idaho batholith that may have been less susceptible to fracturing. Alternatively, their absence may be an artifact of the difficulties in mapping fractures in such relatively homogeneous batholithic rocks.

Although the lineations appear to radiate from a central point, far from that point, their trends deviate significantly from a radial pattern (most notably south of the convergence point along the Northern Nevada rifts in Nevada). This departure from simple radial symmetry is addressed by considering the influ-

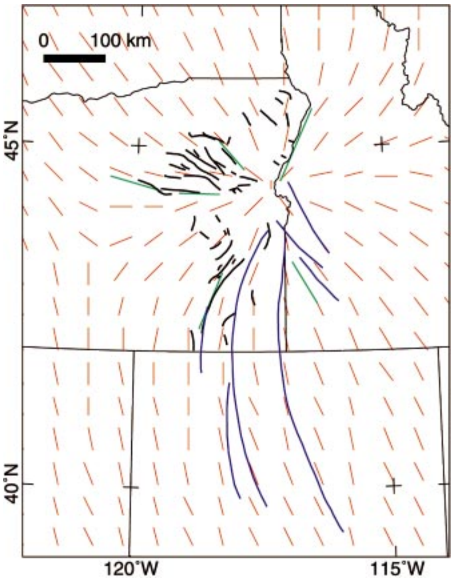

Figure 4. Stress-field model arising from superimposed point and regional stresses overlain on map of observed fracture-related features: blue—magnetic lineations, black—fold axes, short red—dike swarms, and green—mountain ranges. Model stress trajectories of normal to least principal stress are shown in red.

ence of superimposed local and regional stresses.

We modeled the pattern of geologic and geophysical lineations in western North America by using a Coulomb stress model (Toda et al., 1998) to simulate crustal stresses imposed by both hotspot and regional stresses. Figure 4 shows the modeled stress trajectories along the normal to the lesser principal stress calculated from a dilating sphere at the base of the crust and a regional extensional stress aligned with the presumed middle Miocene stress direction. Superimposed on this pattern are the geologic and geophysical lineations.

The model suitably accounts for the curvilinear character of the Northern Nevada rifts: close to the hotspot, point stresses result in a radial fracture pattern, whereas far from the hotspot, regional stresses dominate. This suggests that in central Nevada (nearly 500 km away) the trend of the eastern rift likely approximated the regional stress direction during middle Miocene time.

DISCUSSION

The observed fracture pattern bears on the role that hotspots play in the rifting of continents. The fact that flood basalts are commonly associated with continental rifting has led many to conclude (e.g., Burke and Dewey, 1972; Morgan, 1981; Richards et al., 1989) that plumes arriving at the base of the lithosphere can stress the overlying lithospheric plate sufficiently to actively cause it to rift.

In contrast, others hold that a passive hotspot model is more appropriate to some flood volcanic provinces. Here, rifting facilitates decompression melting to feed flood volcanism (White and McKenzie, 1989; Duncan and Richards, 1991; Hill et al., 1992; Glen et al., 1994). In the case of the Columbia River flood basalts, however, significant extension followed the eruptions. Furthermore, backarc extension seems insufficient to have caused the massive and localized eruptions that are unlike volcanism associated, for example, with Basin and Range extension (Hooper, 1990). Although extension and decompression melting may have played some role in the Columbia River flood-basalt eruptions, the proposed pattern of hotspot-induced fractures appears to support a relatively active hotspot that is sufficient to drive local rifting and trigger eruption of flood-basalt volcanism at its point of inception.

Despite an energetic birth, one might expect the track of the hotspot to be dictated largely by plate motions. From its presumed point of origin to its present location at Yellowstone, however, the hotspot must have deviated significantly from a path predicted simply by plate-motion models (e.g., Engebretson et al., 1984). Geist and Richards (1993) proposed that a curved path was caused by a mantle plume that recovered from having been deflected to the north by the subducting Farallon plate, which presumably has since been removed. As the plume adjusted to a more vertical ascent, it swung from its deflected position under southeastern Washington to the south and then northeast to a steady-state path along the eastern Snake River Plain.

Alternatively, the path may have been controlled by crustal structures. For example, the edge of Precambrian basement (corresponding to the Sr isopleth, Fig. 1) may have acted as a barrier and guided the locus of melting. Camp (1995) noted that the inferred edge of the Precambrian cratonal margin resides just east of the Columbia River flood-basalt eruptive fissures (i.e., the Chief Joseph dike swarm, Fig. 1) and speculated that magma may have ponded against the ancient continental edge. Similarly, the Idaho batholith, a large Cretaceous igneous complex that marks the northern edge of the Snake River Plain, may have influenced the hotspot's path. The lack of hotspot-induced fractures across the Idaho batholith suggests that the batholith may form a uniform, deformation-resistant crustal block that guided the hotspot.

CONCLUSIONS

The Northern Nevada rifts are long arcuate magnetic features likely caused by mafic dikes emplaced in the middle Miocene coincident with flood-basalt eruptions on the Columbia River Plateau. Together with the trends of dike swarms, faults, topography, and fold axes, they produce a radial pattern converging on a point near the Oregon-Idaho border at lat 44°N. We suggest that the source of stress responsible for this radial pattern of structures was the inception of the Yellowstone hotspot ca. 17–16 Ma, coincident with eruption of the Columbia River flood basalt.

A simple three-dimensional stress model demonstrates that superposed point and regional stresses result in stress trajectories that form a radiating pattern near the hotspot, but verged toward the regional stress direction with distance from the point source of stress. This result suggests that the trend of the eastern Northern Nevada rift in central Nevada, far from the hotspot, likely approximates the normal to the mid-Miocene extension direction as first suggested by Zoback (1978).

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