Reappraisal of the relationship between the northern Nevada rift and Miocene extension in the northern Basin and Range Province

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ABSTRACT

The northern Nevada rift is a prominent mafic dike swarm and magnetic anomaly in north-central Nevada inferred to record the Middle Miocene (16.5–15.0 Ma) extension direction in the northern Basin and Range province in the western United States. From the 245°–250° rift direction, Basin and Range extension is inferred to have shifted 45° clockwise to a modern direction of 290°–300° during the late Miocene. The region surrounding the northern Nevada rift was actively extending while the rift formed, and these domains are all characterized by extension oriented 280°–300°. This direction is distinctly different from the rift direction and nearly identical to the modern Basin and Range direction. Although the rate, structural style, and distribution of Basin and Range extension appear to have undergone a significant change in the late Miocene (ca. 10 Ma), the overall spreading direction does not. Middle Miocene extension was directed perpendicular to the axis of the thickest crust formed during Mesozoic shortening and this orientation may reflect gravitational collapse of this thick crust. Orientation of northern Nevada rift dikes may reflect a short-lived regional stress field related to the onset of Yellowstone hotspot volcanism.

INTRODUCTION

The northern Nevada rift (NNR; western United States) is a linear, 250-km-long magnetic anomaly and zone of mafic dikes emplaced in north-central Nevada during the widespread ca. 16–17 Ma magmatic event that signaled the onset of Yellowstone hotspot volcanism (Fig. 1) (Zoback and Thompson, 1978). When the Yellowstone hotspot impinged on the crust in northwestern Nevada, numerous fractures propagated north and south (Fig. 1), rapidly erupting >200,000 km^3 of Steens and Columbia River basalts (Fig. 1) and lesser rhyolite (e.g., Camp and Hanan, 2008). Orientations of NNR and other Miocene dikes (Fig. 1) are thought to record a province-wide Middle Miocene Basin and Range extension direction of 245°–250° that persisted from 16–17 to ca. 10 Ma, when the stress field underwent a ~45° clockwise rotation to the modern direction of 290°–300° (Zoback et al., 1981, 1994). This shift is interpreted to record a change from early extension perpendicular to the Pacific–North American plate boundary, to more northwest-directed extension as right-lateral shear migrated from the plate boundary into the Basin and Range province.

If the least principal stress across western North America was oriented 245° from 17 to 10 Ma, extension within the nascent Basin and Range between the Sierra Nevada and the Colorado Plateau (Fig. 1) would have been in that direction. However, the most recent restoration of the northern Basin and Range found extension oriented ~282° from 36 Ma to the present, similar to the modern direction and ~40° different from the NNR direction (McQuarrie and Wernicke, 2005). Such a large-scale discrepancy between two robust-seeming data sets points to a fundamental problem with how we measure the timing and kinematics of Basin and Range extension, which is a prerequisite for understanding how and why extension took place in the manner that it did. In this paper, I reassess the role of the NNR as a large-scale Miocene stress indicator using recent data that bear directly on extensional faulting close to the NNR (Fig. 2) during the specific time period over which it formed.

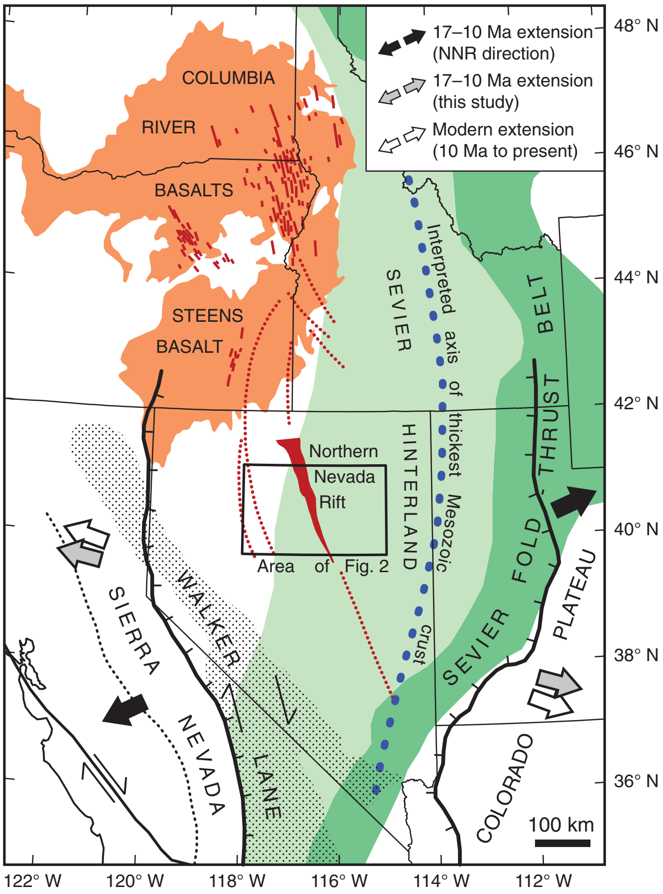

Figure 1. Sketch map of western United States showing selected tectonic provinces and magmatic features. Flood basalts and mafic dikes (solid lines) from Camp and Hanan (2008). Dotted lines are dikes inferred from aeromagnetic data (Blakely and Jachens, 1991; Glen and Ponce, 2002). Outline of northern Nevada rift (NNR) from John et al. (2000) (includes graben surrounding dike zone). Sevier orogenic belt from DeCelles (2004); axis of thickest crust within it from Coney and Harms (1984).

MIOCENE EXTENSION IN NORTH-CENTRAL NEVADA

Dikes of sufficient size and number are good indicators of the stress field at the time they were emplaced, but Miocene dikes are extremely rare in the northern Basin and Range outside the NNR. Even there they are confined to a relatively brief time window of ~1.5 m.y. Although less precise at the outcrop scale, large-scale patterns of extensional faulting provide a more robust picture of the strain field averaged over long spans of time at the scale of the whole province. Here I summarize geologic data that bear on the timing and direction of extension in north-central Nevada (Fig. 2), within and on both sides of the NNR. Extension directions are derived primarily from measured dips of strata tilted during faulting, exploiting the fact that footwall blocks in a system of half-graben normal faults rotate during fault slip around an axis perpendicular to the extension direction. If these blocks include layered strata that were horizontal before tilting, measured dip directions from these layers will point to the

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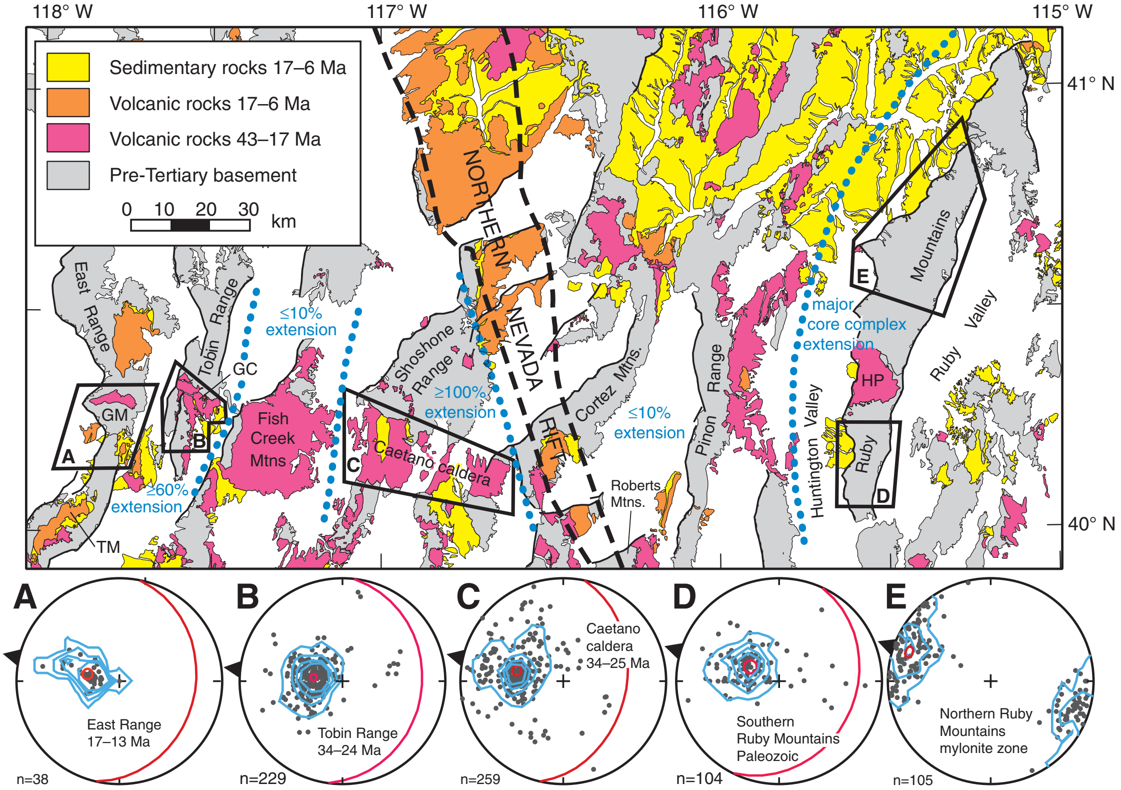

Figure 2. Geologic map of north-central Nevada (western United States), simplified from Crafford (2007). Northern Nevada rift from John et al. (2000). GC—Golconda Canyon; GM—Granite Mountain; HP—Harrison Pass pluton; TM—Table Mountain. Dotted blue lines are approximate boundaries of Miocene extensional domains. Structure data (A–E): Equal area plots. Black arrows are mean dip direction; dark gray circles are poles to bedding and/or compaction foliation in A–D and to mineral lineations in E; blue lines are 1% area contours (contour interval 4%); red ellipse is mean vector to bedding poles (±95%); red great circle is plane normal to mean vector. Sources of data are noted in the text.

extension direction. Provided that fault motion is dip-slip, and that tilting is the result of one episode of extension (not superimposed events with different orientations), the extension direction can be measured as accurately as the average dip direction for a deformed region.

Extension West of the Northern Nevada Rift

The southern East Range (Fig. 2) is bounded by a west-dipping normal fault and exposes Miocene sedimentary rocks interbedded with basalt and rhyolite flows ranging from 17 to 13 Ma (Nosker, 1981; Fosdick and Colgan, 2008). These rocks dip 20°–40°E with an average strike of ~013°, consistent with extension oriented 283° ± 5° (Fig. 2A). This trend is parallel to the apex of a 6-km-long antiformal corrugation in the west-dipping fault at Granite Mountain (GM, Fig. 2), indicating dip-slip fault motion. Apatite fission-track and (U-Th)/He data from Granite Mountain document rapid cooling during fault slip at 17–15 Ma, followed by younger faulting sometime after 10 Ma (Fosdick and Colgan, 2008).

Eocene–Oligocene (34–24 Ma) volcanic and sedimentary rocks in the Tobin Range fill a >1-km-deep paleovalley at Golconda Canyon (GC, Fig. 2) (Burke, 1973; Gonsior and Dilles, 2008). They are cut by closely spaced (1–2 km), west-dipping normal faults and dip 25°–30° E with an average strike of 010°, indicating extension oriented 277° ± 3° (Fig. 2B). Gonsior and Dilles (2008) estimated 25%–46% extension across the central Tobin Range (~3 km), mostly during the Middle Miocene (ongoing before and after 14.1 Ma). Direct kinematic indicators of fault-slip direction are absent, but the steeply dipping northern margin of the Golconda Canyon paleovalley (GC, Fig. 2) is not offset in a strike-slip sense.

The 34 Ma Caetano caldera (Fig. 2) filled with up to 4 km of Caetano Tuff during caldera collapse and an additional ~1 km of 34–25 Ma post-eruption deposits (John et al., 2008). This sequence is now cut by west-dipping normal faults and dips 30°–60°E with an average strike of 013°, indicating extension oriented 283° ± 4° (Fig. 2C) (Colgan et al., 2011). Sparse kinematic indicators from exposed faults indicate dip-slip motion, and the east-trending, steeply dipping (≥70°) margins of the caldera are not offset in a strike-slip sense across the west-dipping normal faults (Colgan et al., 2011). Sedimentary rocks in hanging-wall basins to these faults range from 15.6 to 12.0 Ma, and extension is inferred to have begun ca. 16 Ma (Colgan et al., 2008).

Throughout the domain described above, Middle Miocene faults and their hanging-wall basins are cut by younger, more widely spaced, high-angle faults that formed after 10–12 Ma (Colgan and Henry, 2009). The Fish Creek Mountains and Cortez Mountains (Fig. 2) were not deformed during Middle Miocene extension, and post–10 Ma faulting there resulted in ≤6° tilting. The Stillwater Range is capped at Table Mountain (TM, Fig. 2) by flat-lying mafic lava flows that postdate mid-Miocene extension but predate more-recent high-angle faulting. In other areas there is no direct measure of post–10 Ma tilting. Nowhere is there evidence for more than a few degrees, consistent with much less extension in the late Miocene and Pliocene than in the middle Miocene.

Extension within the Northern Nevada Rift

The NNR formed on the western edge of a block of crust that was not significantly deformed during Middle Miocene extension (Fig. 2) (Colgan and Henry, 2009). The 340°-trending NNR mafic dikes are exposed in the Cortez Mountains and Roberts Mountains (Fig. 2), parallel to the rift magnetic anomaly that Zoback et al. (1994) modeled as a 3–5-km-wide zone extending vertically to a depth of 10–15 km. Coincident with the magnetic anomaly and dikes is a 5–15-km-wide graben bounded by high-angle faults and filled with ~500 m (locally >1 km) of mafic lava flows, lesser silicic lavas, and minor sedimentary rocks from which John et al. (2000) report ^{40}Ar/^{39}Ar dates of 16.5–15.0 Ma. Blakely and Jachens (1991) suggested on the basis of aeromagnetic data that the NNR continues along strike for an additional 250 km past where it is expressed in the surface geology. Together the NNR dikes and graben accommodated ~1 km extension oriented ~245° (John et al., 2000).

Extension East of the Northern Nevada Rift

Although it may have begun earlier, major extension in the Ruby Mountains (Fig. 2) was ongoing in the Middle Miocene (ca. 16–10 Ma), accommodated by the west-dipping detachment fault that bounds the range to the west (e.g., Howard, 2003). Thick deposits (up to several kilometers) of 16–10 Ma Humboldt Formation fill the hanging-wall basin to this fault in Huntington Valley (Fig. 2) (Wallace et al., 2008; Colgan et al., 2010). Apatite fission-track and (U-Th)/He data from the Harrison Pass pluton (HP, Fig. 2) in the southern part of the range record rapid cooling at 17–15 Ma (Colgan et al., 2010), and apatite fission-track data from the northern part of the range indicate cooling between 20 and 14 Ma (Gifford et al., 2007).

In the southern Ruby Mountains, the detachment fault is a west-dipping (10°–30°), northeast-trending (~015°), brittle fault zone from which Burton (1997) reported sparse kinematic data indicating slip directed 300°–310°. Paleozoic sedimentary rocks in the footwall of this fault were locally deformed during emplacement of the Harrison Pass pluton (Barnes et al., 2001), but east-dipping beds outside this zone (>2 km south of the pluton) strike 023° ± 5°. This is consistent with extension oriented 297° ± 6° (Fig. 2D), but not direct proof of extension direction as these strata were probably gently folded prior to Miocene tilting (Willden and Kistler, 1979).

In the northern Ruby Mountains, the west-dipping detachment fault overprints a mylonitic shear zone with stretching lineations oriented 290° ± 5° (Fig. 2E) (MacCready et al., 1997). Slip on this shear zone may have begun in the Oligocene or earlier and the mylonites formed at higher temperatures (>300°C) than those recorded by the apatite fission-track data (120°–60°C) that date the most recent period of unroofing (Howard, 2003). The mylonite fabric is not overprinted by a different extension direction, however, consistent with extension oriented ~290° over the lifetime of the fault (including its Middle Miocene phase).

In summary, all available kinematic indicators from the Ruby Mountains indicate or are consistent with extension oriented 290°–300° ca. 17–10 Ma. No evidence for southwest-directed (~245°) extension has been reported, nor has significant strike-slip on range-bounding faults or other faults. There is no direct measure of tilting on the young, high-angle fault that bounds the west side of Ruby Valley (Fig. 2), but Colgan et al. (2010) estimated only <5° of post–10 Ma tilt that was in any case oriented the same as the mid-Miocene extension direction.

DISCUSSION

Miocene Extension Direction in the Northern Basin and Range

Major extension in the area of Figure 2 was ongoing from 17–16 Ma to 12–10 Ma and was oriented ~280°–300°, close to the modern direction of 290°–300° determined by Zoback et al. (1981). The magnitude and structural style of extension changed ca. 12–10 Ma, from strongly partitioned, large-magnitude strain to the more widely spaced, high-angle faults bounding the modern ranges, but there was no measurable change in the extension direction itself. Both the timing and direction of mid-Miocene extension in north-central Nevada are nearly identical to that determined by Wernicke and Snow (1998) for southern Nevada, and the direction is consistent with McQuarrie and Wernicke's (2005) reconstruction of extension oriented ~282° throughout the Basin and Range from 36 Ma to the present.

Colgan and Henry (2009) reconstructed 50–60 km of extension across the area of Figure 2 (~40% strain), all but ~5 km of which took place between 17 and 10 Ma. McQuarrie and Wernicke (2005) estimated a similar 50% strain (215–255 km extension) across the entire province since the Eocene. At this scale, ~1 km of extension across the NNR represents <0.5% of the total strain, and I suggest that structures accounting for the other >99% more reliably indicate the extensional stress field averaged over the period 17–10 Ma. Right-lateral shear migrated into the Walker Lane (Fig. 2) from the late Miocene (ca. 10–12 Ma) to the present, but there was no province-wide 45° clockwise rotation of the long-term stress field.

In light of the fact that major extension affected the entire Basin and Range after 17–16 Ma, Blakely and Jachens' (1991) extension of the NNR an additional 250 km south along strike (Fig. 1) should be reexamined. It is unlikely that a perfectly linear >600-km-long feature would remain so after being subjected to 50% (locally >100%) extension—but if it did, it would demonstrate that a large part of the northern Basin and Range escaped major extension.

Basin and Range extension is in part the result of gravitational collapse of elevated crust thickened during Mesozoic shortening (e.g., Coney and Harms, 1984). The locus and direction of spreading most likely reflects this process, although the timing and rate of extension may have been paced by the configuration of the Pacific–North American plate boundary. Extension oriented 280°–290° is roughly perpendicular to the Cretaceous thrust belt and the thickest crust in its hinterland (Fig. 1), which may reasonably be expected if extension were the result of lateral spreading during gravitational collapse of this zone.

Orientation of the Northern Nevada Rift

Previous workers have suggested that the location and trend of the NNR may have been controlled by an existing crustal structure (e.g., Theodore et al., 1998; John et al., 2000; Ponce and Glen, 2008). This structure has been interpreted as a near-vertical crustal-scale fault parallel and adjacent to the NNR based on resistivity (Grauch et al., 2003) and gravity data (Ponce and Glen, 2008). In the right circumstances, dikes can propagate along fractures that are not perpendicular to the least principal stress (e.g., Delaney et al., 1986), but NNR dikes do not appear to intrude preexisting faults where exposed in the field and it is difficult to argue they record anything other than the least principal stress in the central part of the area shown in Figure 2 from ca. 16.5–15.0 Ma. On the other hand, there is no direct evidence to support extrapolating these conditions to the entire Basin and Range to as recently as 10 Ma or even 6 Ma (e.g., Zoback et al., 1981, 1994).

One possible explanation for the trend of the NNR—one that for the most part honors both the geologically well-defined part of the NNR (Fig. 2) and the geologic data discussed in this paper—is that the dikes record a transient stress field strongly influenced by Yellowstone hotspot magmatism ca. 16–17 Ma (e.g., Glen and Ponce, 2002), while previous and subsequent extensional faulting records a long-term regional stress field related to the geodynamic processes governing Basin and Range extension. Campbell-Stone et al. (2000) documented a smaller-scale example of a similar process in the Sacramento Mountains of southern California, where initial 19–16 Ma extension was accommodated by dikes and oriented 235°–195°. It was followed immediately by 16–12 Ma extension on detachment faults oriented ~255°, which took up most (80%) of the extensional strain.

CONCLUSIONS

Geologic data consistently indicate a long-term Basin and Range extension direction oriented slightly northwest for the past 17 m.y., while NNR dike swarms have a distinctly different orientation and are not indicative of the former. Their relationship to Basin and Range extension is one facet of a larger problem worthy of further study: the relationship between the coeval onset of spatially distinct Yellowstone hotspot volcanism and Miocene Basin and Range extension.

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