Diachroneity of Basin and Range extension and Yellowstone hotspot volcanism in northwestern Nevada

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ABSTRACT

Some of the earliest volcanic rocks attributed to the Yellowstone hotspot erupted from the McDermitt caldera and related volcanic centers in northwestern Nevada at 17–15 Ma. At that time, extensional faulting was ongoing to the south in central Nevada, leading some to suggest that the nascent hotspot caused or facilitated middle Miocene Basin and Range extension. Regional geologic relationships indicate that the total magnitude of extension in northwestern Nevada is low compared to the amount documented in central Nevada and that extension was accommodated almost entirely by the widely spaced, high-angle normal-fault systems that formed the modern ranges. The Santa Rosa Range is the closest major range to the McDermitt caldera. It was tilted ~15° east and uplifted as an intact crustal block by ~8 km of slip along a west-dipping normal fault on the west side of the range. Apatite fission-track data from the Santa Rosa footwall block indicate that faulting and extension was ongoing ca. 7.5 Ma and began as early as 10 Ma. Data from the Pine Forest Range to the west indicate a similar 8–10 Ma age for extensional faulting. Basin and Range extension in northwestern Nevada is therefore significantly younger than 17–15 Ma hotspot volcanism. This timing argues against a direct link between the Yellowstone hotspot and the initiation of extension, casting additional doubt on the role of the hotspot in extension across the broader Basin and Range Province.

Keywords: Basin and Range, extension, fission-track dating, Nevada, Santa Rosa Range.

INTRODUCTION

The Yellowstone hotspot track (Fig. 1) has been attributed to the migration of the North American plate over a fixed deep-mantle plume in Miocene to Holocene time (e.g., Morgan, 1972). The onset of hotspot volcanism at 17–15 Ma was marked by eruption of the voluminous Columbia River basalts and related basalts in Oregon and northwestern Nevada. Caldera-forming volcanic eruptions then progressed northeastward along the Snake River Plain from the ca. 16 Ma McDermitt caldera in northwestern Nevada to the present locus of volcanism at Yellowstone (Fig. 1) (e.g., Pierce and Morgan, 1992). Parts of the Basin and Range Province south of the hotspot track were actively extending at 19–14 Ma (e.g., Stockli, 1999; Dumitru et al., 2000), and some workers have suggested that the arrival of the plume may have caused or facilitated the onset of extensional faulting (e.g., Parsons et al., 1994). Others have further suggested that Basin and Range–style faulting then migrated eastward in concert with volcanism along the eastern Snake River Plain (e.g., Anders et al., 1989).

However, there are difficulties with hypotheses relating Basin and Range extension to hotspot volcanism, at least in their simplest form. First, a deep-mantle plume origin for the volcanic rocks along the proposed hotspot track has not been universally accepted, and fixed-plume models for the Yellowstone hotspot remain controversial (e.g., Christiansen et al., 2002). Second, the Basin and Range Province has been the site of episodic extension and volcanism since at least Eocene time, long before the first volcanic eruptions attributed to the Yellowstone hotspot (e.g., Christiansen and Yeats, 1992). Third, known areas of major Miocene extension were apparently concentrated well south of the inferred 17–15 Ma position of the hotspot beneath McDermitt caldera (e.g., Dumitru et al., 2000). If the Yellowstone hotspot and associated volcanism facilitated Basin and Range faulting, one would expect that northwestern Nevada would also have been actively extending at 17–15 Ma, when the hotspot was directly beneath the area (Fig. 1).

The Santa Rosa Range and nearby ranges in northwestern Nevada exhibit many of the classic Tertiary structural features of the Basin and Range Province and are located close to the McDermitt caldera (Fig. 1). Geologic relationships are sufficiently well preserved in this region to allow the magnitude, timing, style, and orientation of extensional faulting to be reconstructed. In this paper we use regional geologic data and new apatite fission-track data to assess the relationship between extension in this part of the Basin and Range Province and the onset of hotspot volcanism.

REGIONAL GEOLOGY OF NORTHWESTERN NEVADA

Basement rocks in northwestern Nevada consist primarily of Triassic siliciclastic rift-basin deposits and Paleozoic–early Mesozoic volcanic arc sequences. Deformation and regional metamorphism to greenschist facies occurred during the Jurassic, followed by intrusion of Cretaceous granitic plutons (Wyld, 2002). Detailed mapping of the pre-Tertiary rocks demonstrates that they are cut only by relatively young high-angle normal faults. Older low-angle normal faults, like those in more highly extended parts of the Basin and Range (e.g., Miller et al., 1999; Hudson et al., 2000), have not been identified (e.g., Compton, 1960; Wyld, 1996).

Tertiary rocks older than 17 Ma are locally present in the Pine Forest Range (Fig. 1) and surrounding area, where they unconformably overlie Mesozoic basement. This section is late Oligocene to early Miocene in age, and includes basalts, calc-alkaline ash-flow tuffs, and interbedded sediments (Colgan and Dumitru, 2003).

These older Tertiary rocks are conformably overlain by the basalt-rhyolite sequence associated with the nascent Yellowstone hotspot (Fig. 1). This section consists of older mafic lava flows erupted from the northern Nevada rift and related rifts ca. 17–15 Ma (John et al., 2000; Glen and Ponce, 2002), overlain by rhyolite ash-flow tuffs erupted from the 16–15 Ma McDermitt caldera and related volcanic centers (Rytuba and McKee, 1984).

The Tertiary volcanic rocks are cut and moderately tilted (usually ≤35°) by the normal faults that bound the modern ranges. The absence of major mapped angular unconformities within the Tertiary section (Colgan and Dumitru, 2003) suggests that this was the only significant faulting and tilting event to affect the area. The continuity of the basement geology, the gentle to moderate dips of the Tertiary rocks, and the absence of low-angle, normal-fault systems suggest that the total magnitude of extension across the region is relatively small (<15%–20%), and was accommodated entirely by the high-angle faulting that formed the modern ranges.

SANTA ROSA RANGE TILT BLOCK

The Santa Rosa Range (Figs. 2 and 3) is underlain by a thick sequence of fine-grained

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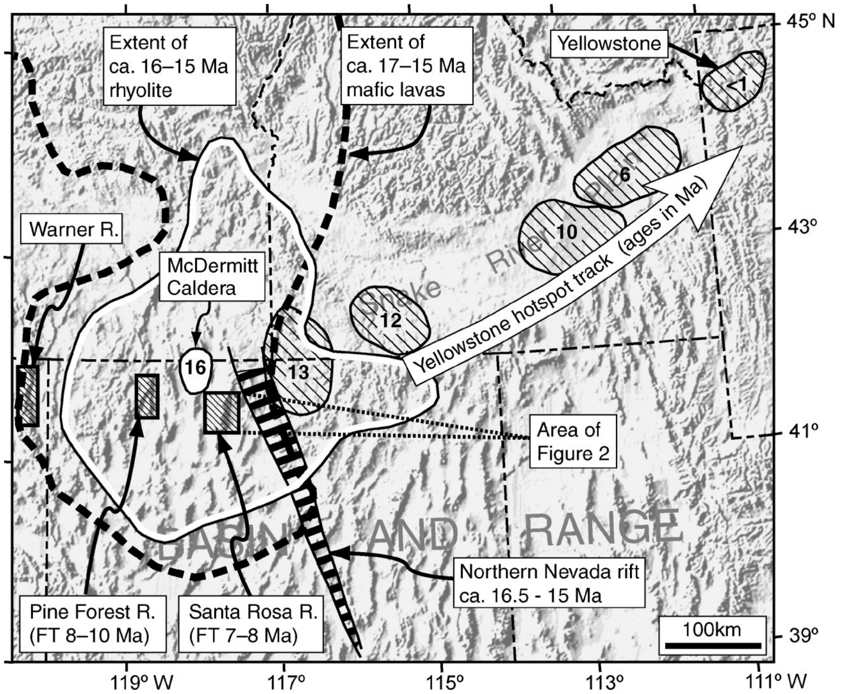

Figure 1. Shaded-relief map of part of western United States, showing location of Santa Rosa Range (R.) relative to start of Yellowstone hotspot track. Eruptive centers that define hotspot track, and their ages, are from Pierce and Morgan (1992); extent of 17–15 Ma volcanic rocks is from Christiansen and Yeats (1992); northern Nevada rift is from John et al. (2000). FT is fission track.

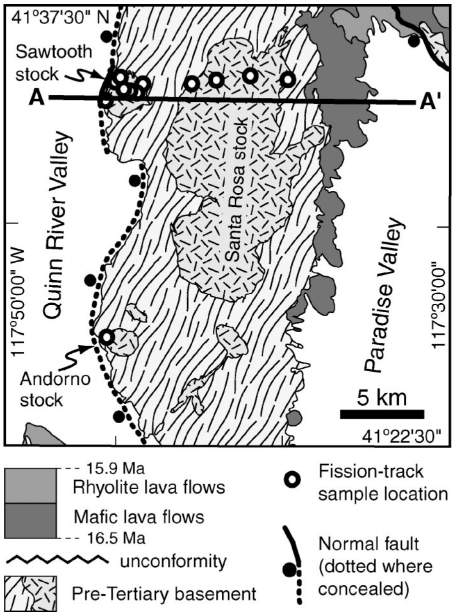

Figure 2. Geologic map of Santa Rosa Range, showing locations of fission-track samples and line of cross section in Figure 3. Geology is from Compton (1960) and LeMasurier (1965).

Triassic mudstones and siltstones, which were tightly folded and regionally metamorphosed to greenschist facies during Jurassic time and intruded by Cretaceous (ca. 102 Ma) granitic plutons (Compton, 1960; Wyld, 2002). Detailed mapping by Compton (1960) demonstrates that the pre-Tertiary rocks are unbroken by major Cenozoic normal faults within the interior of the range.

These basement rocks are unconformably overlain by an 800–1000-m-thick sequence of Miocene volcanic rocks, which dip conformably ~15° to the east (Fig. 3) (LeMasurier, 1965). This section consists of mafic lava flows as old as 16.4 Ma overlain and intruded by rhyolite lavas as young as 15.9 Ma (Brueseke et al., 2003).

The modern Santa Rosa Range was uplifted, tilted, and exhumed as an intact crustal block along a major west-dipping normal fault that bounds the west side of the range (Figs. 2 and 3). The fault surface is exposed at the base of Sawtooth Mountain (Fig. 3), where it dips 35°–40°W, with well-developed quartz-groove lineations indicating approximately dip-slip motion (Fig. 3). Gravity inversion data (Saltus and Jachens, 1995) show the top of the crystalline basement ~2.5 km below the surface of the adjacent Quinn River Valley, which requires ~8 km of slip on the range-bounding fault (Fig. 3). Restoring the Tertiary unconformity to horizontal allows us to infer that the range-bounding fault formed with an initial dip of ~50°–55°; the fault was subsequently rotated ~15° to its present attitude during tilting of the range, accommodating ~6 km of east-west crustal extension.

FISSION-TRACK DATING OF SANTA ROSA RANGE UPLIFT

The fission-track method is routinely used to date the timing of slip on major normal-fault systems, and a detailed explanation of this application was given in Miller et al. (1999). Apatite fission-track ages are totally reset to zero age at subsurface temperatures greater than ~110–135 °C, generally equivalent to subsurface depths greater than ~3–5 km. Ages are partially reset over the temperature range ~60–110 °C, termed the partial annealing zone (PAZ) (e.g., Green et al., 1989). To date slip on normal faults, systematic transects of samples are collected across the footwall of the fault system, in order to obtain samples that resided at the widest possible range of paleodepths, and thus paleotemperatures, before extension and exhumation began.

In the Santa Rosa Range, 11 samples were collected from the Santa Rosa and Sawtooth granitic stocks along an east-west transect, and an additional sample from the Andorno stock farther south along the range front (Fig. 2; see also Fig. DR-1 and Table DR-1[1]). In general, the samples from the Santa Rosa stock yielded abundant, high-quality apatite, whereas apatite from the Sawtooth stock was generally of lower quality (e.g., fewer grains, more fractures and dislocations). We were unable to extract any apatite from the fine-grained Triassic phyllites. The pre-extensional paleodepths of samples shown in Figures 3 and 4 were calculated by restoring the section to horizontal and adding the present thickness of the volcanic rocks along the line of section (~800 m) to the depth of each sample below the projected basal Tertiary unconformity. The 800 m thickness is a minimum because the amount of section removed by erosion is not known, but was probably minimal.

The Santa Rosa fission-track ages exhibit a systematic trend of decreasing ages with increasing structural depth expected in an exhumed normal-fault footwall block. At shallow structural depths (<1.5 km), 75–70 Ma ages record an older cooling event unrelated to extensional faulting. At intermediate depths (~1.5–3.5 km), ages trend progressively younger, reflecting incomplete resetting of the fission-track system within the PAZ before exhumation began. At paleodepths deeper than ~3.5–4 km, samples have nearly uniformly

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[1] GSA Data Repository item 2004017, fission-track sample locality, counting, and age data (Table DR-1) and fission-track length data (Fig. DR-1), is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

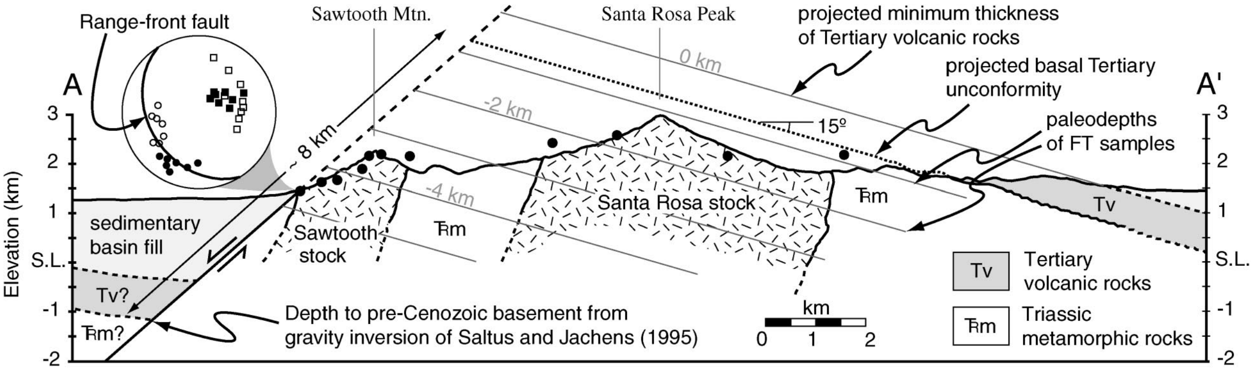

Figure 3. Geologic cross section of Santa Rosa Range, showing locations and paleodepths of fission-track samples and structural data from fault exposure at Sawtooth Mountain. In lower-hemisphere, equal-area stereographic plot, circles are trend and plunge of fault striations, and squares are poles to fault surfaces. Filled symbols are data from single large (>100 m²) fault exposure; open symbols are from small individual fault exposures. FT—fission track; S.L.—sea level.

young apparent ages, indicating that they were fully reset to zero age (hotter than ~110 °C) prior to rapid cooling.

The three structurally deepest samples yield a weighted mean age of 7.5 ± 0.8 Ma (Fig. 4), indicating that faulting and cooling was ongoing at that time. Faulting began no earlier than indicated by the cluster of 10–12 Ma samples at ~3.5 km paleodepth (Fig. 4), although the precise onset is impossible to pinpoint because these samples resided at the edge of the PAZ and thus may not have been fully reset prior to faulting. Therefore we prefer a 10 Ma or younger age for the onset of faulting. The range-front sample from the Andorno stock (Fig. 2) yielded a partially reset age of 15.4 Ma (Fig. 4), consistent with lesser offset on the range-bounding fault to the south. The geologic and fission-track data indicate that (1) the Santa Rosa Range was structurally intact prior to development of the modern range-bounding fault, and (2) major fault slip, exhumation, and tilting were ongoing ca. 7.5 Ma, and probably began no earlier than 10 Ma.

Results from the Santa Rosa Range are corroborated by two reconnaissance fission-track samples from the next major range to the west, the Pine Forest Range (Fig. 1), where ongoing mapping and preliminary fission-track dating suggest high-angle faulting at 10–8 Ma (Colgan and Dumitru, 2003). Regional stratigraphic relations as far west as the Warner Range in northern California (Fig. 1) also suggest a post–10 Ma age for the onset of faulting (Duffield and McKee, 1986), and more detailed sampling between these two areas is currently under way. Thus, based on existing data it appears that the period of intense volcanism that affected this region at 17–15 Ma was accompanied by very little supracrustal extension. The high-angle normal faulting that formed the modern ranges did not begin until ~5–9 m.y. later.

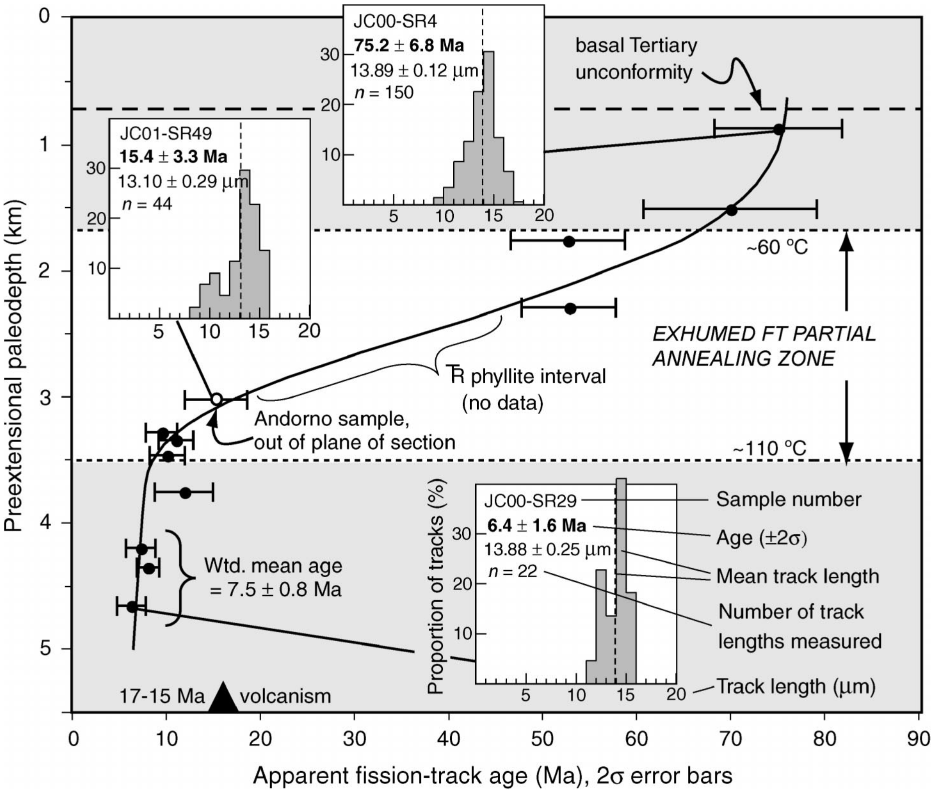

Figure 4. Age vs. paleodepth plot for Santa Rosa Range fission-track (FT) samples. Also shown are three representative track-length histograms from above, within, and below partial annealing zone; see Miller et al. (1999) for information on interpreting these data.

DISCUSSION AND CONCLUSION

In some parts of the Basin and Range Province, extension and volcanism are spatially and temporally linked (e.g., Gans et al., 1989), whereas in other regions the two processes appear to have proceeded independently (e.g., Best and Christiansen, 1991). In northwestern Nevada, 16.5–15 Ma dike swarms of the northern Nevada rift (Fig. 1) indicate extensional stresses oriented west-southwest–east-northeast during middle Miocene time (Zoback et al., 1994), but the amount of extension accommodated by the rift was no greater than a few kilometers (John et al., 2000). Thus, although northwestern Nevada was in a state of extensional stress during 17–15 Ma magmatism, the upper crust apparently remained unextended despite the formation of deep fractures that allowed large volumes of basalt to reach the surface. Specific discussion of the origins of the Yellowstone hotspot and the causes of middle Miocene volcanism are beyond the scope of this paper (see recent review in Christiansen et al., 2002), but the 5–9 m.y. time lag between 17–15 Ma volcanism and the onset of faulting suggests that northwestern Nevada was too cold or otherwise too strong to undergo extension by Basin and Range normal faults in the middle Miocene.

Rather, the conditions necessary for extensional faulting were apparently not established in northwestern Nevada until after 10 Ma, and the resulting extension was of low magnitude and accommodated entirely by widely spaced high-angle normal faults. This younger age of faulting coincides with a suggested change from dip-slip to more oblique-slip (right lateral) normal faulting in western Nevada ca. 10–7 Ma (e.g., Zoback et al., 1994; Cashman and Fontaine, 2000). The younger faulting also appears to belong to a regional pattern of younging-outward extension, in which faulting has migrated both east and west at the margins of the northern Basin and Range since the middle Miocene (e.g., Wernicke, 1992). Geologic and thermochronologic studies of both the eastern (Armstrong et al., 2000) and western (Surpless et al., 2002; Stockli et al., 2003) margins of the Basin and Range document rapid unroofing between 20 and 15 Ma, followed by younger faulting that has continued to the present day. Global positioning system data from the northern Basin and Range are consistent with this pattern, showing modern deformation focused on the eastern and western edges of the province (Thatcher et al., 1999). In addition to progressive east-west widening, the onset of extensional faulting in northwestern Nevada at 10–7 Ma suggests that Basin and Range faulting also migrated north over time into previously unextended crust.

Although additional work is clearly needed to fully document the timing and extent of extensional faulting in northwestern Nevada, the new data presented here indicate that Basin and Range extensional faulting is distinctly younger than the inferred development of the Yellowstone hotspot in the same region at 17–15 Ma. This disparity in timing argues against a direct link between the Yellowstone hotspot and the initiation of Basin and Range–style extension in this area and casts additional doubt on the role of the hotspot in extension across the broader Basin and Range Province.

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