# The northern Nevada rift: Regional tectono-magmatic relations and middle Miocene stress direction

MARY LOU ZOBACK
EDWIN H. McKEE
RICHARD J. BLAKELY
*U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025*
GEORGE A. THOMPSON *Department of Geophysics, Stanford University, Stanford, California 94305*

## ABSTRACT

**As defined by the most recent aeromagnetic surveys, the north-northwest–trending northern Nevada rift zone extends for at least 500 km from southern Nevada to the Oregon-Nevada border. At several places along the rift, the magnetic anomaly is clearly related to north-northwest–trending dikes and flows that, based on new radiometric dating, erupted between 17 and 14 Ma and probably during an even shorter time interval. The tectonic significance of the rift is dramatized by its length, its coincidence in time and space (at its northern terminus) with the oldest silicic caldera complex along the Yellowstone hotspot trend, and its parallelism with the subduction zone along the North American coast prior to the establishment of the San Andreas fault.**

**The northern Nevada rift is also equivalent in age, trend, and composition to feeder dikes that fed the main eruptive pulse (~95% volumetrically) of the Columbia River flood basalts in northern Oregon ~15.5–16.5 Ma. Because of these similarities, both regions are considered to be part of an enormous lithospheric rift that propagated rapidly south-southeast and north-northwest, respectively, from a central mantle plume. The site of the initial breaching of the North America plate by this plume is probably the McDermitt volcanic center at the north end of the rift near the Oregon-Nevada border. The present north-northwest trend of the rift and its internal elements, such as dikes and lava-filled grabens, record the orientation of the arc-normal extensional stress in this back-arc region at the time of emplacement. Paleomagnetic evidence presented by others and interpreted to indicate block rotations at three sample localities is not consistent with either a rotation of dikes within the rift or with a regional rotation of the entire rift. The present north-northwest trend of the rift reflects the state of stress in the Basin and Range during middle Miocene time and is consistent with stress indicators of similar age throughout the Basin and Range and Rio Grande rift provinces.**

## INTRODUCTION

The northern Nevada rift, prominently expressed in aeromagnetic maps, is a middle Miocene alignment of basaltic (and some rhyolitic) dikes and associated graben-filling lava flows that we believe is a significant key to tectono-magmatic processes throughout a broad region (Zoback and Thompson, 1978) (Fig. 1). The rift originated at the same time the Yellowstone mantle plume broke through the North American lithosphere and fed the Columbia River flood basalts. As shown in Figure 1, feeder dikes of the Columbia River basalts have the same north-northwest trend as the rift, and both are interpreted as superb mid-Miocene stress indicators related to extension in a direction perpendicular to the then-active subduction zone along the western margin. This subduction zone was gradually replaced by the San Andreas fault as the Mendocino triple junction progressed northward (Atwater, 1970, 1989). As the San Andreas transform lengthened, a new Basin and Range opening direction ensued in the Great Basin, rotated about 50° clockwise from the previous opening direction (Zoback and Thompson, 1978; Zoback and others, 1981). This change probably occurred between 10 and 6 Ma based on crosscutting fault relationships and timing of inception of modern basins (Anderson and Ekren, 1977; Stewart, 1978, Zoback and others, 1981). The modern direction of least principal stress is between N60°–70°W (Zoback and Zoback, 1980; Zoback, 1989). As the timing of this change coincides generally with growth of the San Andreas transform system, the clockwise change in stress tensor orientation has been attributed to the superposition of broad-scale right-lateral lithospheric shear along the western plate boundary. Beyond the influence of the San Andreas system, north of the Snake River plain in northeastern Nevada and Idaho, the earlier direction of extension (which is generally perpendicular to the modern regional topographic bulge) is still dominant (for example, Stickney and Bartholomew, 1987).

Our present objective is to marshal and interpret recent data from the northern Nevada rift, including (1) aeromagnetic data showing the full extent of the rift, (2) detailed geologic maps of the dikes in two ranges where they are extensively exposed, (3) improved radiometric dating, and (4) data on the deformational history of the rift after its formation. These data provide a foundation for reassessing tectonic events in light of recent research on mantle plumes. We also want to reaffirm our earlier interpretation of the northern Nevada rift as an indication of mid-Miocene stress direction (Zoback and Thompson, 1978), an interpretation that has recently been called into question. Li and others (1990) suggested, on the basis of paleomagnetic data, that blocks "comparable to or smaller than the width of the rift" have been tectonically rotated about 19° counterclockwise and that this rotation should be applied as a correction to the pre-rotation stress direction. Although small blocks within or adjacent to the normal-oblique fault zones may have been rotated, this interpretation is not viable on a larger scale because the dike swarms within the rift are precisely parallel to the 500-km-long rift trend as defined by aeromagnetic anomalies. Thus the individual dikes, the dike swarms, and the entire rift

---

Geological Society of America Bulletin, v. 106, p. 371–382, 7 figs., 2 tables, March 1994.

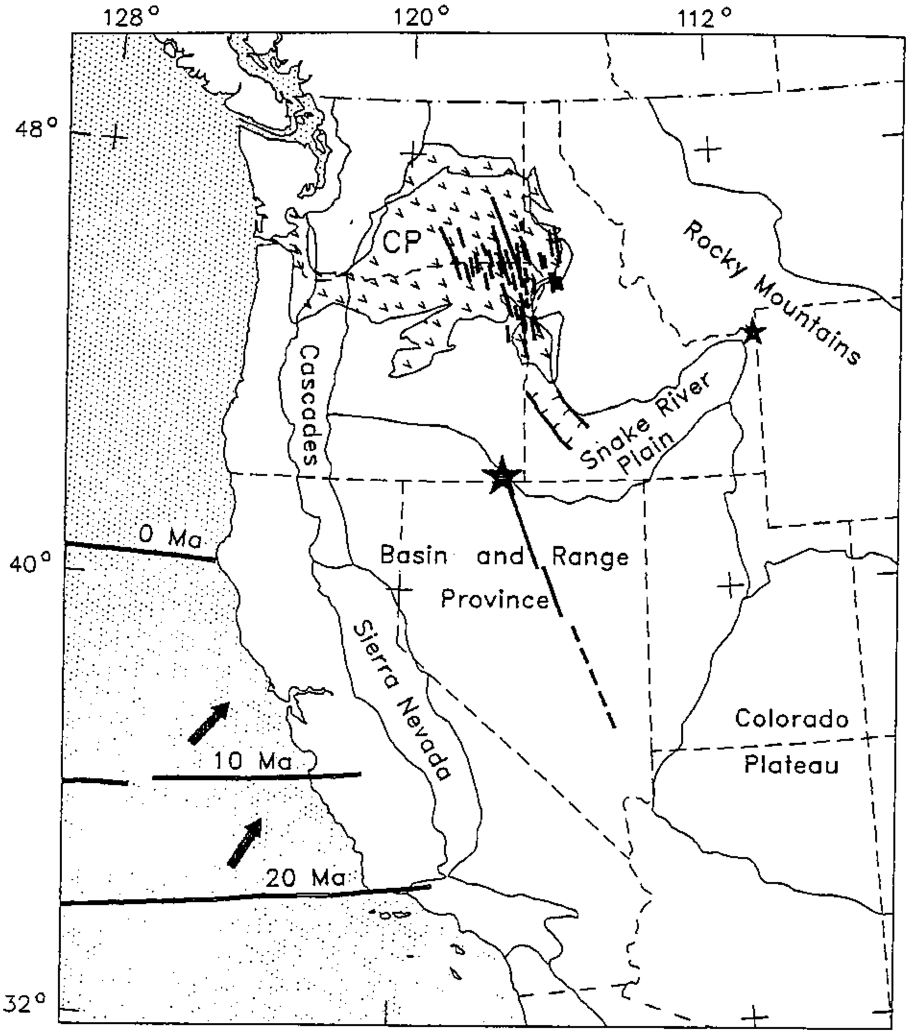

**Figure 1. Middle Miocene igneous and tectonic features in the western United States. Main part of north-northwest–trending northern Nevada rift is shown by heavy dark lines; southern extension is interpreted from aeromagnetic data indicated by dashed line. The left-stepping offset of the central part of the rift is diagrammatic and representative of cumulative offset on several cross faults (Table 2). The left step and gap separating the southern segment from the main part of the rift is real and inferred directly from the aeromagnetic data shown in Figure 2B. The large star at north end of rift indicates McDermitt caldera, the middle Miocene location of the Yellowstone hot spot; current position of hot spot is indicated by small star. The Columbia River Basalt Group is shown by checked pattern; feeder dikes in eastern Oregon and Washington are indicated by heavy lines. Western graben of the Snake River Plain is shown by hachured lines. East-west lines along coast give approximate location of the Mendocino triple junction at the different ages indicated (Atwater, 1989); heavy arrows indicate convergence direction of Juan de Fuca plate relative to North America corresponding to the adjacent times (Stock and Molnar, 1988). CP = Colorado Plateau.**

all yield the same mid-Miocene stress direction.

## NORTHERN NEVADA RIFT

The northern Nevada rift (Fig. 1) can be traced magnetically for at least 500 km southward from the Oregon border to southern Nevada (McKee and Noble, 1986; Blakely and Jachens, 1991). Basaltic rocks that define the rift are middle Miocene, about the same age as the silicic McDermitt volcanic center (Rytuba and McKee, 1984), which is located at the north end of the rift in the emergence area of the Yellowstone hot spot (for example, Pierce and Morgan, 1992). From this focal area the hot spot tracked northeastward to its present position at Yellowstone, forming the eastern Snake River Plain in its wake (Morgan, 1972).

As originally described on the basis of aeromagnetic anomalies, the northern Nevada rift extends north-northwest from about Eureka, Nevada (point A, Fig. 2A), to approximately the Oregon-Nevada border (point B, Fig. 2A). Philbin and others (1963) first described this north-northwest–trending aeromagnetic anomaly, and Roberts (1966) noted its trend in the context of northwest alignments of mineral deposits, which he considered to be mineral belts. Mabey (1966) and Robinson (1970) described the anomaly and expanded on the interpretation that the aeromagnetic pattern is caused by basaltic rocks concentrated in a deep, narrow zone. Stewart and others (1975) considered the anomaly to be the southern segment of a lineament across Oregon and Nevada; they noted that many of the volcanic rocks that lie on or near the lineament are middle Miocene in age. They considered the Oregon segment of the lineament to be the Brothers fault zone, a series of linear features seen on air photos trending northwest across Oregon, whereas they considered the Nevada segment to have formed within a deep-seated extensional system. Zoback and Thompson (1978) named the then-known 250-km-long Nevada segment the *northern Nevada rift* and used it to determine the middle Miocene least principal stress direction. Rather than tying the rift into the Brothers fault zone, Zoback and Thompson linked its formation to a much more extensive zone of rifting of the lithosphere that included similarly oriented feeder dikes of the Columbia Plateau flood basalts and the middle Miocene location of the Yellowstone hot spot. The north-northwest trend of the rift and the feeder dikes for the contemporaneous major pulse of Columbia River flood-basalt volcanism is consistent with geologic evidence throughout the Basin and Range and Rio Grande rift that supports a Miocene least principal stress direction perpendicular to this north-northwest trend (Zoback and others, 1981; Rehrig and Heidrick, 1976; Lipman, 1981; Henry and Price, 1986).

From analysis of low-altitude (National Uranium Resource Evaluation [NURE]) aeromagnetic profiles, Blakely and Jachens (1991) suggested that the magnetic anomaly associated with the rift extends much farther to the south-southeast than previously recognized, to at least latitude 38°N and perhaps to

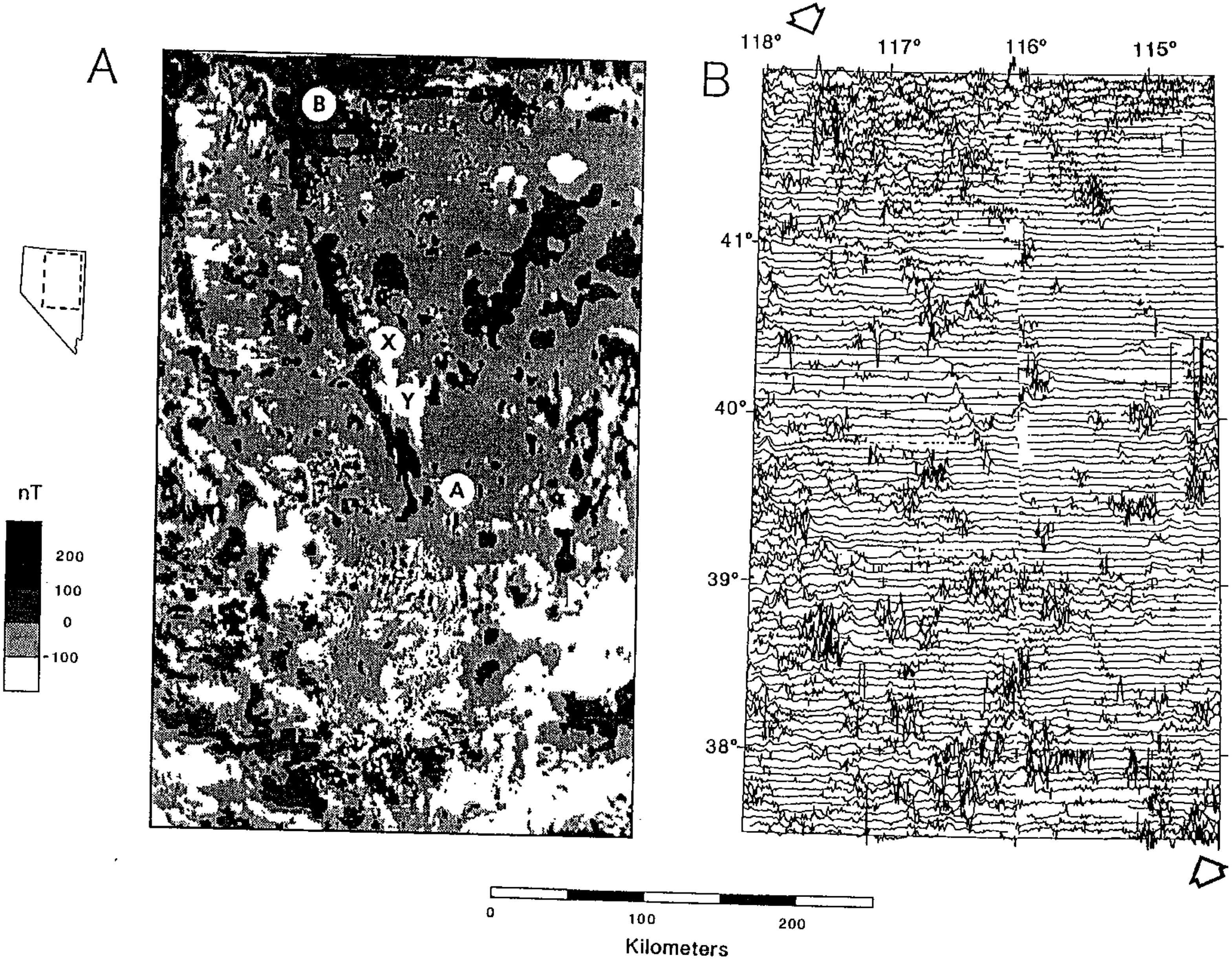

Figure 2. Magnetic anomalies over the northern Nevada rift. A. Aeromagnetic compilation modified from Hildenbrand and Kucks (1988). Points A and B indicate approximate ends of the anomaly caused by the northern Nevada rift; X and Y indicate regions of left-lateral offsets of the rift (better shown in B). B. Aeromagnetic profiles from the National Uranium Resource Evaluation (NURE). Arrows indicate the position of the northern Nevada rift as inferred from these magnetic data.

latitude 37°N (Fig. 2B), resulting in a total length in Nevada of at least 500 km. Parallel magnetic anomalies west of the northern Nevada rift may have a similar source but lack the associated basaltic dikes in outcrop (McKee and Blakely, 1990).

Geologically, the northern Nevada rift may be divided into northern, central, and southern segments. Each segment displays characteristic features.

### Northern Segment

The northern part of the rift, from the Oregon-Nevada border to Midas, Nevada (Fig. 3), crosses a broad tableland capped by rhyolites and basalt, tuffaceous sedimentary rocks, and gravel of late Miocene age. Along the southern part of the northern segment of the rift in more mountainous terrain, middle Miocene rhyolitic dikes, domes, and flows with some interfingering basaltic andesite and basalt flows seem to coincide with the aeromagnetic anomaly. Several large north-northwest–trending feeder dikes for the rhyolite exposed in the Midas region (Zoback and Thompson, 1978) lie along the aeromagnetic anomaly; basaltic flows underlie the rhyolite. The northern part of the northern segment, north of latitude 41°30′N, is defined solely on the basis of the aeromagnetic high.

### Central Segment

The central part of the rift from Midas to the southern edge of the Roberts Mountains (Fig. 3) is characterized by middle Miocene trachybasalt flows, which generally lie on Paleozoic bedrock. Minor rhyolite flows and domes are locally associated with the trachybasalt. Locally the aggregate thickness of these mafic flows exceeds 1 km (Beowawe region, Fig. 3), but most exposures are generally <300 m thick. North-northwest–trending basalt and trachybasalt dike swarms are well exposed in two ranges in the southern part of the central segment of the rift, the Cortez Mountains (Figs. 3 and 4) and the Roberts Mountains (Figs. 3 and 5), where they structurally underlie remnants of the basalt flows. Individual dikes in the Cortez Mountains are as much as 5 km long and range in width from 3 m to as much as 250 m where they join, although the average is <10 m (Fig. 4) (Gilluly and Masursky, 1965; Gilluly and Gates, 1965). The overall width of the swarm exposed in the Cortez Range is about 6 km; however, the main zone of intrusion, as indicated by the region of the largest and most continuous dikes, is only about 3 km wide.

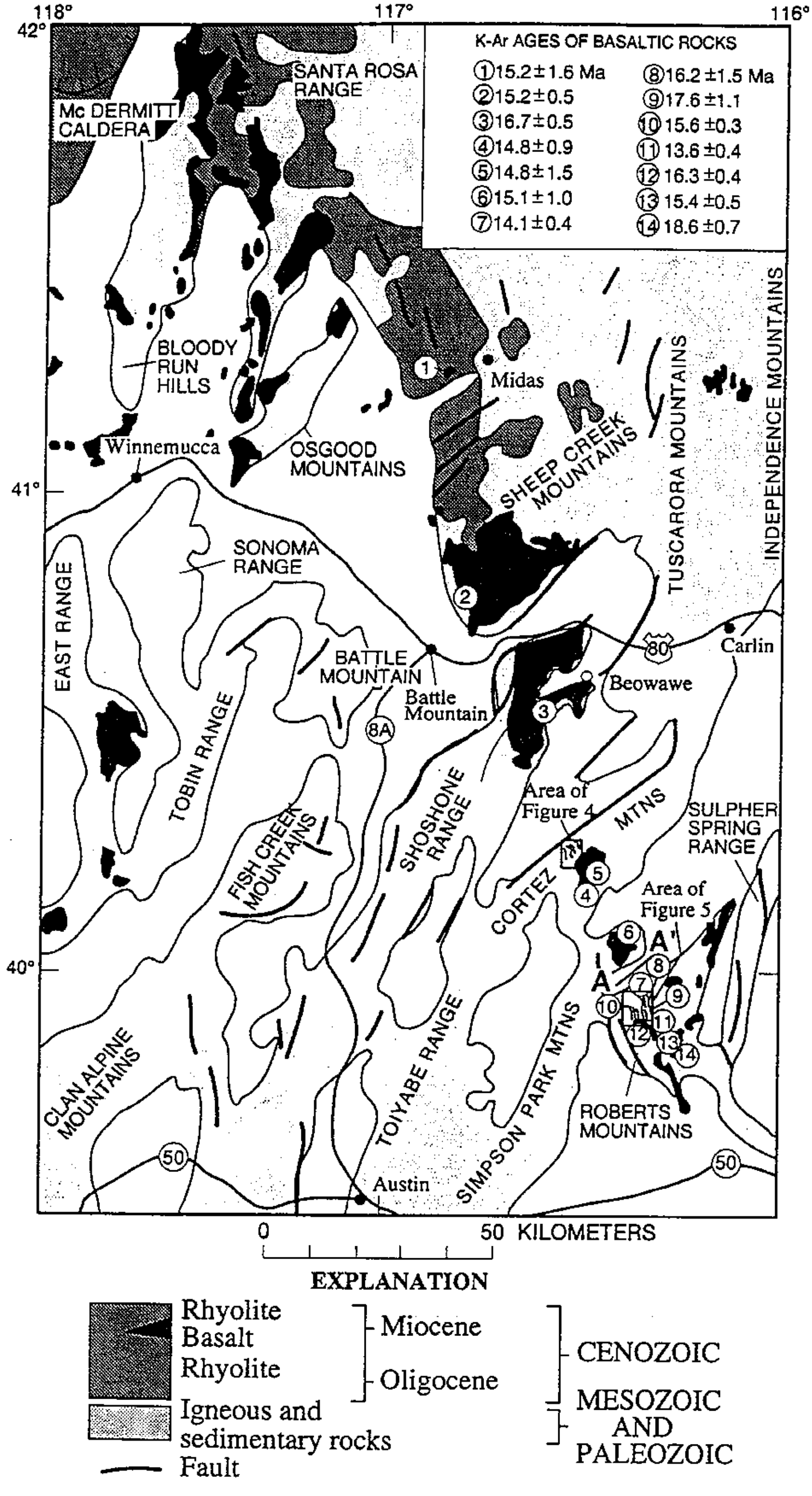

**Figure 3. Generalized geologic map of north-central Nevada showing the distribution of middle Miocene igneous rocks associated with the aeromagnetic anomaly and the northern Nevada rift. Location of samples of basalt for isotopic age determinations noted by number. Section line A–A′ gives location of gravity and magnetic profile shown in Figure 7.**

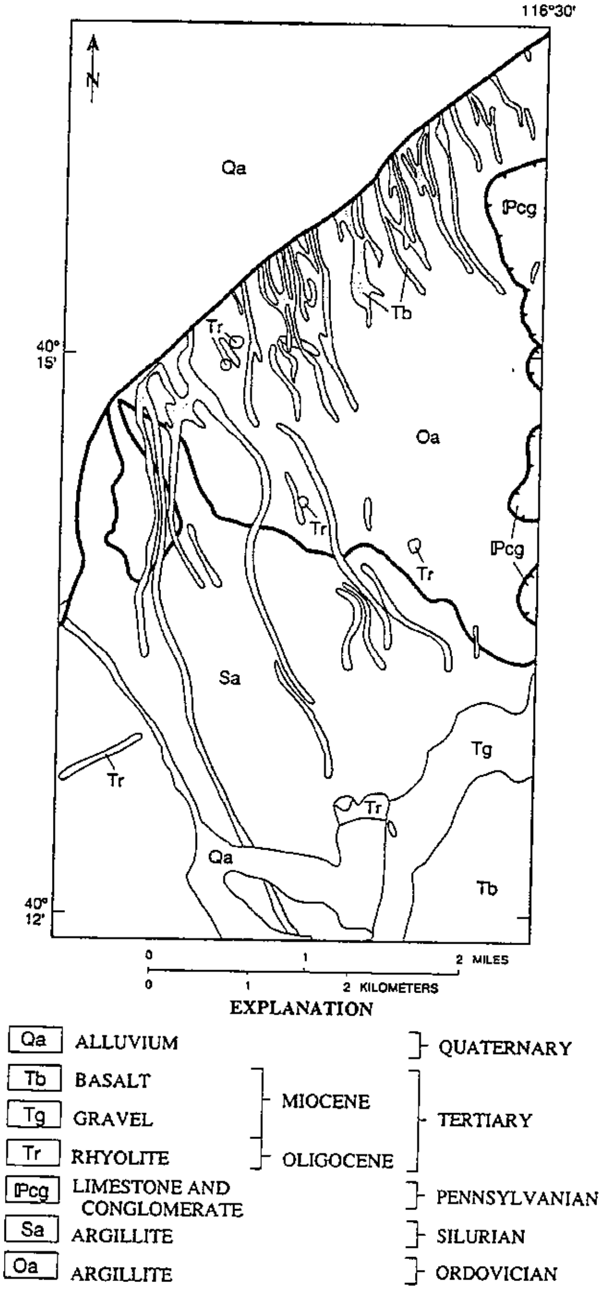

**Figure 4. Mapped middle Miocene basaltic dike swarm in the Cortez Mountains. Note that the average trend of the dikes is about N22°W, the same as dikes in the Roberts Mountains (Fig. 5) and as the northern Nevada rift as a whole. Map modified from Gilluly and Masursky (1965) and Muffler (1964).**

The strike of the zone of dike intrusion is N23°W ± 2°.

A spectacular north-northwest–trending basaltic dike swarm is exposed in the Roberts Mountains (McKee, 1986; Fig. 5; cover of this volume). Here the dikes intrude lower Paleozoic limestone and dolomite. Many of the dikes are fine grained and commonly exhibit an ophitic texture. As shown in Figure 5, the main zone of dikes is exposed for a length of nearly 10 km with a consistent N22°W trend despite the obvious structural complexity in the range. This complexity is partly associated with west-to-east thrusting during the Devonian to Mississippian Antler orogeny along the Roberts Mountains thrust and later high-angle and low-angle faulting in Mesozoic time (Winterer, 1968). The overall width of the zone of dike exposures in the Roberts Mountains is about 6 km; however, the main zone of intrusion is only about 2 km wide. Average dike width is on the order of 10–25 m, although some individual dikes are >150 m wide.

### Southern Segment

The southern segment of the rift, south of latitude 39°30′N, has little surface volcanic or intrusive expression and is defined almost entirely on the basis of low-altitude aeromagnetic profiles (Blakely and Jachens, 1991), confirmed in a few places by ground magnetic traverses. Although basaltic dikes do not crop out along this segment of the rift, magnetic anomalies indicate that magnetic (presumably mafic intrusive) rocks extend from depth to very near the topographic surface. A few exposures of basaltic flows, presumably of middle Miocene age, are located beneath the linear magnetic anomaly south of latitude 39°30′N, notably in the White River Valley south of the town of Lund; these exposures may be related to the southern segment of the northern Nevada rift. In the southern segment, the anomaly decays in amplitude, loses continuity, and appears to be offset left-laterally at about latitude 39°30′N (Fig. 2B).

### Composition of Basaltic Rocks along the Rift

The rocks that cause the strong aeromagnetic anomaly defining the northern Nevada rift are basaltic in character. Most are trachybasalts to trachyandesites (Le Maitre, 1984) with $SiO_2$ content around 50 wt% but some as high as 59 wt% (Gilluly and Gates, 1965; Stewart and McKee, 1977). Others are olivine-bearing basalt with $SiO_2$ content of about 48 wt% and total alkalies of <5 wt% (McKee and Mark, 1971). In the Roberts Mountains, dikes and flows of both basaltic types occur together and yield overlapping K-Ar ages (see, for example, numbers 8 and 9, Table 1).

North of the northern Nevada rift in eastern Oregon, middle Miocene (~15 Ma) basaltic rocks from the eastern Oregon volcanic plateaus province show a wide variation in silica, aluminum, and potassium content (Carlson and Hart, 1987). The eastern Oregon basalts are generally less alkalic than basaltic rocks from the northern Nevada rift region, and the relative amounts of high-silica versus lower silica types are opposite in these two regions, but the overall range in variation is comparable.

The Columbia River Basalt Group exhibits subtle differences in composition as compared to most basaltic rocks to the south both in the eastern Oregon volcanic plateaus and the northern Nevada rift. Trachyandesite and trachybasalt are rare in the Columbia River Basalt Group (Swanson and others, 1979); most of the Columbia River basalts are less alkalic, more iron rich, and average several

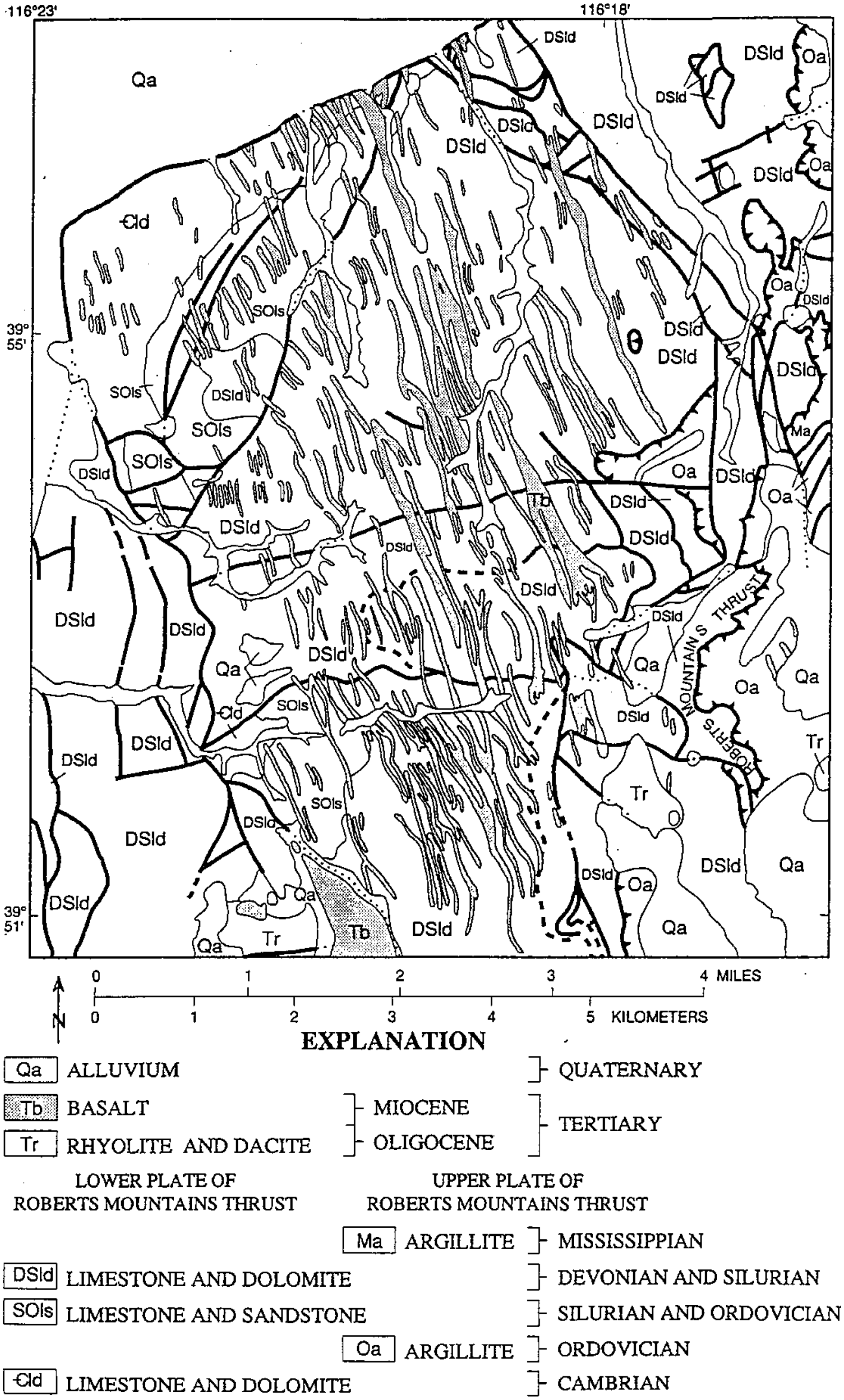

Figure 5. Geologic map of the northwest part of the Roberts Mountains, Nevada. Note the well-exposed N22°W–trending middle Miocene basaltic dikes. These dikes are the surface manifestation of a pronounced regional aeromagnetic anomaly, referred to as the northern Nevada rift. Map modified from Murphy and others (1978) and McKee (1986).

TABLE 1. K-Ar AGES OF BASALTIC ROCKS (DIKES AND FLOWS) FROM NORTH TO SOUTH ALONG THE CENTRAL NEVADA MAGNETIC ANOMALY

| No. of figures | General location | Occurrence (material dated, w.r. = whole rock) | $K_2O$ (wt%) | $^{40}Ar^*$ (mol/g) | $\%^{40}Ar^*$ | Age in m.y. $\pm\sigma$ | Reference |
|---|---|---|---|---|---|---|---|
| 1 | N. side Midas Canyon | lava flow (w.r.) | 0.884 | $1.9369 \times 10^{-11}$ | 17 | 15.2 ± 1.6 | Wallace and others, 1990 |
| 2 | Southern Sheep Creek Range | lava flow (w.r.) | 0.733 | $1.6120 \times 10^{-11}$ | 36 | 15.2 ± 0.5 | McKee and Silberman, 1970 |
| 3 | N.E. Shoshone Range | lava flow (w.r.) | 1.575 | $3.8087 \times 10^{-11}$ | 43 | 16.7 ± 0.5 | McKee and Silberman, 1970 |
| 4 | E. side Cortez Mountains | lava flow (plagioclase) | 0.295 | $0.713 \times 10^{-11}$ | 19 | 16.7 ± 0.9 | Wells and others, 1971 |
| 5 | S.E. Cortez Mountains | lava flow (w.r.) | 1.56 | $3.3465 \times 10^{-11}$ | 19 | 14.8 ± 1.5 | Armstrong, 1970 |
| 6 | N. Simpson Park Range | lava flow (w.r.) | 1.44 | $3.1502 \times 10^{-11}$ | 16 | 15.1 ± 1.0 | Armstrong, 1970 |
| 7 | N. Roberts Mountains | dike (w.r.) | 1.385 | $2.8281 \times 10^{-11}$ | 28 | 14.1 ± 0.4 | |
| 8 | N. Roberts Mountains | dike (w.r.) | 2.360 | $5.4569 \times 10^{-11}$ | 6.2 | 16.2 ± 1.5 | |
| 9 | N. Roberts Mountains | dike (w.r.) | 0.358 | $9.1091 \times 10^{-12}$ | 13 | 17.6 ± 1.1 | |
| 10 | N. Roberts Mountains | dike (w.r.) | 1.161 | $2.6192 \times 10^{-11}$ | 51 | 15.6 ± 0.3 | |
| 11 | Central Roberts Mountains | lava flow (w.r.) | 1.661 | $3.2745 \times 10^{-11}$ | 42 | 13.6 ± 0.4 | |
| 12 | Central Roberts Mountains | lava flow (w.r.) | 1.948 | $4.6043 \times 10^{-11}$ | 50 | 16.3 ± 0.4 | |
| 13 | S. Roberts Mountains | lava flow (w.r.) | 1.760 | $3.9224 \times 10^{-11}$ | 24 | 15.4 ± 0.5 | |
| 14 | S. Roberts Mountains | lava flow (w.r.) | 1.725 | $4.6506 \times 10^{-11}$ | 34 | 18.6 ± 0.7 | |

Constants used: $\lambda_\varepsilon + \lambda_{\varepsilon'} = 0.581 \times 10^{-10}\,yr^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10}\,yr^{-1}$; $^{40}K/K_{tot} = 1.167 \times 10^{-4}$ mol/mol.

percent more $SiO_2$ (Hooper, 1988) than does basalt from eastern Oregon and northern Nevada rift regions. The northern Nevada rift basaltic rocks are somewhat alkalic and of relatively small volume, the Oregon volcanic plateaus are characterized by more voluminous and less alkalic basalts, and the Columbia River basalts, by extremely voluminous high-alumina olivine tholeiitic basalt. These tholeiites exhibit trace-element characteristics, in particular high concentration of Ba and low Cs, Rb, and K, that suggest a mid-ocean-ridge basalt type of mantle source. The other basalts, with their wide variation in major- and trace-element composition, including the sensitive source indicator elements, suggest that varying amounts of crustal contamination and/or differentiation have taken place as the mantle-derived basalts ascended to the surface. It is clear that in middle Miocene time a very large volume of mafic magma was emplaced beneath the western United States from the Columbia Plateau region in the north to the northern Great Basin in the south. We believe that these magmas were produced from a single mantle plume and experienced differentiation and varying crustal contamination during ascent (see also Pierce and Morgan, 1992). Thompson and Gibbs (1991) have also associated Columbia River basaltic volcanism with emergence of a mantle plume near the Oregon-Nevada-Idaho border.

### Age of Basaltic Rocks along the Rift

Fourteen samples of basaltic rocks from the central part of the rift between Midas and the Roberts Mountains, a distance of about 150 km, have been dated by K-Ar methods (Table 1; Figs. 3 and 6). Ten samples are from lava flows and four are from dikes. Dates range from 18.6 ± 0.7 to 13.6 ± 0.4 Ma with most values falling between about 14 to 17 Ma (Fig. 6). The uncertainties in these dates preclude determination of the time span of emplacement; it could be nearly instantaneous, or it could be as great as 5–6 m.y. Geologic relationships such as crosscutting contacts do not improve this resolution. The 14 dates clearly indicate that most of the basaltic volcanism along the rift took place in the middle Miocene in the interval from 17 to 14 Ma and perhaps as short as 16 to 15 Ma. This age interval is one of widespread igneous activity throughout the northern Great Basin, eastern Oregon volcanic plateaus, and the Columbia Plateau as shown in Figure 6, which emphasizes the synchroneity of the main pulse of basaltic activity on the Columbia Plateau (~95% of the voluminous flood basalts erupted in this time interval; Hooper, 1988; Baksi, 1988) and mafic activity to the south, including the basaltic rocks that define the northern Nevada rift.

### Aeromagnetic Anomaly along the Rift

The amplitude and areal extent of the central segment of the aeromagnetic anomaly requires deep-seated magnetic sources in addition to surface volcanic rocks (Robinson, 1970). Although flows at the surface yield

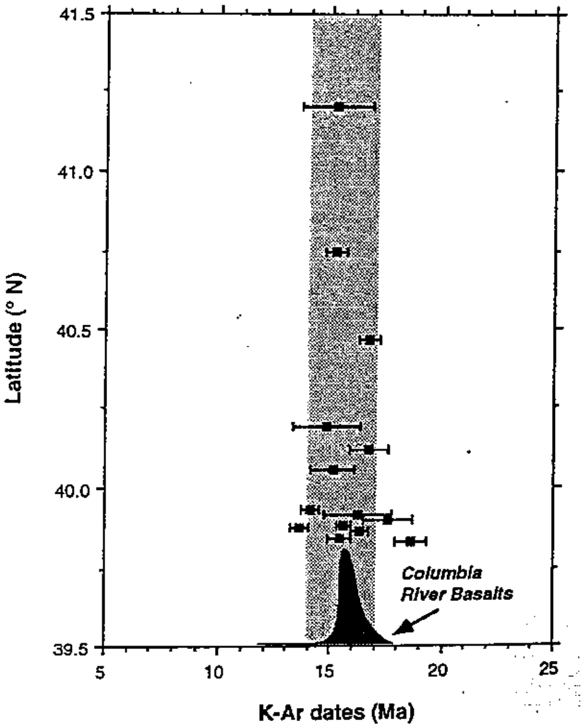

**Figure 6. Plot of the K-Ar ages of the basaltic rocks along the northern Nevada rift. Note the age range is middle Miocene, between 17 and 14 Ma, indicated by the shaded zone. This age range overlaps the 17.2 to 15.5 Ma time interval of the eruption of 90%–95% of the Columbia River Basalt Group, indicated by volume versus time curve at the bottom of the figure after McKee and others (1977) and Baksi (1988).**

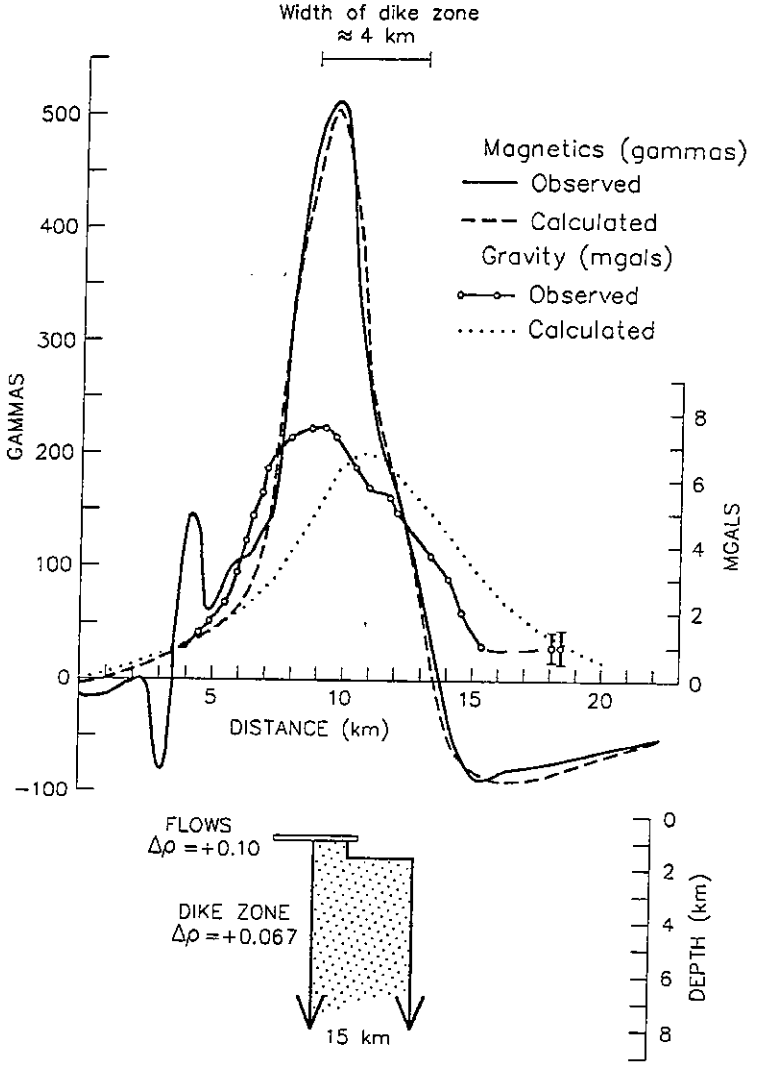

**Figure 7. Ground gravity and magnetic data collected along a profile perpendicular to the rift in Horse Creek Valley (profile A–A′, Fig. 3). The calculated two-dimensional magnetic model based on near-surface flows and an underlying dike zone (see text for details of model) fits the observed magnetic data quite well. Predicted gravity based on the same model (using measured densities and assuming the dike zone is composed of 33% dike rock, see text) generally matches the overall shape and amplitude of the observed gravity values but is shifted to the east, suggesting that at least part of the observed gravity anomaly is due to lateral variations in basement lithologies and densities.**

normal, reversed, as well as transitional field directions (Zoback, 1978; Li and others, 1990), the marked throughgoing positive aeromagnetic anomaly indicates that the bulk of the magnetization must be induced. Modeling of both airborne and ground magnetic profiles across the well-defined central segment of the rift magnetic anomaly suggests that the primary source of the anomaly is a 3.0- to 5.5-km-wide zone of magnetic material that extends from the surface to depths of around 10–15 km (Zoback, 1978). The inferred "base" of the magnetic material generally coincides with the inferred depth to the Curie-temperature isotherm in this region (Blakely, 1988). On the basis of the exposed geologic relations, this deep magnetic zone is interpreted to be a zone of dike intrusion extending nearly vertically through the crust and feeding the basaltic andesite flows (Zoback, 1978).

Magnetic models of the southern part of the anomaly, south of latitude 39°30′N, also indicate narrow, deeply projecting, vertical magnetic sources suggestive of dike intrusion. Based on models of low-altitude magnetic profiles, the magnetic part of the rift in the southern section has a cross-sectional structure similar to, but somewhat smaller than, the northern parts of the anomaly. In particular, magnetic sources associated with the rift are located very near the present-day topographic surface, project to at least 6-km depth, and are generally <4 km wide (Blakely and others, 1989).

### Other Geophysical Expression

A single, well-sampled ground gravity profile across the rift in Horse Creek Valley (A–A′ on Fig. 3) indicates a gravity high spatially associated with the magnetic high (Fig. 7). In this region, the main dike zone is overlain by a thin series of basaltic andesite flows. Calculated gravity and magnetic anomalies are also shown in Figure 7 based on a model that fits both the ground magnetic and aeromagnetic data (measured remanent direction and magnetic intensity were used for the flows, and a susceptibility of $k = 0.0027$ emu [0.034 SI units] was used for the dike zone, which extends to about 15-km depth). Predicted gravity values derived from this magnetic model are based on the assumption that one-third of the main zone of intrusion is occupied by dikes, and hence the estimated density contrast is correspondingly divided by three. The densities used in the model were based on measurements of field samples: 2.65 g/cm$^3$ for the Paleozoic sedimentary rocks, which are dominantly siliciclastic (from Mabey, 1965); 2.75 g/cm$^3$ for the basaltic andesite (from the Cortez Range); and 2.85 g/cm$^3$ for the dike rock (both values from Zoback, 1978). These densities resulted in a +0.1 g/cm$^3$ density contrast between the flows and the Paleozoic rocks and a +0.067 g/cm$^3$ (0.20/3) density contrast for the underlying dike zone. Between 6- and 12-km depth, this density contrast was decreased to +0.05 g/cm$^3$, and below 12-km depth, because of the general increase in density with depth of crustal rocks (for example, Catchings, 1992), the density contrast was assumed to be zero.

The calculated gravity anomaly is centered over the magnetic body, as expected; however, the observed gravity anomaly is shifted to the west. This westward shift suggests that at least part of the observed gravity anomaly may be due to lateral variations in basement rocks and densities (possibly related to the previously mentioned Roberts Mountains thrust). Alternately, a body centered beneath the observed gravity high could be consistent with the magnetic anomaly if the overall magnetization vector was oriented about due west. This magnetization direction predicts a slightly differently shaped magnetic anomaly, however, and was not observed in any of the paleomagnetic investigations of the dikes or flows along the rift (Zoback, 1978). Furthermore, a 4-km westward shift of the ~4-km-wide magnetic body would result in the source of the magnetic anomaly being significantly offset from the exposed dike swarms, rather than lying directly beneath them. For these reasons, we believe that the observed gravity anomaly is not entirely due to the dike zone. The observed gravity data do limit the maximum gravity signature associated with the magnetically inferred dike zone to be <5 mGal. Clearly, a dike zone consisting of 100% dike rock would create very large gravity anomalies, between 15 and 20 mGal, which are not observed here or anywhere else along the trend. Thus, probably no more than 25%–30% of the zone of intrusion is occupied by dikes.

Seismic reflection profiles across the rift at about latitude 40°N (Allmendinger and others, 1987; Potter and others, 1987) indicate a well-developed zone of subhorizontal layering in the middle and lower crust (between depths of about 18 to 35 km). Lower crustal layering was pervasive on the entire Basin and Range COCORP seismic reflection transect (Allmendinger and others, 1987); however, this layering apparently was best developed and thickest directly beneath the northern Nevada rift and in a zone extending 25 km to the west-southwest (Potter and others, 1987). Potter and others (1987) suggested that this strongly layered fabric might be produced by intrusions related to the rift. Holbrook and others (1991) attributed the subhorizontal reflections in this area to both sill-like mafic intrusions and ductile shearing.

We note that this zone of subhorizontal layering closely coincides with a regional gradient in residual gravity anomalies. This correlation is best seen in maps showing "basement gravity" (Jachens and Moring, 1990). Such maps are constructed by first eliminating the gravitational effects of long-wavelength topography (Simpson and others, 1986) and then eliminating the gravitational effects of low-density materials in the basins. When applied to the entire state of Nevada, this analysis shows a north-northwest–trending gravity gradient lying parallel to and centered about 10 km west of the northern Nevada rift between latitudes 41°N and 39°30′N (Blakely and Jachens, 1991), generally coinciding with the zone of well-developed subhorizontal layering in the middle and lower crust interpreted by Potter and others (1987). We suggest that both the gravity gradient and the seismic layering may represent a broad zone of intrusion and extension in the middle and lower crust related to middle Miocene rifting, significantly broader than the magnetic and geologic expression of the rift. Therefore, the rift, as represented by magnetic anomalies and geologic mapping, may be simply the upper crustal part of a deeper and broader zone of crustal extension and magmatic intrusion.

### Offsets and Extension

The consistent N20°–25°W trend of the magnetic anomaly, of the exposed basaltic feeder dike swarms, and of the structural troughs that were filled by basaltic flows indicate an extensional origin for the northern Nevada rift. The consistent trend of all these features suggests that the rift did not exploit a pre-existing feature but instead responded to the prevailing least principal stress at the time of formation, horizontal and oriented N65°–70°E (Zoback and Thompson, 1978; Christiansen and McKee, 1978). As described in the introduction, some time after formation of the rift (between ~10 and 6 Ma) there was a clockwise change in the least principal stress orientation throughout the northern Basin and Range, which has been attributed to the superposition of broad-scale right-lateral lithospheric shear along the western plate boundary (Zoback and Thompson, 1978). The modern direction of least principal stress is between N60°–70°W (Zoback and Zoback, 1980; Zoback, 1989).

In the vicinity of the northern Nevada rift the typical north-northeast–trending range and basin blocks of the northern Basin and Range province are largely replaced by complementary north-northwest and east-northeast trends. The modern direction of least principal stress is oriented approximately perpendicular to the typical north-northeast ranges and the bounding normal faults have nearly pure dip-slip displacements (Zoback and Zoback, 1980; Zoback, 1989). Of the typical north-northeast–trending basins judged on the basis of gravity to be deeper than 1 km, only two cut across the rift, whereas at least five others change trend near the rift (Blakely and Jachens, 1991). Zoback and Zoback (1980) suggested that the complementary north-northwest (parallel to the rift) and east-northeast trends in the modern topography represent reactivation of pre-existing faults that locally were able to accommodate strain by oblique-normal slip, whereas regionally, favorably oriented (north-northeast) faults were breaking through the upper crust.

In detail, the aeromagnetic high associated with the central part of the northern Nevada rift is segmented, offset both laterally (in a left-stepping sense, see Fig. 2A, sites X and Y, and diagrammatically in Fig. 1) and vertically, by the Basin and Range normal faults that strike approximately orthogonal to it. These normal faults strike between about N40°–80°E, and striae measurements demonstrate that they have oblique left-lateral normal slip (Zoback, 1978, 1989). Detailed gravity and geologic investigations were used to constrain the minimum amount of vertical displacement across these major east-northeast–striking normal faults (it is impossible to estimate the amount of material eroded from the range tops, as most ranges are capped by the middle Miocene volcanic rocks). Detailed modeling of magnetic profiles straddling these fault zones limits the total lateral offsets. This modeling is described in detail in Zoback (1978), and the results are summarized in Table 2. Note that for the four main fault zones crossing the central part of the rift (fault zones bound the northwestern sides of the associated ranges; see Fig. 3), the estimates of lateral offsets are significant and in some cases exceed the vertical offsets on the faults. Note too that the mean best estimate of extension direction (representing total post–middle Miocene deformation) across the four fault zones is N72°W ± 9°, close to the modern extension direction, indicating that the rift has not rotated on a regional scale.

## POST-RIFT TECTONIC ROTATION?

Recent paleomagnetic results have been interpreted as casting doubt on the suitability of the northern Nevada rift and its present orientation as an indicator of middle Miocene stress orientation. Li and others (1990) sampled three localities along the northern Nevada rift: 18 sites at the Midas trough, 22 sites at Argenta rim, and 19 sites at the Cortez Mountains. After eliminating several sites judged to reflect transitional field behavior, they found locality mean paleomagnetic directions to be statistically indistinguishable but rotated approximately 19° counterclockwise with respect to the expected middle Miocene direction. Moreover, when data from all three localities were combined, the overall mean showed the same discordant direction. Li and others (1990) concluded that all three localities have rotated ~19° counterclockwise about vertical axes since the formation

TABLE 2. ESTIMATES OF FAULT OFFSETS ALONG MAJOR EAST-NORTHEAST–TRENDING CROSS FAULTS ALONG THE NORTHERN NEVADA RIFT[*]

| Fault zone (south to north) | Fault trend | Vertical offset (m)[†] | Horizontal separation (m)[§] | Lateral offset (m)[**] | Extension direction[††] |
|---|---|---|---|---|---|
| Roberts Mountains | N 65° E | 3,260<br>(2,900–3,350) | 2,283<br>(1,670–3,350) | 1,585<br>(830–1,740) | N 60° W<br>(N 39° W–N 71° W) |
| Simpson Park Range (northeast end of range) | N 69° E | 1,680<br>(1,250–2,120) | 1,176<br>(720–2,120) | 1,720<br>(1,130–2,290) | N 77° W<br>(N 49° W–N 93° W) |
| Cortez Range | N 54° E | 3,510<br>(3,170–3,660) | 2,458<br>(1,830–3,660) | 1,680<br>(1,520–1,830) | N 70° W<br>(N 66° W–N 83° W) |
| Argenta Rim (northeast end Shoshone Range) | N 75° E | 2,350<br>(2,290–2,440) | 1,645<br>(1,320–2,440) | 3,445<br>(3,140–3,750) | N 79° W<br>(N 67° W–N 86° W) |

[*] Faults bound northwest side of range. Uncertainty ranges in offsets given in parentheses.

[†] Minimum estimate determined from gravity modeling of basin fill, and combined topography of range and projection of dip slope.

[§] Computed from vertical offset estimate assuming a 55° dipping fault; uncertainty range from uncertainties in vertical offset estimate and allowing for a possible fault dip between 45°–60°.

[**] Determined from offset of main magnetic source zone as determined from modeling of two-dimensional profiles that straddle these offsets.

[††] Net horizontal direction of opening along fault, $\epsilon$ (in northwest quadrant) = $(90° - \text{fault trend}) + \tan^{-1}$ (lateral offset/horizontal separation); uncertainty range broadest possible using end members uncertainty values for separation and offset.

of the northern Nevada rift about 15 Ma. Accordingly, the northern Nevada rift would have been oriented nearly north-south during its formation in the middle Miocene, and paleostress orientations inferred from the present-day orientation of the northern Nevada rift would thus be in error.

The aeromagnetic anomaly manifested by the northern Nevada rift has several characteristics that should be considered in this regard. First, the gradients that define the boundaries of the exposed rift are extraordinarily linear and continuous over distances of more than 200 km. This suggests that the rift is similarly continuous without significant lateral offsets except those related to the younger east-northeast–trending, rift-crossing, basin-bounding faults (Table 2). Only two models could accommodate 19° of vertical-axis rotation and leave the rift so homogeneous: (1) either the rotating block was sufficiently large to include the entire rift *in situ* or (2) the rotation was accommodated by numerous crustal blocks with lateral dimensions comparable to or smaller than the width of the rift. The first model is highly unlikely, as noted also by Li and others (1990), because the rift can now be seen to span nearly the entire state of Nevada (Fig. 1), and there is no evidence of such a large-scale rotation in surrounding Basin and Range deformation. In fact, paleomagnetic data for an Oligocene ash-flow tuff crossing the southern segment of the rift rules out any large-scale systematic rotation. Declinations in the Windous Butte Formation at two sites along the southernmost part of the aeromagnetic anomaly (Stone Cabin and Wells Station) are identical to the declination at the type locality and everywhere else sampled (except one anomalous site) (Gromme and others, 1972). Moreover, MacDonald and others (1992) measured a magnetic direction in Eocene rocks in the Roberts Mountains that is consistent with no post-Eocene rotation.

Li and others (1990) favored the second model, systematic counterclockwise rotation of numerous small crustal blocks within the rift. Such rotations would produce right-stepping offsets of geological elements such as dikes or, on a larger scale, of the entire rift. Actual offsets of the rift step left, however, as shown by the aeromagnetic data and by measurements of left-lateral oblique-normal slip vectors on the cross faults (Table 2). One dike (the Sawtooth dike) internal to the rift also shows a left step, which, on the basis of field evidence indicating the absence of fault offset, has been interpreted as originating at the time of intrusion (Zoback and Thompson, 1978).

The observation that the overall orientation of the rift (~N20°W) is equivalent to the orientation of mapped dike swarms now contained in fault blocks within the rift is also difficult to reconcile with a block-rotation model. For example, Figures 3 and 4 show numerous dikes longer than 2 km in outcrop with orientations of approximately N20°W. This parallelism of dikes and overall trend of the rift is inconsistent with a model of systematic block rotation throughout the rift but does not rule out rotation of small blocks within fault zones having a left-lateral component of slip. As shown on their map, all three of the paleomagnetic locations of Li and others (Cortez Range, Argenta Rim, Midas trough) are within or adjacent to the major cross-fault zones that offset the rift in a left-lateral sense. Therefore, counterclockwise rotations might be related to localized deformation directly adjacent to the fault zone and unrelated to the overall orientation of the rift or to the dike swarms within it.

## REGIONAL RELATIONS: FLOOD BASALTS AND EMERGENCE OF THE YELLOWSTONE HOT SPOT

The interval between 17 and 14 Ma was a dynamic period in parts of Nevada, Oregon, Idaho, and Washington. During this geologically short interval the intrusive and extrusive rocks of the northern Nevada rift were emplaced, the bulk of the flood basalts of the Columbia River Basalt Group was erupted through its feeder dikes, and the McDermitt caldera was formed at the northern terminus of the northern Nevada rift (Fig. 1). The McDermitt caldera was the first of a succession of calderas tracking northeastward at a rate of 35 to 45 mm/yr along the eastern arm of the Snake River Plain toward the youngest caldera at Yellowstone (Armstrong and others, 1975; Christiansen and McKee, 1978; Rodgers and others, 1990). This rate is the sum of southwestward movement of the North American plate across the mantle plume and concomitant extension of the Basin and Range crust.

Hot-spot plumes are thought to ascend through the mantle as mushroom-shaped heads that are fed from below by narrow cylindrical conduits (Duncan and Richards, 1991; Sleep, 1992). The voluminous plume head is the source of flood basalts associated worldwide with the initial eruption of plumes through the lithosphere. The plume head and the thermal lithospheric uplift that accompanies it are ~2,000 km in diameter (Sleep, 1992). Thus it should not be surprising that the combined extent of the feeder dikes of the Columbia Plateau flood basalts, the graben of the western Snake River Plain, and the northern Nevada rift is about 1,000 km (Fig. 1). The topographic swell of about 1 km at the hot spot would have facilitated outward flow to the dikes. Thermal subsidence followed as the hot spot swell progressed toward its present position at Yellowstone, and waning, mainly basaltic volcanism continued in its track along the eastern Snake River Plain.

There is direct evidence from other areas that dikes can propagate great distances from hot-spot sources. Maps of Precambrian diabase dikes of the Canadian shield (Fahrig and West, 1986) show dikes extending hundreds of kilometers. Dikes radiating from the Mackenzie hot spot (1220 Ma) in northwestern Canada curve into the regional stress field and extend southeastward for 1,500 km. Rubin and Pollard (1987) analyzed active blade-like propagation of dikes extending for tens of kilometers in Iceland and Hawaii.

Thompson and Gibson (1991) have also interpreted the Columbia River basalts and the emergence of the Yellowstone hot spot as linked parts of a fundamental process associated with a hot mantle plume penetrating the continental lithosphere. They attribute the larger eruptive volume to the north as localized by previously rifted and thinned lithosphere evidenced by the underlying Eocene Pasco basin.

## CONCLUSIONS

The northern Nevada rift, as defined by an alignment of basaltic dikes and associated middle Miocene lava flows prominently expressed in aeromagnetic maps, can be traced magnetically for at least 500 km southward from the Oregon border to southern Nevada (Zoback and Thompson, 1978; McKee and Noble, 1986; Blakely and Jachens, 1991). The consistent N20°–25°W trend of the magnetic anomaly, of the exposed basaltic feeder dike swarms, and of the structural troughs that were filled by basaltic flows indicates an extensional origin for the northern Nevada rift. The consistent trend of all these features indicates that the rift did not exploit a pre-existing feature but instead responded to the prevailing least principal stress at the time of formation, horizontal and oriented N 65°–70° E (Zoback and Thompson, 1978; Christiansen and McKee, 1978). New isotopic age determinations indicate that this rifting event occurred between ~17 and 14 Ma, and possibly over an even shorter interval. Both the rift and dikes within it have the same north-northwest trend as feeder dikes of the Columbia Plateau flood basalts, the bulk of which erupted ~16–15 Ma, the same general time interval as basalt eruptions of the northern Nevada rift. On the basis of similar age, trend, and chemistry, the voluminous Columbia Plateau flood basalts and the northern Nevada rift basalts are considered to be related and to represent two end members (both spatially and stylistically) of an enormous lithospheric "rift" that propagated north-northwest and south-southeast of the initial point of breaching of the North American lithosphere by the Yellowstone hot spot, at the 16 Ma silicic McDermitt volcanic center located at the north end of the northern Nevada rift. Differences in silica and alkali content as well as $^{87}$Sr/$^{86}$Sr of basaltic rocks in the northern and southern parts of the rift may reflect different compositions of the lower crust through which the magma rose. The higher $^{87}$Sr/$^{86}$Sr andesitic to trachyandesitic basalts from northern Nevada may have been derived partly from an Early Proterozoic continental lithosphere; the lower-silica tholeiitic basalts from Washington and Oregon with lower $^{87}$Sr/$^{86}$Sr may have come through a Late Proterozoic oceanic lithosphere. Both the overall trend of this rift as well as the parallelism of the individual dike zones within it indicate a regional middle Miocene least principal stress direction of east-northeast–west-southwest, which is consistent with the stress direction for that time inferred in other parts of the Basin and Range province and Rio Grande rift (for example, Zoback and others, 1981).

## ACKNOWLEDGMENTS

We are indebted to John Bartley, Myron Best, John Geissman, Sherman Grommé, Bob Jachens, and Tony Lowry for careful reviews that greatly improved the paper.

## *NOTE ADDED IN PROOF:*

Ongoing paleomagnetic investigations along the northern Nevada rift (Geissman and others, 1993), yield preliminary data that indicate that the Roberts Mountains have not sustained a significant post-Miocene counterclockwise vertical-axis rotation.

## REFERENCES CITED

Allmendinger, R. W., Hauge, T. A., Hauser, E. C., Potter, C. J., Klemperer, S. L., Nelson, K. D., Knuepfer, P., and Oliver, J., 1987, Overview of the COCORP 40°N Transect, western United States: The fabric of an orogenic belt: Geological Society of America Bulletin, v. 98, p. 308–319.

Anderson, R. E., and Ekren, E. B., 1977, Late Cenozoic fault patterns and stress fields in the Great Basin and westward displacement of the Sierra Nevada Block—Comment: Geology, v. 5, p. 388–389.

Armstrong, R. L., 1970, Geochronology of Tertiary igneous rocks, eastern Basin and Range province, western Utah, eastern Nevada, and vicinity, U.S.A.: Geochimica et Cosmochimica Acta, v. 34, p. 203–232.

Armstrong, R. L., Leeman, W. P., and Malde, H. E., 1975, K-Ar dating Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho: American Journal of Science, v. 275, p. 225–251.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3535.

Atwater, T., 1989, Plate tectonic history of the northeast Pacific and western North America, *in* Winterer, E. L., Hussong, D. M., and Decker, R. W., eds., The eastern Pacific Ocean and Hawaii: The geology of North America, Volume N: Boulder, Colorado, Geological Society of America, p. 21–72.

Baksi, A. K., 1988, Estimation of lava extrusion and magma production rates for two flood basalt provinces: Journal of Geophysical Research, v. 93, p. 11,809–11,815.

Blakely, R. J., 1988, Curie temperature isotherm analysis and tectonic implications of aeromagnetic data from Nevada: Journal of Geophysical Research, v. 93, p. 11,817–11,832.

Blakely, R. J., and Jachens, R. C., 1991, Regional study of mineral resources in Nevada: Insights from three-dimensional analysis of gravity and magnetic anomalies: Geological Society of America Bulletin, v. 103, p. 795–803.

Blakely, R. J., Jachens, R. C., and McKee, E. H., 1989, The northern Nevada rift: A 500-km long zone that resisted subsequent deformation [abs.]: Eos (American Geophysical Union Transactions), v. 70, p. 1336.

Carlson, R. W., and Hart, W. K., 1987, Crustal genesis on the Oregon plateau: Journal of Geophysical Research, v. 92, p. 6191–6206.

Catchings, R. D., 1992, A relation among geology, tectonics, and velocity structure, western to central Nevada Basin and Range: Geological Society of America Bulletin, v. 104, p. 1178–1192.

Christiansen, R. L., and McKee, E. H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane regions, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 283–311.

Duncan, R. A., and Richards, M. A., 1991, Hotspots, mantle plumes, flood basalts, and true polar wander: Reviews of Geophysics, v. 29, p. 31–50.

Fahrig, W. F., and West, T. D., 1986, Diabase dyke swarms of the Canadian Shield: Geologic Survey of Canada Map 1627A.

Geissman, J. W., Acton, G. D., and Schneider, M., 1993, Revisional strain histories: an analysis of new paleomagnetic data from Miocene dikes in the Northern Nevada rift [abs.]: Eos (American Geophysical Union Transactions), v. 74, in press.

Gilluly, J., and Gates, O., 1965, Tectonic and igneous geology of the northern Shoshone Range, Nevada: U.S. Geological Survey Professional Paper 465, 153 p.

Gilluly, J., and Masursky, H., 1965, Geology of the Cortez quadrangle, Nevada, with a section on gravity and aeromagnetic surveys by D. R. Mabey: U.S. Geological Survey Bulletin 1175, 117 p.

Grommé, S. H., McKee, E. H., and Blake, M. C., Jr., 1972, Paleomagnetic correlations and potassium-argon dating of middle Tertiary ash-flow sheets in the eastern Great Basin, Nevada and Utah: Geological Society of America Bulletin, v. 83, p. 1619–1638.

Henry, C. D., and Price, J. G., 1986, Early Basin and Range development in Trans-Pecos Texas and adjacent Chihuahua: magmatism and orientation, timing and style of extension: Journal of Geophysical Research, v. 91, p. 6213–6224.

Hildenbrand, T. G., and Kucks, R. P., 1988, Total-intensity magnetic anomaly map of Nevada: Nevada Bureau of Mines and Geology Map 93A, scale 1:750,000.

Holbrook, W. S., Catchings, R. D., and Jarchow, C. M., 1991, Origin of deep crustal reflections: Implications of coincident seismic refraction and reflection data in Nevada: Geology, v. 19, p. 175–179.

Hooper, P. R., 1988, The Columbia River Basalt, *in* Macdougall, J. D., ed., Continental flood basalts: Dordrecht, The Netherlands, Kluwer Academic Press, p. 1–33.

Jachens, R. C., and Moring, B. C., 1990, Maps of thickness of Cenozoic deposits and the isostatic residual gravity over basement for Nevada: U.S. Geological Survey Open-File Report 90-404, 2 sheets, scale 1:1,000,000.

John, D. A., Stewart, J. H., Kilbourn, J. E., Silberling, N. J., and Rowan, L. C., 1993, Geology and mineral resources of the Reno 1° × 2° quadrangle, Nevada and California: U.S. Geological Survey Bulletin 2019, 65 p.

Le Maitre, R. W., 1984, A proposal by the IUGS Subcommission on the systematics of igneous rocks for a chemical classification of volcanic rocks based on the total alkali silica (TAS) diagram: Australian Journal of Earth Sciences, v. 31, p. 243–255.

Li, Y., Geissman, J. W., Nur, A., Ron, H., and Huang, Q., 1990, Paleomagnetic evidence for counterclockwise block rotation in the north Nevada rift: Geology, v. 18, p. 79–82.

Lipman, P. W., 1981, Volcano-tectonic setting of Tertiary ore deposits, southern Rocky Mountains: Arizona Geological Society Digest, v. 14, p. 199–213.

Mabey, D. R., 1965, Gravity and aeromagnetic surveys, *in* Gilluly, J., and Masursky, H., Geology of the Cortez quadrangle, Nevada: U.S. Geological Survey Bulletin 1175, p. 105–111.

Mabey, D. R., 1966, Regional gravity and magnetic anomalies in part of Eureka County, Nevada, *in* Hansen, D. A., Heinrichs, W. E., Jr., Holmer, R. C., MacDougall, R. E., Rogers, G. R., Sumner, J. S., and Ward, S. H., eds., Mining geophysics, Volume 1: Tulsa, Oklahoma, Society of Exploration Geophysicists, p. 77–83.

MacDonald, W. D., Palmer, H. C., and Hayatsu, A., 1992, Perspectives on interpretation of paleomagnetic results from block-faulted regions: Roberts Mountains, Nevada: Eos (American Geophysical Union Transactions), v. 73, p. 146.

McKee, E. H., 1986, Geologic map of the Roberts Wilderness Study Area, Eureka County, Nevada: U.S. Geological Survey Miscellaneous Field Studies Map MF-1844, scale 1:48,000.

McKee, E. H., and Blakeley, R. J., 1990, Tectonic significance of linear, north-trending anomalies in north-central Nevada, *in* Geology and ore deposits of the Great Basin, *sponsored by* Geological Society of Nevada and U.S. Geological Survey, Program with Abstracts, p. 49.

McKee, E. H., and Mark, R. K., 1971, Strontium isotopic composition of two basalts representative of the southern Snake River volcanic province, *in* Geological Survey Research 1971: U.S. Geological Survey Professional Paper 750-B, p. B92–B95.

McKee, E. H., and Noble, D. C., 1986, Tectonic and magmatic development of the Great Basin of western United States during late Cenozoic time: Modern Geology, v. 10, p. 39–49.

McKee, E. H., and Silberman, M. L., 1970, Geochronology of Tertiary igneous rocks in central Nevada: Geological Society of America Bulletin, v. 81, p. 2317–2328.

McKee, E. H., Swanson, D. A., and Wright, T. L., 1977, Duration and volume of Columbia River Basalt volcanics, Washington, Oregon and Idaho: Geological Society of America Abstracts with Programs, no. 9, p. 463.

Morgan, W. J., 1972, Plate motions and deep mantle convection: Geological Society of America Memoir 132, p. 7–22.

Muffler, L.J.P., 1964, Geology of the Frenchie Creek Quadrangle north-central Nevada: U.S. Geological Survey Bulletin 1179, 99 p.

Murphy, M. A., McKee, E. H., Winterer, E. L., Matti, J. C., and Dunham, J. B., 1978, Preliminary geologic map of the Roberts Creek Mountain quadrangle, Nevada: U.S. Geological Survey Open-File Map 78-376, scale 1:31,250.

Philbin, F. W., Meuschke, J. L., and McCaslin, W. E., 1963, Aeromagnetic map of the Roberts Mountains, central Nevada: U.S. Geological Survey Open-File Map, March 7, 1963, scale 1:25,000.

Pierce, K. L., and Morgan, L. A., 1992, The track of the Yellowstone hot spot: Volcanism, faulting, and uplift: Geological Society of America Memoir 179, p. 1–53.

Potter, C. J., Liu, C.-S., Huang, J., Zheng, L., Hauge, T. A., Hauser, E. C., Allmendinger, R. W., Oliver, J. E., Kaufman, S., and Brown, L., 1987, Crustal structure of north-central Nevada: Results from COCORP deep seismic profiling: Geological Society of America Bulletin, v. 98, p. 330–337.

Rehrig, W. A., and Heidrick, T. L., 1976, Regional tectonic stress during the Laramide and late Tertiary intrusive periods, Basin and Range province, Arizona: Arizona Geological Society Digest, v. 10, p. 205–228.

Roberts, R. J., 1966, Metallogenic provinces and mineral belts in Nevada, *in* Papers presented at the AIME Pacific Southwest mineral industry conference, Sparks, Nevada, May 5–7, 1965, Part A, General session on exploration and mine development in Nevada: Nevada Bureau of Mines Report 13, p. 47–72.

Robinson, E. S., 1970, Relation between geological structure and aeromagnetic anomalies in central Nevada: Geological Society of America Bulletin, v. 81, p. 2045–2060.

Rodgers, D. W., Hackett, W. R., and Ore, H. T., 1990, Extension of the Yellowstone plateau, eastern Snake River Plain, and Owyhee plateau: Geology, v. 18, p. 1138–1141.

Rubin, A. M., and Pollard, D. D., 1987, Origins of blade-like dikes in volcanic rift zones, *in* Decker, R. W., Wright, T. L., and Stauffer, P. H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, p. 1449–1470.

Rytuba, J. J., and McKee, E. H., 1984, Peralkaline ash-flow tuffs and calderas of the McDermitt volcanic field, southeast Oregon and north central Nevada: Journal of Geophysical Research, v. 89, p. 8616–8628.

Simpson, R. W., Jachens, R. C., Blakely, R. J., and Saltus, R. W., 1986, A new isostatic residual gravity map of the conterminous United States with a discussion on the significance of isostatic residual anomalies: Journal of Geophysical Research, v. 91, p. 8348–8372.

Sleep, N. H., 1992, Hotspot volcanism and mantle plumes: Annual Reviews of Earth and Planetary Science, v. 20, p. 19–43.

Stewart, J. H., 1978, Basin-range structure in western North America: A review: Geological Society of America Memoir 152, p. 1–31.

Stewart, J. H., and McKee, E. H., 1977, Geology and mineral deposits of Lander County, Nevada, with a section on mineral deposits by Harold K. Stager: Nevada Bureau of Mines and Geology Bulletin 88, 106 p.

Stewart, J. H., Walker, G. W., and Kleinhampl, F. J., 1975, Oregon-Nevada lineament: Geology, v. 3, p. 265–268.

Stickney, M. C., and Bartholomew, M. J., 1987, Seismicity and late Quaternary faulting of the northern Basin and Range province, Montana and Idaho: Bulletin of the Seismological Society of America, v. 77, p. 1602–1625.

Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula and Pacific plates: Tectonics, v. 7, p. 1339–1384.

Swanson, D. A., Wright, T. L., Hooper, P. R., and Bentley, R. D., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, p. G1–G59.

Thompson, R. N., and Gibson, S. A., 1991, Subcontinental mantle plumes, hotspots, and pre-existing thinspots: Geological Society of London Journal, v. 148, p. 973–977.

Wallace, A. R., McKee, E. H., Zoback, M., and Zimmerman, R. A., 1990, New ages for volcanic rocks, western Elko County, Nevada: Isochron/West, no. 55, p. 3–6.

Wells, J. D., Elliott, J. E., and Obradovich, J. D., 1971, Age of the igneous rocks associated with ore deposits, Cortez-Buckhorn area, Nevada: U.S. Geological Survey Professional Paper 750-C, p. C127–C135.

Winterer, E. L., 1968, Tectonic erosion in the Roberts Mountains, Nevada: Journal of Geology, v. 76, p. 347–357.

Zoback, M. L., 1978, A detailed study of late Cenozoic deformation in the northern Basin and Range [Ph.D. thesis]: Stanford, California, Stanford University, 247 p.

Zoback, M. L., 1989, State of stress and modern deformation of the northern Basin and Range province: Journal of Geophysical Research, v. 94, p. 7105–7128.

Zoback, M. L., and Thompson, G. A., 1978, Basin and Range rifting in northern Nevada: Clues from a mid-Miocene rift and its subsequent offsets: Geology, v. 6, p. 111–116.

Zoback, M. L., and Zoback, M. D., 1980, Faulting patterns in north-central Nevada and strength of the crust: Journal of Geophysical Research, v. 85, p. 275–284.

Zoback, M. L., Anderson, R. E., and Thompson, G. A., 1981, Cenozoic evolution of the state of stress and style of tectonism in the western United States: Philosophical Transactions of the Royal Society of London, ser. A, v. 300, p. 407–434.

MANUSCRIPT RECEIVED BY THE SOCIETY FEBRUARY 8, 1993
REVISED MANUSCRIPT RECEIVED JUNE 28, 1993
MANUSCRIPT ACCEPTED JULY 8, 1993

Printed in U.S.A.