# New Perspectives on the Geology and Origin of the Northern Nevada Rift

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## ABSTRACT

The northern Nevada rift is a term applied to a prominent, north-northwest-trending aeromagnetic anomaly that extends about 500 km from near the Nevada-Oregon border to southeast Nevada. Its surface trace is marked in places by an alignment of middle Miocene volcanic and hypabyssal rocks and epithermal gold-silver and mercury deposits that formed during west-southwest-east-northeast directed extension. On regional aeromagnetic maps, the rift appears as a narrow positive anomaly that probably reflects the presence of abundant intrusive mafic rocks emplaced mostly between about 16.5 and 15 Ma. The rift may correspond in part to a pre-Cenozoic deep crustal structure that was reactivated during the late Cenozoic. Thermal bulging and shallow intrusion of mafic magmas related to the Yellowstone hot spot near McDermitt led to the inception of the rift at about 16.5 Ma and rapid propagation of the rift to the south. The northern Nevada rift evolved in a manner similar to the Mid-Continent rift of North America and dissimilar to many intracontinental rifts, such as the long-lived Rio Grande rift. However, duration of rifting along the northern Nevada rift was short (mostly between about 16.5 to 15 Ma), the total amount of extension of the crust along the rift was generally less than a few kilometers, and the amount of subsidence was generally less than 1 kilometer. Interbedded sedimentary deposits generally are uncommon along the rift, and the total volume of igneous rocks erupted along the rift also was small.

Three distinct groups of middle Miocene igneous rocks are associated with the rift: an early group of mafic (basalt to andesite) compositions and later groups of trachydacite and rhyolite compositions. The early mafic magmas probably were related to the Yellowstone hot spot and were derived from upper mantle magmas. The more silicic compositions probably represent lower crustal melts that may have formed as a result of hot-spot-related deep crustal heating. All magmas had low oxygen fugacities and low water contents.

## INTRODUCTION

The northern Nevada rift coincides with a prominent north-northwest-trending aeromagnetic anomaly in north-central Nevada (Figs. 1 and 2). The surface expression of the anomaly is marked in places by an alignment of middle Miocene volcanic and hypabyssal rocks and epithermal gold-silver and mercury deposits that formed during west-southwest–east-northeast extension (Zoback and Thompson, 1978; Zoback et al., 1994; John and Wallace, 2000). Based upon previous and current studies, the aeromagnetic anomaly formed mostly between about 16.5 and 15 Ma (see geochronology section below; Zoback et al., 1994). It extends approximately 500 km in a south-southeast direction from near the Nevada-Oregon border to southeast Nevada (Blakely and Jachens, 1991; Figs. 1 and 2). It is readily visible on regional aeromagnetic maps as a fairly narrow positive anomaly for about 250 km (Mabey, 1966; Robinson, 1970; Zoback and Thompson, 1978; Blakely and Jachens, 1991).

The term "northern Nevada rift" has been applied to a linear array that includes a pronounced aeromagnetic anomaly, north-northwest-striking mafic dikes and high-angle normal faults, volcanic flow units related to the dikes, and epithermal, volcanic-hosted mineral deposits (Fig. 2; Zoback and Thompson, 1978; Zoback et al., 1994; Wallace and John, 1998). To date, however, comprehensive evidence for the formation of the northern Nevada rift as an actual rift has not been presented. Our studies focus on the central part of the rift between the Malpais Rim and Midas (Fig. 2). In this paper, we define the northern Nevada rift in this area as a 5- to 30-km wide, north-northwest-trending zone broadening to the north that corresponds to the aeromagnetic anomaly, to mafic dikes and high-angle normal faults that parallel the anomaly, and to middle Miocene volcanic flow units that overlie the anomaly (Fig. 2). This definition generally corresponds to the central segment of the northern Nevada rift as described by Zoback et al. (1994). Geologic mapping, geochemical and geophysical studies, and radiometric dating were undertaken to improve the understanding of this zone and the associated mineralization.

In this paper, we examine features along the northern Nevada rift, as defined on Figure 2, that characterize intracontinental rifts. These features include: the stratigraphy of rocks along this zone; the relationship of sedimentation; the structure of this zone, including both its structural margins and internal grabens; the geophysical expression of this zone; the nature of magmatism related to and associated with this zone; the age of the zone and rocks along it; and the origin of this zone and possible precursors to it. In the final section, we compare the northern Nevada rift to intracontinental rifts of similar to disparate nature.

In the northern part of the rift, rift-related processes extended well beyond the axis of the aeromagnetic anomaly. The Midas and Ivanhoe districts are east of the anomaly, yet

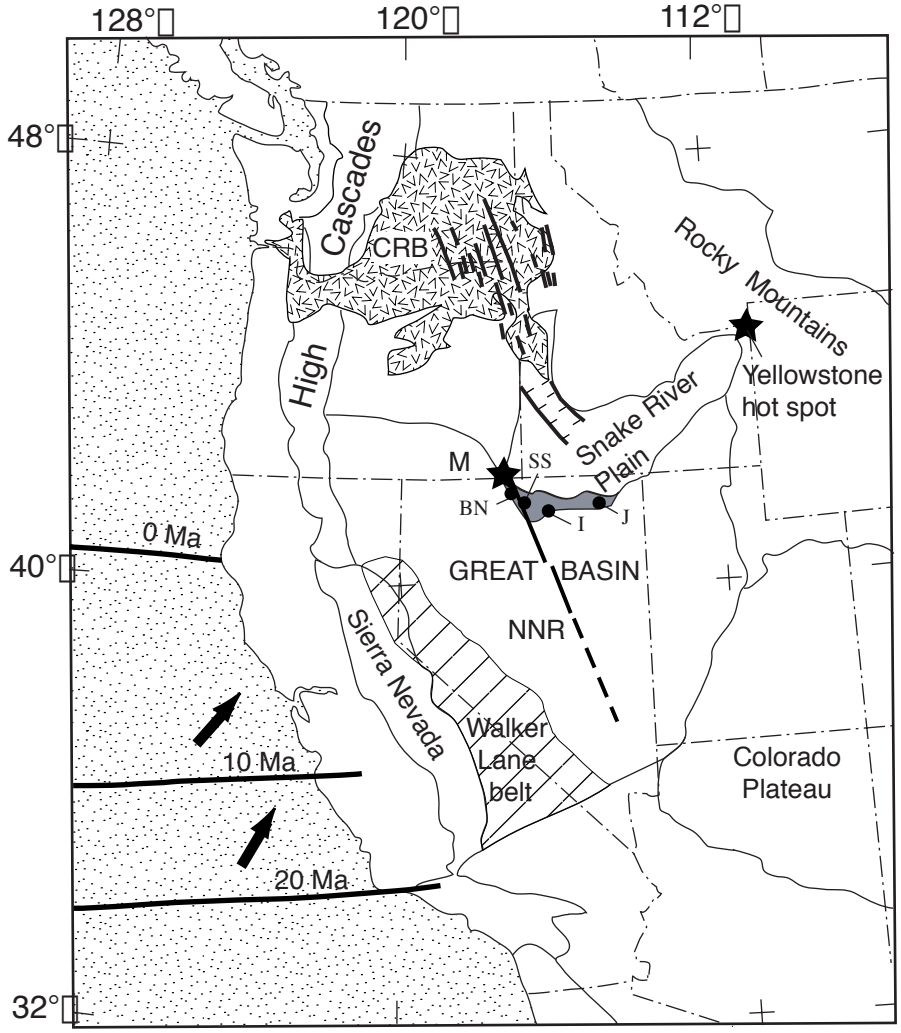


**FIGURE 1. Index map of the western United States showing middle Miocene igneous and tectonic features. Heavy line indicates the northern Nevada rift. The heavy star at the north end of rift is the McDermitt caldera (M) and the approximate location of the Yellowstone hot spot at 16.5 Ma. Western graben of the Snake River Plain is shown by hachured lines. Columbia River Basalt Group (CRB) shown by vee pattern; feeder dikes in Oregon and Washington indicated by heavy lines. Shaded area represents middle Miocene rhyolites that are along the southern margin of the Snake River Plain. East-west lines along Pacific Coast show approximate southern end of the Farallon plate that was being subducted beneath North America at the different ages indicated. Modified from Zoback and others (1994, Figure 1). Walker Lane Belt from Stewart (1988). BN, Buckskin-National; I, Ivanhoe; J, Jarbidge; SS, Snowstorm Mountains.**

igneous and structural characteristics of those two districts closely match those in areas astride the axis of the anomaly (Zoback and Thompson, 1978; Wallace, 1993; Zoback et al., 1994; Wallace and John, 1998). The Midas district contains the only known or exposed middle Miocene (approx. 16 to 15 Ma) mafic intrusive rocks in the Snowstorm Mountains, rift age volcanic rocks pinch out just east of the district, and the middle Miocene structural fabric is identical to that seen closer to the magnetic anomaly. The Ivanhoe district contains igneous rocks that have the same compositions and are the same age as those exposed along the anomaly, and sources for these rocks are less than 10 km to the west. The middle Miocene structural fabric at Ivanhoe indicates that the area was influenced by the west-southwest–east-northeast extension that was prevalent at the time of formation of the aeromagnetic anomaly.

## HISTORY OF IDEAS ABOUT THE NORTHERN NEVADA RIFT

Zoback and Thompson (1978) used the term northern Nevada rift for a pronounced positive linear aeromagnetic anomaly that extends south-southeastward from the Oregon-Nevada border into east-central Nevada. They suggested that the rift was the southern part of a 700-km-long north-north-

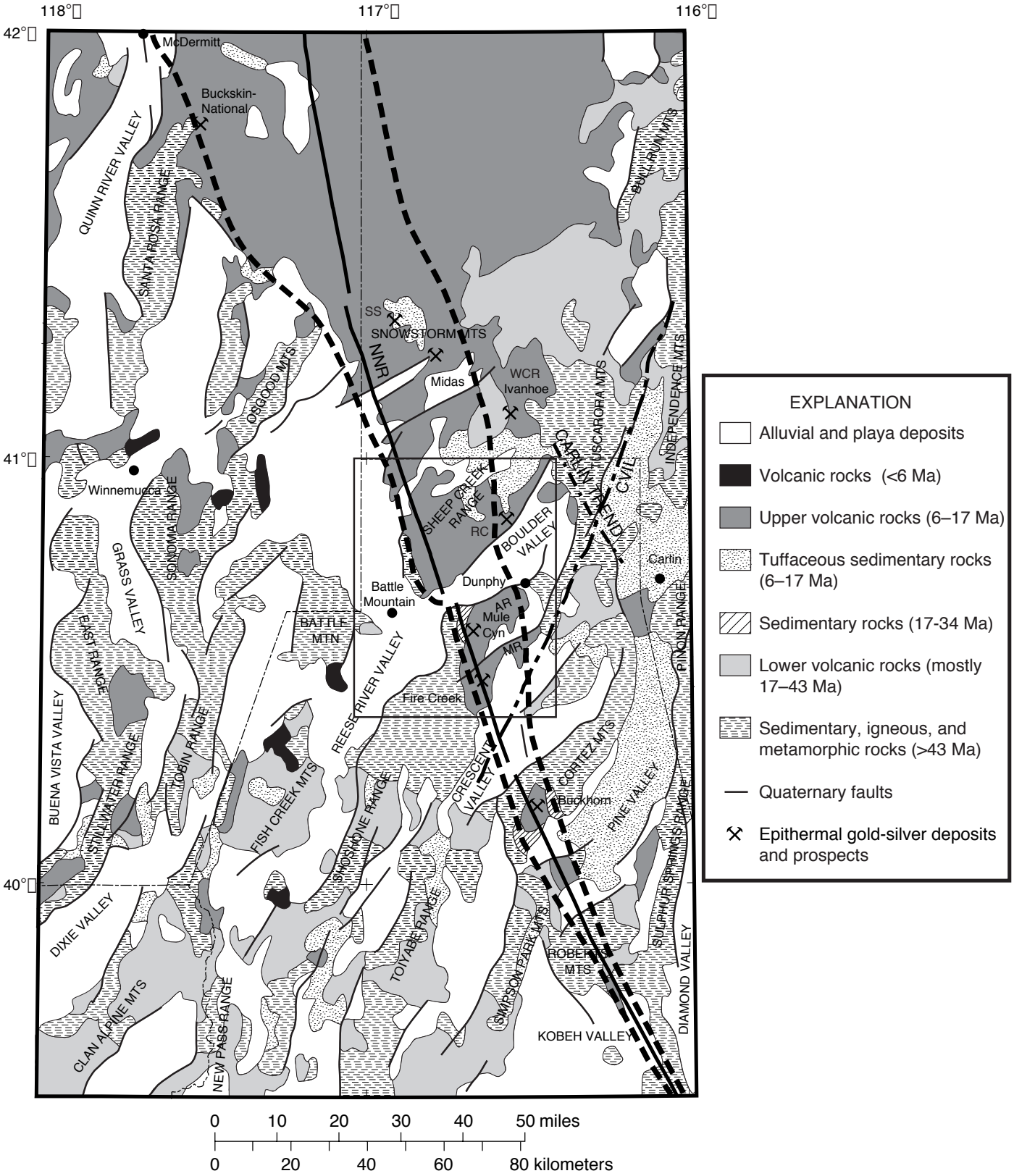


**FIGURE 2. Location map showing principal geologic, geographic, and physiographic features in north-central Nevada. Heavy dashed line shows outline of the northern Nevada rift as defined in this paper. Heavy line traces approximate center of the aeromagnetic anomaly. Box shows outline of Figure 3. AR, Argenta Rim; CVIL, Crescent Valley-Independence lineament; MR, Malpais Rim; NNR, northern Nevada rift; WCR, Willow Creek Reservoir. Geology modified from Stewart and Carlson (1976).**

west-trending feature which included feeder dikes for the Columbia River basalts in southeastern Washington and suggested that it was related to impingement of the Yellowstone hot spot on the upper crust near the Oregon-Nevada border. Work by Blakely and Jachens (1991) extended the aeromagnetic anomaly farther to the southeast and showed that it had a total length of about 500 km between the Oregon-Nevada border and southeast Nevada. Parts or all of the magnetic anomaly were recognized by earlier workers (Roberts, 1966; Mabey, 1966; Robinson, 1970), who applied the anomaly to interpretations of regional tectonics and mineral deposits. Stewart et al. (1975) included the rift in their "Oregon-Nevada lineament," a structural zone that extends northwestward from the northern end of the rift into eastern Oregon. Theodore et al. (1998) postulated that the rift may have had a structural origin as a conjugate right-lateral shear zone related to south-directed Late Paleozoic compression. Tosdal et al. (2000) note that part of the rift corresponds to major breaks in radiogenic isotopic and geophysical data that they interpret to represent deep crustal breaks formed during Late Proterozoic rifting of North America. The restriction of mafic volcanism, dikes, and the aeromagnetic anomaly to a narrow zone also indicate that the rift may have formed along preexisting structural breaks that were reactivated during the middle Miocene.

At the surface, mafic to intermediate composition dike swarms and related lava flows coincide with the axis of the central part of the magnetic anomaly (Robinson, 1970; Zoback and Thompson, 1978; McKee and Blakely, 1990; Zoback et al., 1994). High-angle normal faults parallel the dikes, and some of the dikes were emplaced along similar faults, notably in the Mule Canyon area (John et al., 1999; John and Wallace, 2000). The magmas were intruded largely between about 16.5 and 15 Ma (McKee and Blakely, 1990; Zoback et al., 1994; John et al., 1999; see below), and the faulting was both contemporaneous with and post-dated magmatic activity (Wallace, 1993; Wallace and John, 1998). Modeling of magnetic data by Mabey (1966), Robinson (1970), and Zoback et al. (1994) indicates that the dikes are the surface expression of a narrow, linear zone of magnetic rocks that extends vertically to a depth of about 15 km. Using both the dikes and the overall structural and stratigraphic setting of the north end of the Roberts Mountains as evidence, McKee and Blakely (1990) suggested that the amount of extension related to this "rift" was a total of a few kilometers or less and equal to the combined width of the dikes.

The magnetic anomaly and its subsequent offsets reflect regional extension directions in the Neogene. The age and orientation of the magnetic anomaly and dike swarms led Zoback and Thompson (1978) to conclude that the regional extension direction in the middle Miocene was west-southwest–east-northeast, perpendicular to the axis of the rift (the present extension direction in central Nevada is west-northwest–east-southeast).

Hydrothermal activity produced hot spring and epithermal precious metal deposits along the axis of the rift during igneous activity and faulting. These include, from south to north, Buckhorn, Fire Creek, Mule Canyon, Ivanhoe, Midas, Buckskin-National, and McDermitt (Fig. 2). These deposits and their volcano-tectonic setting are summarized in John et al. (1999), and several are described more fully in John and Wallace (2000).

Numerous geologic maps provide data on the nature and distribution of rock types and structures along the magnetic anomaly. These include maps of the Roberts Mountains (Murphy et al., 1978; McKee, 1986; McKee and Conrad, 1998), the northern Simpson Park Mountains (McKee and Conrad, 1994), Sulphur Springs Range (Carlisle and Nelson, 1990), Cortez Mountains (Gilluly and Masursky, 1965; Muffler, 1964), the northern Shoshone Range (Gilluly and Gates, 1965), the Malpais Rim (Struhsacker, 1980), the southern Sheep Creek Range (John and Wrucke, 2000; House et al., 1998; Ramelli et al., 1999), the Snowstorm Mountains (Wallace, 1993), and the Buckskin/National area (Vikre, 1985). Mapping currently (2000) is in progress in the Mule Canyon area, northern Shoshone Range (D.A. John and others) and the Ivanhoe district (A.R. Wallace).

## STRUCTURE AND LITHOLOGY OF THE CENTRAL PART NORTHERN NEVADA RIFT (ROBERTS MOUNTAINS TO THE SNOWSTORM MOUNTAINS)

### GENERAL CHARACTERISTICS OF MIDDLE MIOCENE ROCKS AND STRUCTURAL MARGINS OF THE CENTRAL PART OF THE NORTHERN NEVADA RIFT

The types of rocks associated with the northern Nevada rift vary significantly from south to north and consist of sequences of mafic to felsic volcanic and hypabyssal intrusive rocks locally underlain by and interbedded with clastic sedimentary rocks. The margins of the rift are indistinct, and the rift is not bounded by prominent faults with large displacement. Overall, few faults have been mapped along the margins of most parts of the rift. In general, major rift-margin normal faults or other evidence of significant extension are not present along the rift. The following sections provide brief descriptions of the types of rocks deposited within the rift and the nature of the margins of the rift from the Roberts Mountains north to the Snowstorm Mountains (Fig. 2).

*Roberts Mountains*—A mafic dike swarm about 2 to 6 km wide and 10 km long marks the northern Nevada rift in the northern Roberts Mountains (Murphy et al., 1978; McKee, 1986; Zoback et al., 1994). Individual dikes are generally 10-25 m wide (but locally reach 150 m wide) and are continuous along strike for up to 1.5 km. Thin sequences of middle Miocene basalt flows are present locally south of the dike swarm. North-northwest-striking, high-angle faults that are subparallel to the trend of the rift bound the Roberts Mountains and the dike swarm. However, they do not appear to control or have any genetic relationship to the dikes.

*Cortez Mountains*—On the south side of the Cortez Mountains, the northern Nevada rift is a 15-km-wide basin filled with gently dipping Tertiary gravels that contain clasts of ca. 34 Ma Caetano Tuff. Gravels on both sides dip gently into the basin. The gravels are >400 m thick on the west side of the basin and about 230 m thick on the east side (Gilluly and Masursky, 1965). The gravels are overlain by as many as eight flows of basaltic andesite that have a total thickness of as much as 110 m (Gilluly and Masursky, 1965). The flows yielded K-Ar dates of 16.7±0.9 and 14.8±1.5 Ma (Armstrong, 1970; Wells et al., 1971). The lava flows thin to the southwest and northeast (Gilluly and Masursky, 1965). The west side of the basin appears to be a north-northwest-striking high-angle fault that bounds the gravel deposits and drops them against Paleozoic rocks (D.A. John, unpub. mapping, 1999). No faults bounding the gravels have been mapped on the east side of the basin. Monroe et al. (1988) note that the basaltic andesite flows were deposited over a physiography of low-relief, north-northwest elongated, fault-bounded grabens that resulted in thinning of the flows over paleohighs. On the north side of the range, a north-northwest-trending mafic dike swarm is present (Gilluly and Gates, 1965; Gilluly and Masursky, 1965). Individual dikes are 3 m wide to as much as 250 m where they coalesce. Dikes are as long as 5 km. The zone of dikes is as much as 6 km wide, but most dikes are within a zone about 3 km wide. The dikes strike toward the basaltic andesite flows, and in one place, they intrude the underlying gravels (Gilluly and Masursky, 1965).

*Northern Shoshone Range (south of latitude 40°30' N.)*—The northern Nevada rift here is marked by a series of middle Miocene andesite/basaltic andesite lava flows that overlie Tertiary gravel and alluvial-fan deposits. The gravels are as much as 200 m thick, overlie Paleozoic sedimentary rocks, and locally contain clasts of middle Tertiary granitic and volcanic rocks (Gilluly and Gates, 1965). The lava flows range in thickness from about 80 m in Corral Canyon, where they are covered by pediment gravels, to more than 300 m on the south side of Horse Heaven (Figs. 2 and 3; Gilluly and Gates, 1965). The lava flows are correlative with the andesite of Horse Heaven exposed farther north in the Mule Canyon area (see next section below). Locally, a thin mafic tuff unit (<1 m thick) underlies massive andesite flows. No north-northwest-striking, basin-forming faults or feeder dikes for the lava flows are found in this area.

*Mule Canyon quadrangle and Argenta and Malpais Rims, northernmost Shoshone Range*—Middle Miocene igneous rocks within the northern Nevada rift in this area consist of several thick volcanic units that locally reach 1,200 m total thickness (Struhsacker, 1980; John et al., 1999). The rocks range in composition from basalt to trachydacite (Struhsacker, 1980; John et al., 1999). A zone of mafic dikes about 3 to 5 km wide and 15 km long is present along the west side of the rift between the north end of the range (Humboldt River valley) and the south end of the Mule Canyon Mine (Fig. 3). The area where these dikes crop out generally corresponds to the aeromagnetic anomaly (see below). Thin units of interbedded air-fall tuffs and volcaniclastic sedimentary rocks are present locally in the upper part of the volcanic sequence. On the west, the middle Miocene volcanic rocks are bounded locally by a north-striking, high-angle fault that does not appear to have large displacement. Farther south, the volcanic rocks appear to lie with pronounced angular unconformity on the early Oligocene Caetano Tuff and on Paleozoic rocks. On the east side of the rift, middle Miocene volcanic rocks thin markedly (sections I, K, Fig. 4). These rocks locally overlie middle Tertiary gravel deposits and middle Miocene(?) air-fall tuffs; elsewhere, they overlie Paleozoic rocks. North-northwest-striking faults with small displacements are present locally near the east ends of both the Argenta and Malpais Rims and juxtapose middle Tertiary gravel deposits against Paleozoic rocks.

*Southern Sheep Creek Range*—Middle Miocene mafic to silicic igneous rocks unconformably overlie and intrude Paleozoic sedimentary rocks along the west side of the southern part of the Sheep Creek Range (Wallace and John, 1998; Ramelli et al., 1999; John and Wrucke, 2000). These rocks consist of five principal units that range in composition from olivine basalt to rhyolite porphyry. The present mountain range is bounded on the west by a series of late Cenozoic high-angle normal faults that locally have late Quaternary displacement (Dohrenwend and Moring, 1991). No major faults that bound the middle Miocene rocks are evident along the west side of the rift, and aeromagnetic data suggest that the range front is near the west margin of the middle Miocene volcanic field. The east margin of the rift is not exposed and is covered by slightly younger volcanic and sedimentary rocks that extend about 25 km to the northeast (Fig. 2).

*Northern Sheep Creek Range to Midas trough*—Most of the rocks in the northern part of the Sheep Creek Range are younger than about 14.9 Ma. These rocks mostly are coalescing rhyolite porphyry flow-dome complexes. Middle Miocene rocks are exposed in the northeastern part of the range at the Ivanhoe district. These units are predominantly lacustrine sedimentary rocks, with minor interbedded basaltic andesite and rhyolite flow units. The latter units thin and pinch out to the east and thicken and are concealed by domes to the west. Any north-northwest-trending structures in the northern Sheep Creek Range that formed prior to about 15 Ma were disrupted and obscured by later faulting. One north-northwest-trending, 14.92±0.05 Ma rhyolite porphyry dike in the Ivanhoe district indicates a west-southwest–east-northeast extension direction.

*Snowstorm Mountains*—Middle Miocene basaltic andesite flows and rhyolite tuffs form the lowermost part of the Miocene section in the Snowstorm Mountains. To the west, these units overlie Paleozoic rocks, and, to the east, they pinch out between Oligocene andesite flows and Miocene rhyolite flows; the base of the Miocene section is not exposed in the main part of the Snowstorm Mountains. The only known or exposed middle Miocene mafic intrusive rocks are in the Midas district in the southeastern part of the area. Extensive rhyolite flows and tuffs dated at about 14.3 and 13.0 Ma (Wallace, 1993) overlie and conceal much of the

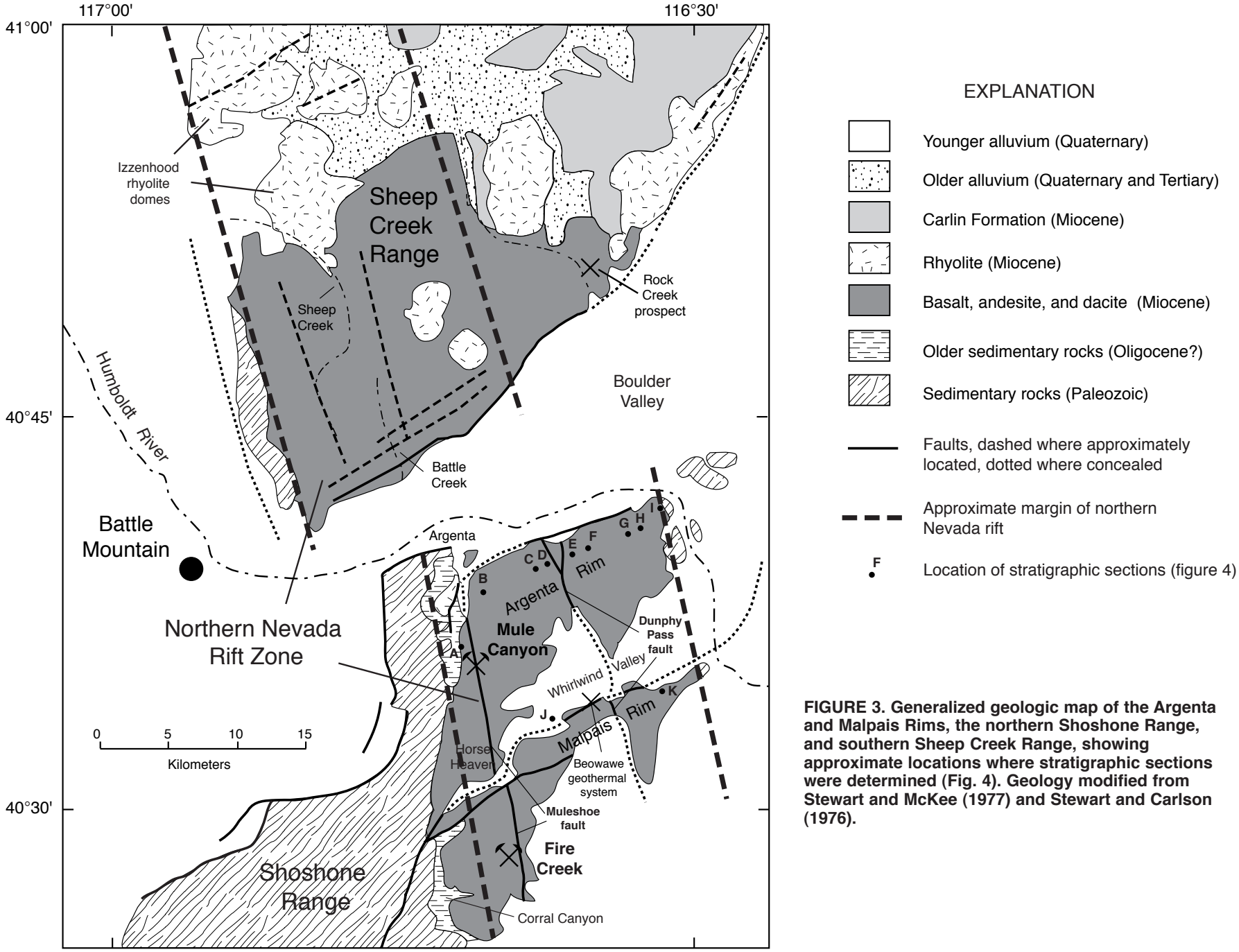


**FIGURE 3. Generalized geologic map of the Argenta and Malpais Rims, the northern Shoshone Range, and southern Sheep Creek Range, showing approximate locations where stratigraphic sections were determined (Fig. 4). Geology modified from Stewart and McKee (1977) and Stewart and Carlson (1976).**

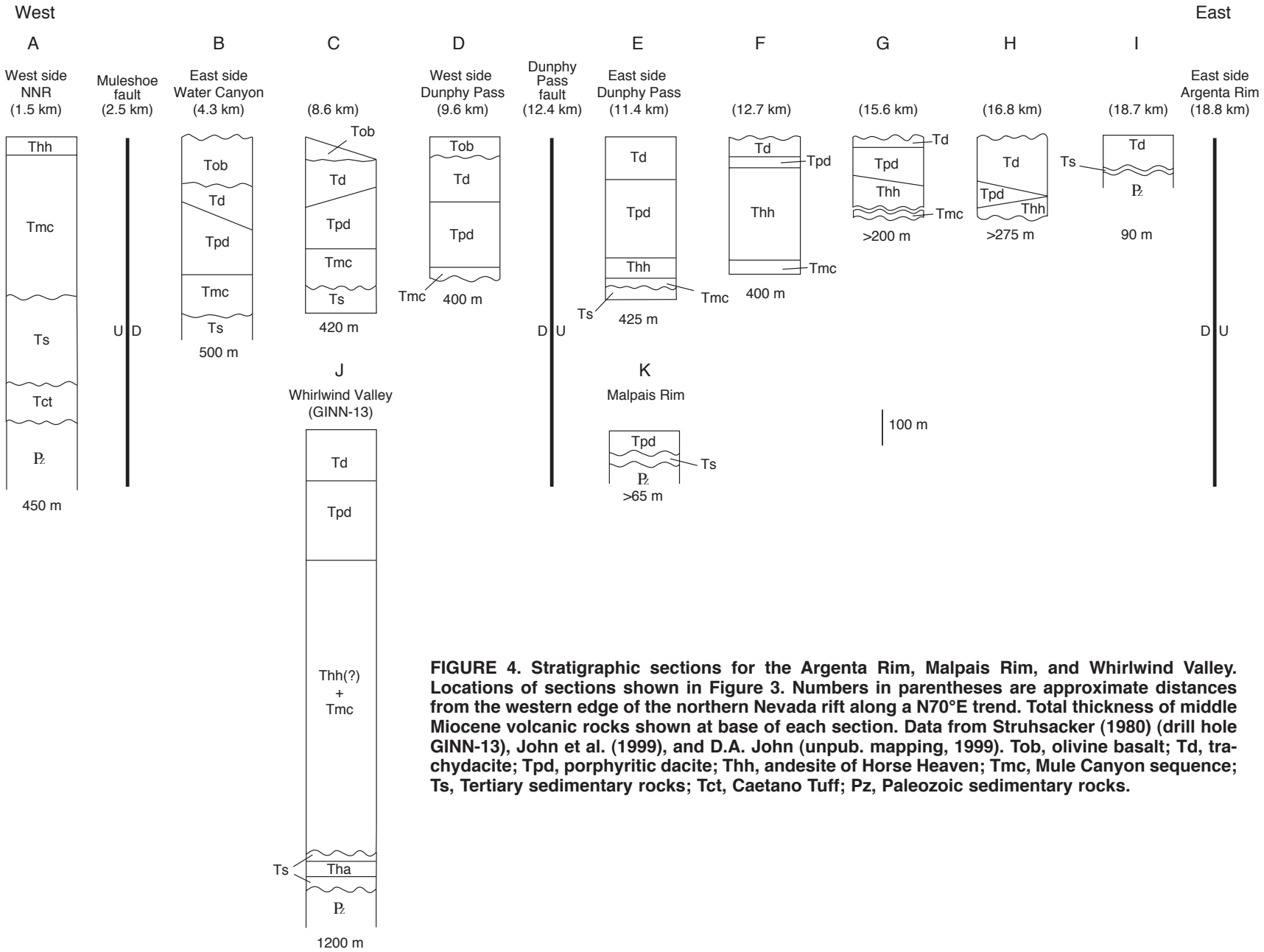


**FIGURE 4. Stratigraphic sections for the Argenta Rim, Malpais Rim, and Whirlwind Valley. Locations of sections shown in Figure 3. Numbers in parentheses are approximate distances from the western edge of the northern Nevada rift along a N70°E trend. Total thickness of middle Miocene volcanic rocks shown at base of each section. Data from Struhsacker (1980) (drill hole GINN-13), John et al. (1999), and D.A. John (unpub. mapping, 1999). Tob, olivine basalt; Td, trachydacite; Tpd, porphyritic dacite; Thh, andesite of Horse Heaven; Tmc, Mule Canyon sequence; Ts, Tertiary sedimentary rocks; Tct, Caetano Tuff; Pz, Paleozoic sedimentary rocks.**

older part of the Miocene section. North-northwest-striking faults and mafic and felsic dikes began to form before 15. 3 Ma, and fault and dikes of similar orientation continued to form until at least 13.0 Ma (Wallace, 1993).

## PRE-MIDDLE MIOCENE FAULTING AND TILTING

Regional tilt data for middle Tertiary volcanic and sedimentary rocks suggest that a zone of pre-middle Miocene tilting and extension may be present along the axis of the northern Nevada rift. In the northernmost part of the Shoshone Range and in the Willow Creek Reservoir area near Ivanhoe (Fig. 2), prominent angular unconformities separate Eocene to early Oligocene (ca. 39-34 Ma) volcanic rocks and middle Miocene volcanic and sedimentary rocks (Wallace and John, 1998). In the Mule Canyon quadrangle in the northern Shoshone Range, fine- to coarse-grained sedimentary rocks unconformably overlie the early Oligocene Caetano Tuff indicating the presence of considerable local topography and formation of a small sedimentary basin that now occupies the axis of the rift (see below; John et al., 1999). The early Oligocene rocks here dip steeply (50-80°) to the east with a north to northwest strike subparallel to the trend of the aeromagnetic anomaly. The middle Tertiary sedimentary rocks generally dip 30-40° east. In contrast, the overlying middle Miocene rocks were gently (<10-20°) tilted to the southeast by late Miocene to Quaternary faulting that formed the Argenta and Malpais Rims. In the Willow Creek Reservoir area, late Eocene tuffs dip approximately 20° more steeply than middle Miocene rocks, suggesting a pre-middle Miocene period of tilting (Wallace and John, 1998). The regional extent of this middle Tertiary unconformity is unknown, and it is only known along the northern Nevada rift is these two areas. However, the distribution of post-34 Ma, pre-middle Miocene sedimentary rocks described below also suggest that a northwest-elongated, extensional(?) basin may have been present along the axis of the magnetic anomaly between the Humboldt River and the Simpson Park Range.

## FAULTING AND INTERNAL STRUCTURE OF THE RIFT

The internal structure of the northern Nevada rift is poorly exposed in most places, due in large part to cover by younger rocks and alluvial deposits. In some other areas, structures characteristic of a rift are absent. The internal structure of the rift is well exposed only in two areas, the Argenta and Malpais Rims, which are described below. In general, north-northwest-striking high-angle faults characterize the structural fabric of the rift across the Argenta and Malpais Rims.

*Argenta and Malpais Rims*—The Argenta and Malpais Rims are northeast- to east-northeast-trending upthrown fault blocks that were formed by late Miocene to Quaternary faulting. The faulting produced gentle southeast tilting of middle Miocene rocks that are exposed within the rift (Figs. 2 and 3; Zoback, 1979; Struhsacker, 1980; Zoback et al., 1994; John et al., 1999). A series of steep north-dipping faults bound the north sides of both blocks, and nearly 1 km of topographic relief is present on the Argenta Rim. Consequently, the Argenta and Malpais Rims provide cross sections of many of the rocks that erupted along the northern Nevada rift and glimpses of the internal structure of the rift.

An approximately equant middle Miocene graben, formed by north- to northwest- and northeast-striking faults, underlies the area. The most prominent middle Miocene faults exposed in this area are north- to northwest-striking high-angle faults that divide the area into several structural blocks. The blocks are characterized by variable stratigraphy, and, along the Malpais Rim, by variable total thickness of middle Miocene volcanic rocks (Fig. 4). The Muleshoe and Dunphy Pass faults are the most important of these faults and form the west and east boundaries, respectively, of the deepest part of the graben along the Malpais Rim and in Whirlwind Valley (Fig. 3; Zoback, 1979; Struhsacker, 1980; John et al., 1999). Drilling for geothermal resources in Whirlwind Valley near Beowawe Hot Springs indicate that as much as 1,200 m of middle Miocene volcanic and sedimentary rocks fill this structural graben (Figs. 3 and 4; Zoback, 1979; Struhsacker, 1980). However, traverses across the north face of the Argenta Rim indicate that middle Miocene volcanic rock units there have a relatively constant total thickness of about 400-500 m, much less than the total thickness of the same units in Whirlwind Valley (Fig. 4). This suggests that northeast–striking faults must have cut across the central part of the rift in this area to form a box-like graben (Fig. 3). The southern bounding fault probably lies on the south side of the Malpais Rim between the south side of Horse Heaven and the Fire Creek deposit and confines the lower part of middle Miocene volcanic rocks (Mule Canyon sequence) to its north side. The northern bounding fault must lie between Whirlwind Valley and the north edge of the Argenta Rim.

In addition to the major north-northwest- and northeast-striking faults, numerous other north- to northwest- and northeast-striking high-angle faults with small amounts of displacement were active during volcanism. These faults are well exposed in the open pits at the Mule Canyon Mine (John et al., 1999; John and Wallace, 2000) and along both the Argenta and Malpais Rims (Struhsacker, 1980; D.A. John, unpub. mapping, 1999).

Abundant fine-grained basalt to andesite and sparse dacite dikes are exposed along the west side of the rift between Argenta and the south end of the Mule Canyon Mine (Fig. 3). The area where the dikes crop out corresponds generally to the aeromagnetic anomaly which is about 2-3 km wide in this area (see below). The dike swarm straddles the contact between Paleozoic and Tertiary rocks. Individual dikes range from a few meters wide to masses several hundred meters across. Dikes generally strike N5-20°W and are continuous along strike for as much as 2 km (Ramelli et al., 1999; D.A. John, unpub. mapping, 1999). The dikes generally have steep (≥70°) dips. Many dikes exposed in the open pits at the Mule Canyon Mine were emplaced along faults

that had small displacements and were active during eruption of the middle Miocene volcanic rocks. Dikes are not exposed on either the Argenta or Malpais Rims and mostly appear to be absent east of the Muleshoe fault (Fig. 3), although Struhsacker (1980) noted that diabase dikes or sills intrude the Valmy Formation in the deep drill holes in Whirlwind Valley.

*Southwestern Sheep Creek Range*—The internal structure of the southwestern part of the Sheep Creek Range is more poorly known than along the Argenta and Malpais Rims, and in general, the stratigraphy is simpler (John and Wrucke, 2000). As noted above, faults that might represent the structural margins of the rift are not recognized in this area, although aeromagnetic data suggest that the western margin of the middle Miocene rocks was near the present western edge of the range (see geophysics section below). A prominent north-northwest-striking, steeply east-dipping fault is present in Sheep Creek canyon (Fig. 3; John and Wrucke, 2000). This fault displaces the northern part of a northwest-elongated, 10 by 3 km, 15.3-Ma stock of porphyritic dacite, but it appears to end within the southern part of the stock. Apparent displacement on this fault is small and the age of movement(s) is uncertain (John and Wrucke, 2000). The pronounced north-northwest elongation of this stock may reflect emplacement along a cryptic north-northwest-striking fault. Another north- to north-northwest-striking, steeply east-dipping fault juxtaposes olivine basalt against trachydacite on the east side of Battle Creek; olivine basalt is absent farther west in the range and porphyritic dacite is absent east of the fault, suggesting that the fault may have been active during the middle Miocene volcanic activity and controlled distribution of the middle Miocene rocks similar to the Dunphy Pass and Muleshoe faults along the Argenta and Malpais Rims.

*Northern Sheep Creek Range*—The only exposures of 16-15 Ma rocks and structures in the northern Sheep Creek Range (north of Izzenhood Ranch and Antelope Creek) are in the Ivanhoe district in the northeastern part of the range about 40 km east of the aeromagnetic anomaly. Rhyolite flows and domes younger than about 15 Ma conceal the middle Miocene rocks in the north-central and northwestern parts of the range. At Ivanhoe, the middle Miocene rocks include tuffaceous lacustrine sedimentary rocks, with relatively minor interbedded basalt and rhyolite flows. The flows pinch out to the east and extend westward beneath the post-middle Miocene volcanic rocks. Numerous high-angle faults are present in the district, and stratigraphic evidence indicates that faulting did not begin until about 15 Ma. The only known dike in the district is a north-northwest-striking rhyolite porphyry dike that fed a 14.9 Ma rhyolite dome.

*Snowstorm Mountains*—Extensive 15 Ma and younger volcanic rocks obscure most of the 16-15 Ma volcanic rocks in the Snowstorm Mountains. Throughout the Snowstorm Mountains, north-northwest-striking normal faults cut the 16-15 Ma units and extend into the overlying younger volcanic rocks. Some of these faults originally may have formed during the development of the rift and were reactivated during continued west-southwest extension. None, however, have a significant amount of offset. Therefore, although the lateral limit of 16 to 15 Ma volcanic rocks can be determined, the pre-15 Ma internal structure of the Snowstorm Mountains is unknown.

## SEDIMENTARY DEPOSITS ASSOCIATED WITH THE RIFT AND WITH PRE-MIDDLE MIOCENE FAULTING

The amount and type of sedimentary rocks associated both spatially and temporally with the rift vary considerably along its length. Sedimentary rocks interbedded with or overlying middle Miocene volcanic rocks are rare from the southern Sheep Creek Range south for about two-thirds of the length of the rift, whereas they are more common to abundant in the northern Sheep Creek Range and in the Snowstorm Mountains. Most of the sedimentary rocks are fine grained and were deposited in a shallow lacustrine environment; minor gravel deposits are interbedded with these units. Post-34 Ma fanglomerate and fine-grained lacustrine deposits are present beneath the middle Miocene volcanic sequence between the Humboldt River and the Simpson Park Range, and their distribution may indicate deposition into a northwest-elongated, pre-middle Miocene basin along the axis of the rift in this area.

Middle Miocene sedimentary deposits in the Cortez Mountains and in the northern Shoshone Range are uncommon. In the Buckhorn district in the Cortez Mountains (Fig. 2), Tertiary rocks include a basal conglomerate, an overlying basaltic andesite sequence, and a cap of fine-grained lacustrine sedimentary rocks (Monroe et al., 1988; Jennings, 1991). The lacustrine rocks are exposed in a relatively restricted area in the northern part of the district, and they served as the primary host rocks at the West Sinter gold deposit (Jennings, 1991). The 25-m-thick unit includes laminated silty claystone and sandstone; fossil reeds are present in the lower part of the unit (Jennings, 1991). The conglomerate is exposed east, northwest, and southwest of the district, and drilling in the district indicates its presence beneath the basaltic andesite flows. To the south in the northern Simpson Park Range, older Tertiary conglomerates that are about 125 m thick lie on Oligocene rhyodacitic volcanic rocks and are overlain by three or four thin flows of basaltic andesite that may be correlative with flows in the southern Cortez Mountains (McKee and Conrad, 1994). To the southwest and east of the Buckhorn district, the conglomerate unit is about 400 and 230 m thick, respectively (Gilluly and Masursky, 1965), and it is about 230 m thick beneath the district (Jennings, 1991). The conglomerate contains clasts of Paleozoic rocks and of the ca. 34 Ma Caetano Tuff (Gilluly and Masursky, 1965; Jennings, 1991). Clast size increases to the west, suggesting a sediment source in that direction. Compositionally similar conglomerates are exposed 15 km to the west on the west side of the Toiyabe Range (Gilluly and Masursky, 1965). Thus, the total width of exposure is about 20 km. The conglomerate may represent a post-34 Ma

alluvial-fan deposit with no relation to a middle Miocene basin, or it may indicate fluvial and debris-flow sedimentation into a middle Miocene depression.

In the northern Shoshone Range, coarse gravel deposits that locally contain well-rounded to subangular pebbles and cobbles of late Eocene to early Oligocene volcanic and granitic rocks are present along the west side of the rift and underlie a thick sequence of middle Miocene basaltic andesite flows (Gilluly and Gates, 1965). These gravel deposits are as much as 250 m thick in Corral Canyon, and Gilluly and Gates (1965) suggested that they are stream or alluvial-fan deposits that filled an east-trending paleovalley. No sedimentary deposits are interbedded with the middle Miocene volcanic rocks.

Along the Argenta and Malpais Rims and on the west side of the rift at the north end of the Shoshone Range (Fig. 2), fine- to coarse-grained clastic sedimentary rocks and minor limestone locally underlie the middle Miocene volcanic rocks. These rocks range from coarse conglomerates and sedimentary breccias that contain clasts of the Caetano Tuff to finely laminated mudstones and siltstones and ostracod-bearing limestones. Some of the rocks are tuffaceous. These rocks are intruded by diabase dikes and are overlain unconformably by middle Miocene basalts. Along the west side of the rift, the sedimentary rocks generally overlie the Caetano Tuff with a pronounced angular discordance, and they have easterly dips of as much as 50°. Here, these rocks have a minimum thickness of about 250 m. Elsewhere along the Argenta and Malpais Rims, these sedimentary rocks have shallower dips and generally appear to be thinner and locally absent. Data from geothermal drill holes in Whirlwind Valley just north of the Malpais Rim indicate a maximum thickness of about 125 m for these rocks (Fig. 4; Struhsacker, 1980).

The age and relationship of these sedimentary rocks to the northern Nevada rift are uncertain, but their distribution suggests the presence of a shallow basin prior to emplacement of the middle Miocene dikes. Struhsacker (1980) noted that a biotite-hornblende andesite or dacite lava flow interbedded with the sedimentary rocks along the Malpais Rim yielded biotite K-Ar ages of 38.7±1.3 and 38.8±1.3 Ma. However, along the west side of the rift, the sedimentary rocks overlie and contain clasts of the Caetano Tuff, which has a sanidine $^{40}Ar/^{39}Ar$ age of 33.87±0.08 Ma (see geochronology section below). Here, angular unconformities between the sedimentary rocks, the underlying Caetano Tuff, and the overlying middle Miocene volcanic rocks suggest that there were multiple periods of north- to northwest-striking extensional faulting and tilting that began prior to the middle Miocene.

In the northernmost Shoshone Range (Argenta Rim) and along the Malpais Rim, thin deposits of fine-grained volcaniclastic sedimentary rocks and rhyolite air-fall tuff are interbedded locally with middle Miocene volcanic rocks (John et al., 1999). Along the east side of the Malpais Rim, the White Canyon tuffaceous sedimentary rocks consist of fluvial and lacustrine sandstone with interbedded felsic tuffs and reworked tuffs that reach thicknesses of 40 m (Struhsacker, 1980). These rocks mark a prominent unconformity in the volcanic section and lie between a thick sequence of middle Miocene trachydacite lava flows and a thinner, overlying sequence of olivine basalt lavas that represent the end of middle Miocene volcanism in the area. The sedimentary rocks appear to have been deposited largely along the Dunphy Pass fault, a north-northwest-striking fault that marks the east boundary of the deepest middle Miocene graben in this area (Figs. 3 and 4). Elsewhere in the northern Shoshone Range and in the southwestern Sheep Creek Range, thin rhyolite air-fall tuffs are present locally at the unconformity between trachydacite and overlying olivine basalt sequences. Middle Miocene sedimentary rocks are absent near the magnetic anomaly in the remainder of the northern Shoshone Range and in the southwestern Sheep Creek Range (D.A. John, unpub. data, 1999; John and Wrucke, 2000).

Middle Tertiary sedimentary rocks are absent in the southwestern Sheep Creek Range (John and Wrucke, 2000; Ramelli et al., 1999).

Middle Miocene sedimentary rocks are widespread in the northeastern Sheep Creek Range and, to a much lesser extent, in the Snowstorm Mountains. Throughout much of the Snowstorm Mountains, the base of the Tertiary section is not exposed. Where the base of the Miocene section is exposed in the western and eastern parts of the Snowstorm Mountains, basal sedimentary units are not present (Wallace, 1993; A.R. Wallace, unpub. mapping, 1989). Elsewhere in the Snowstorm Mountains, middle Miocene sedimentary rocks are rare. Most of the middle Miocene sedimentary rocks are exposed in the Midas district. The units there are fine-grained, thinly bedded lacustrine sediments, with minor conglomerate beds containing clasts of Paleozoic chert and quartzite. The units both overlie and are interbedded with locally derived pyroclastic units (Wallace, 1993). Middle Miocene (16-15 Ma) basalt to basaltic andesite dikes and sills intrude both the sediments and the tuffs; the youngest K-Ar age on the mafic rocks is 14.7±0.5 Ma (Wallace et al., 1993; Wallace and McKee, 1994; Casteel et al., 1999).

Extensive fine-grained lacustrine and subaerial sedimentary rocks underlie the northeastern Sheep Creek Range in the Ivanhoe district. Several units within the section are roughly the same age and resemble the lacustrine beds at Midas. At Willow Creek Reservoir (Fig. 2), sedimentation commenced at about 16.5 Ma (Perkins et al., 1998), and the uppermost units are 15.1 m.y. or younger (Wallace and John, 1998). Here, the total thickness of the sedimentary rocks is more than 200 m (Wallace, 2000). In the central part of the Ivanhoe district, the sedimentary rocks are a few tens of meters or less thick (Bartlett et al., 1991). The upper units in the section persist across this interval, whereas the lower part of the section progressively pinches out to the south (A.R. Wallace, unpub. mapping, 1998). Bartlett et al. (1991) identified a Paleozoic-cored paleotopographic high in the central part of the Ivanhoe district, and the southerly stratigraphic thinning likely represents a pinch-out against that high.

Southeast of Ivanhoe, the uppermost units of the Ivanhoe section comprise the basal units of the Miocene Carlin Formation, which, some 13 km southeast of Ivanhoe, is approximately 600 m thick (Theodore et al., 1998). Radiometric ages on one of the lower Carlin Formation units range from 15.1 to 14.4 Ma (Fleck et al., 1998). The Carlin Formation is exposed extensively between Ivanhoe and the town of Carlin (Theodore et al., 1998; Regnier, 1960), and is the center of a widespread Miocene depositional basin. In the Ivanhoe district, middle Miocene basaltic andesite and rhyolite were erupted prior to eruption of a 15.1 Ma vitric tuff, and the flows are interbedded with the sedimentary rocks.

The small amount of middle Miocene sedimentary rock from the southwestern part of the Sheep Creek Range south suggests that the rate of volcanic eruption was similar to or greater than the rate of downfaulting. In the Mule Canyon area, middle Miocene volcanic rocks approximately 1.2 km thick were erupted in a little more than 1 m.y. (John et al., 1999). In the southwestern part of the Sheep Creek Range, middle Miocene volcanic rocks more than 1 km thick were erupted and a porphyritic dacite pluton was emplaced in about 300,000 years (see below; John and Wrucke, 2000). Thus, the area along these parts of the magnetic anomaly was not a topographic low into which sediments could be shed. If the basal conglomerates at Buckhorn and in the Corral Canyon area in the northern Shoshone Range are related to middle Miocene subsidence, then a substantial amount of middle Miocene subsidence took place prior to the eruption of the middle Miocene basaltic andesites. At Buckhorn, thin sequences of graben-filling middle Miocene sedimentary rocks locally overlie the basaltic andesites (Monroe et al, 1988), and along the Malpais and Argenta Rims thin sequences of sedimentary rocks are present near the top of the middle Miocene volcanic sections. However, the rate of post-basinal volcanism in these areas generally was equivalent to the amount of subsidence, as shown by the absence of sedimentary rocks interbedded in the volcanic sequence.

The sedimentological evidence from the Snowstorm Mountains and the northeastern Sheep Creek Range indicate a broad, shallow lacustrine basin near Willow Creek Reservoir that began accumulating sediments at about 16.5 Ma. This lake progressively expanded, and sediments were deposited in more distal areas, eventually reaching Midas and merging with the basin in which the Carlin Formation sediments began accumulating by about 15.1 Ma. The depocenter mostly is east of the aeromagnetic anomaly that defines the rift. The apparent absence of 16-15 Ma sedimentary rocks in the western part of the Snowstorm Mountains, an area coincident with the trace of the aeromagnetic anomaly, might indicate that the rate of volcanism there was equal to the rate of subsidence, similar to the scenario proposed for the southwestern Sheep Creek and northern Shoshone Ranges. However, the western Snowstorm Mountains could not have been a highland, as shown by the absence of volcanic clasts in the sediments at Midas.

The presence of pre-middle Miocene, coarse- to fine-grained sedimentary rocks (mostly fanglomerates and conglomerates) beneath all exposures of middle Miocene mafic lava flows along the rift between the Humboldt River and the Simpson Park Range suggests that a shallow, northwest-elongated basin may have been present along the axis of the rift prior to emplacement of the mafic dikes. Because these sedimentary rocks are only constrained to be younger than about 34 Ma and older than about 16 Ma, it is not possible to determine if they formed a single continuous basin or represent several small basins that could have formed at different times.

## VARIATIONS IN AMOUNT OF CRUSTAL EXTENSION AND REGIONAL LEVELS OF EXPOSURE OF THE RIFT

Rocks and structures exposed along the northern half of the northern Nevada rift suggest that the amount of extension and rifting across the zone may increase from south to north. This variation may reflect increased extension with increased proximity to the middle Miocene site of the Yellowstone hot spot. In the southernmost exposed part of the rift in the Roberts Mountains (the central part of the magnetic anomaly), the total width of the zone is less than 6 km, and only about 1.5 km of extension is indicated by the combined width of the mafic dikes injected into Paleozoic wallrocks (McKee and Blakely, 1990). Farther north along the Argenta and Malpais Rims, the magnetic anomaly, which probably reflects deep-seated mafic dikes, is about 2-3 km wide (see geophysics section below), but the width of the graben that is filled with middle Miocene volcanic rocks is much wider, about 14-19 km (Fig. 3). The total amount of extension is unknown and may only be a few kilometers. In the Snowstorm Mountains, the magnetic anomaly remains narrow, but middle Miocene rocks are exposed across a zone more than 30 km in width. These overall relations suggest that initial rifting resulted in the emplacement of a narrow, deep-seated mafic dike swarm along the length of the rift that formed the magnetic anomaly seen today. In the Roberts Mountains and areas to the south, extension related to the northern Nevada rift ended following dike emplacement. Middle Miocene extension and normal faulting may have continued for progressively longer periods of time north of the Roberts Mountains, resulting in progressively wider areas filled with volcanic and sedimentary rocks and more poorly defined margins of the rift. This protracted extension may have been due to proximity to the middle Miocene location of the Yellowstone hot spot near McDermitt (Fig. 1), where thermal bulging and related crustal extension may have been greater and had a longer influence than in more distant areas.

The level of exposure in the rift generally increases to the south to the latitude of the Roberts Mountains. To the north, in the Snowstorm Mountains and northern Sheep Creek Range, middle Miocene rocks and structures mostly are concealed beneath younger volcanic rocks. To the south, in the Roberts Mountains, only mafic dikes are exposed at

the surface, and flows and other rift-related surficial units seen in the northern part of the rift are rare. In the south-southeastward continuation of the aeromagnetic anomaly south of the Roberts Mountains (Blakely and Jachens, 1991), the rift does not have any surface exposure. Variations between these extremes are visible along the length of the rift, with generally deeper exposures to the south as far south as the Roberts Mountains. Also, the anomaly-producing dikes may have been emplaced at increasingly greater depths to the south, resulting in the weaker anomaly south of the Roberts Mountains. In the northern part of the rift, post-middle Miocene, northwest-oriented extension produced a north-northwest-oriented belt of east-northeast-trending horsts (in or adjacent to the Snowstorm Mountains, Sheep Creek Range, northern Shoshone Range, Cortez Mountains, and the Roberts Mountains) with intervening grabens or half grabens. The northern Nevada rift is exposed at the western ends of the horsts. Assuming a generally horizontal datum along the rift prior to the formation of the horsts, and noting the apparent increase in depth of exposure of the rift to the south, relative uplift of the horsts was greater to the south (as far south as the Roberts Mountains) than to the north.

## GEOPHYSICAL STUDIES OF THE NORTHERN SHOSHONE AND SHEEP CREEK RANGES AND RELATIONSHIP TO THE NORTHERN NEVADA RIFT

Aeromagnetic data (Hildenbrand and Kucks, 1988) and greatly improved gravity data (Ponce, 1997; D.A. Ponce, unpub. data, 1999) in north-central Nevada reveal several prominent geophysical features along the northern Nevada rift (Figs. 5 and 6). The northern Nevada rift coincides with a prominent aeromagnetic anomaly in north-central Nevada that reflects mafic intrusive and associated volcanic rocks. In addition to the aeromagnetic anomaly, a steep isostatic gravity gradient also is associated with the rift. The improved gravity data indicate that a basement gravity anomaly correlates with the northern Nevada rift, rather than with the Battle Mountain–Eureka mineral trend as described previously by Grauch et al. (1995).

### NORTHERN SHOSHONE RANGE

In the northern part of the Shoshone Range (Fig. 5), the aeromagnetic expression of the northern Nevada rift occurs over the western margin of exposed middle Miocene mafic volcanic and intrusive rocks (Wallace and John, 1998; John et al., 1999). The aeromagnetic anomaly directly overlies a series of middle Miocene basalt and andesite flows and a 3- to 5-km-wide zone containing some mafic dikes. The western margin of the Shoshone Range is characterized by a gravity high (Fig. 6) that is related to exposed Paleozoic rocks. Gravity values are highest south of Argenta and may reflect an increase in density that may be partly related to massive sedimentary barite deposits. Some barite beds are up to 12 m thick, 300 m long, and 300 m wide (Stewart and McKee, 1977). Gravity data do not indicate the presence of low-density pediments or slide blocks along the western margin of the Shoshone Range. A steep gravity gradient of 7.2 mGal/km indicates a prominent Basin and Range fault with an inferred vertical offset of about 4.3 km based on a depth-to-basement map of the Winnemucca quadrangle (Ponce, 1998) and the relief on exposed Paleozoic rocks.

Both magnetic and somewhat subdued gravity highs extend about 10 km east-northeast from the center of the magnetic anomaly in the northern Shoshone Range along the Argenta Rim. The prominent magnetic high probably reflects the exposed, moderately magnetic basalts. Because the dense basaltic rocks are relative thin (see below) and a gravity high extends across the rim, Paleozoic rocks are probably present at shallow to moderate depths. At the eastern margin of the Argenta Rim and east of Dunphy, a broad, but low-amplitude gravity high correlates with scattered Paleozoic outcrops, and it indicates that the entire area is underlain by Paleozoic rocks at shallow depth. The Paleozoic rocks are exposed along the easternmost edge of Argenta Rim (D.A. John, unpub. mapping, 1999).

### BOULDER VALLEY

Boulder Valley lies between the Sheep Creek and Shoshone Ranges, trends east-northeast, and is one of the few basins that offsets the magnetic anomaly (Figs. 2 and 3). Gravity data indicate that Boulder Valley is a narrow fault-bounded basin that reflects a left-lateral offset of the northern Nevada rift by about 3 km, similar to and coincident with an offset in the aeromagnetic anomaly previously described by Zoback et al. (1994).

Boulder Valley is characterized by a gravity low that extends the entire length of the valley approximately along its topographic axis. The gravity low reaches an amplitude of about -12 mGal, which indicates a depth to basement of about 1 km. Several local gravity highs cut across the valley. North of Dunphy, a prominent gravity high extends some 8 km northward from the Argenta Rim to the center of Boulder Valley and probably reflects Paleozoic rocks at shallow depth. In the northern part of Boulder Valley, another gravity high extends across the valley, suggesting that buried Paleozoic(?) rocks form a structural ridge across the valley at shallow depth.

### SHEEP CREEK RANGE

Along the western margin of the Sheep Creek Range, a steep isostatic gravity gradient (Fig. 6) of about 6 mGal/km indicates the presence of a prominent range-bounding fault. The fault strikes from N10°W along the northern part to N30°W along the southern part. The vertical displacement of this fault is about 2.5 km, based on a depth-to-basement map of the Winnemucca quadrangle (Ponce, 1998) and on the topographic relief of exposed Paleozoic rocks. A gravity

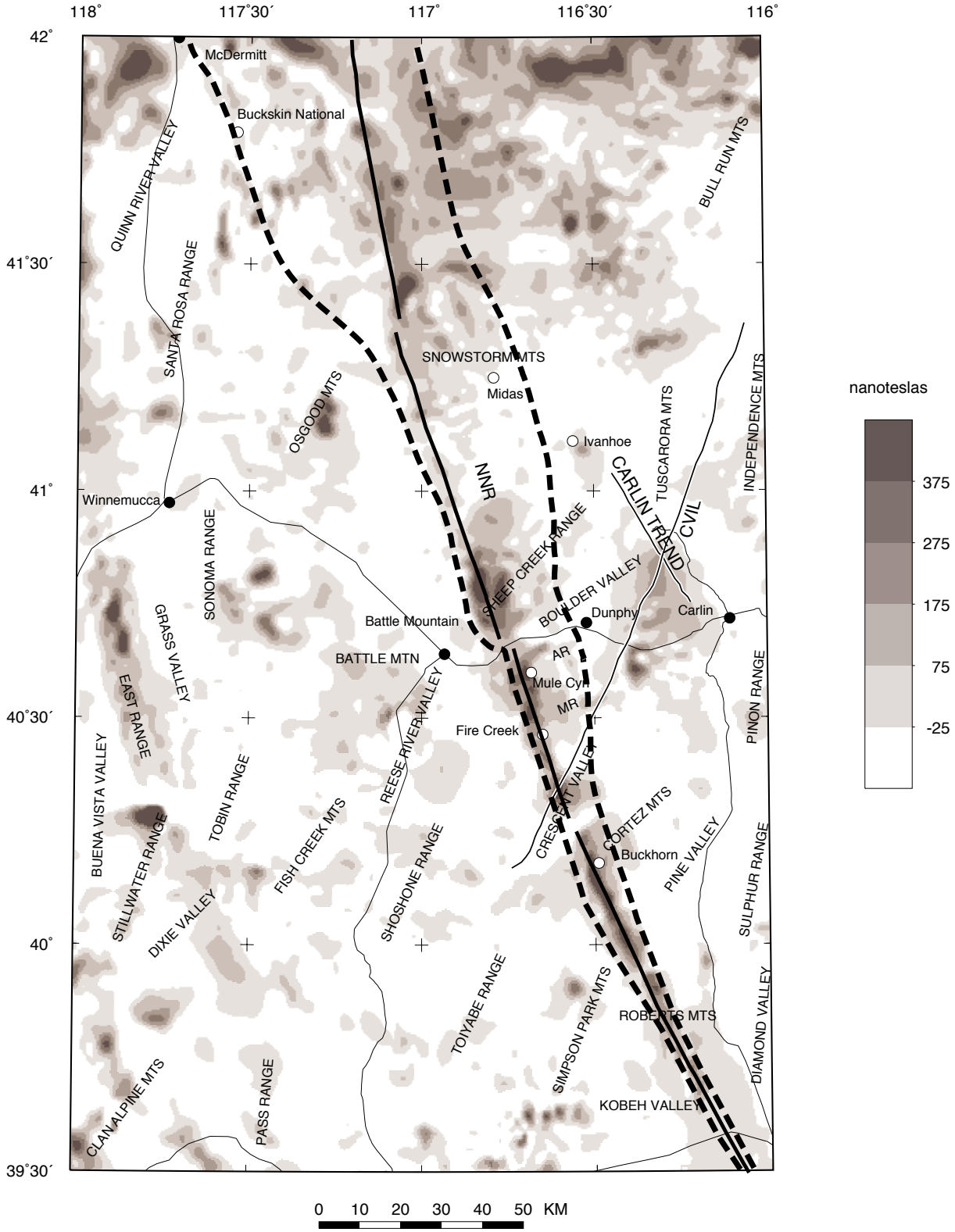


**FIGURE 5. Aeromagnetic map of north-central Nevada. Aeromagnetic data were analytically continued to 305-m above terrain and are a subset of a compilation by Hildenbrand and Kucks (1988). Contour interval 100 nanoteslas. AR, Argenta Rim; CVIL, Crescent Valley-Independence lineament; MR, Malpais Rim; RIFT, northern Nevada Rift; open circles, epithermal gold-silver deposits.**

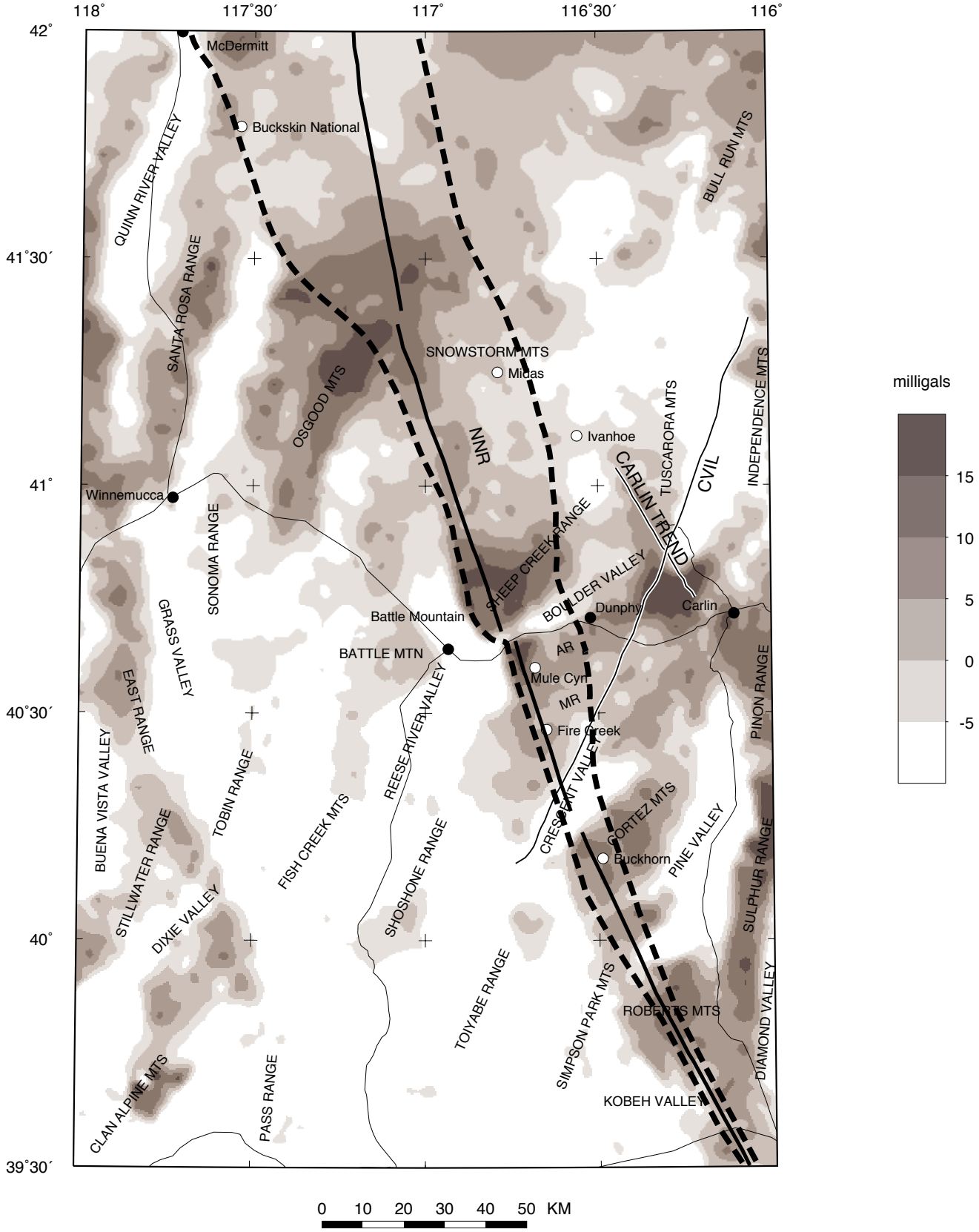


**FIGURE 6. Isostatic gravity map of north-central Nevada. Gravity data were reduced using standard geophysical methods and include an isostatic correction to remove long-wavelength variations of the Earth's gravity field. Contour interval 7 milligals. AR, Argenta Rim; CVIL, Crescent Valley-Independence lineament; MR, Malpais Rim; RIFT, northern Nevada Rift; open circles, epithermal gold-silver deposits.**

high along the western margin of the range is associated with exposed Paleozoic rocks, and a gravity high in the central part of the range may indicate the presence of similar rocks at shallow depths or the presence of relatively dense mafic igneous rocks at depth. A local 2-4 mGal gravity low across the southwestern third of the Sheep Creek Range probably reflects the presence of lower density volcanic or felsic intrusive rocks. This gravity low is south of, and does not appear to be related to, a dacite stock mapped in the central part of the Sheep Creek Range by John and Wrucke (2000). The location of this feature is also distinct from a possible intrusive body just west of the southernmost extent of the Sheep Creek Range that was inferred by Gott and Zablocki (1968) on the basis of geochemical and geophysical anomalies.

Physical property data (D.A. Ponce, unpub. data, 1999) indicate that volcanic rocks exposed in the Sheep Creek Range have low induced magnetizations. Furthermore, magnetic anomalies in the range transect exposed volcanic rock units without disruption, indicating that these rocks are neither the source nor contribute significantly to the prominent magnetic anomaly (Fig. 5). These results are consistent with previous studies that indicate the magnetic anomaly probably is caused by a 3-5-km-wide mafic dike that extends to great depth (Robinson, 1970; Zoback et al., 1994). A preliminary geophysical model across the Sheep Creek Range indicates that exposed Paleozoic rocks and a mafic dike zone about 7 km wide and about 15 km deep can account for the observed gravity and magnetic anomalies. Physical property parameters used for the mafic dikes were a susceptibility of 0.0027 emu/cm$^3$ (0.0034 SI units) and a density of 3.05 g/cm$^3$ (Zoback et al., 1994). Although volcanic flows along the anomaly include, from north to south, rocks with normal, transitional, and reversed polarities (Zoback, 1978), the prominent positive magnetic anomaly associated with the entire length of the anomaly probably indicates that it is dominated by rocks with normal polarity (Robinson, 1970; Zoback et al., 1994). Because of the moderate susceptibility and the through-going magnetic anomaly, magnetite is probably the mineral responsible for producing the anomaly. The absence of short-wavelength, high-amplitude magnetic anomalies west of the Sheep Creek Range, which often reflect the presence of volcanic rocks, suggests that the anomaly and associated volcanic rocks occur entirely east of the prominent range-bounding fault. Thus, this late Miocene to Quaternary fault may be a reactivated structure that formed during middle Miocene rifting. North of the Sheep Creek Range, the magnetic anomaly in the vicinity of the Midas trough is relatively narrow, which in part might reflect thick, nonmagnetic rhyolite domes that overlie the middle Miocene rocks (Wallace, 1993).

In general, the linear aeromagnetic anomaly narrows from north to south (Fig. 5). Although there may be a number of possible causes, if this feature reflects a wider zone of mafic dikes and associated volcanic rocks in the north, this implies a southward decrease in the width of the rift zone and a southward decrease in the amount of extension.

# MAGMATISM IN THE RIFT BETWEEN THE ROBERTS MOUNTAINS AND THE SNOWSTORM MOUNTAINS

## REGIONAL MIOCENE VOLCANIC SETTING

Following a general regional hiatus in magmatism between about 20 and 17 Ma (McKee et al., 1970), middle Miocene volcanic activity produced extensive flows and tuffs in northwestern Nevada, eastern Oregon, and southern Idaho. Much, if not all, of this activity was related to the penetration of the Yellowstone hot spot through the crust at about 16.6 Ma (Swisher et al., 1990). Plume heads of hot spots can reach 2,000 km in diameter (Sleep, 1992), and thus the area affected by the plume head can be substantial, a fact noted by Zoback et al. (1994) and substantiated by the widespread volcanic units. Major volcanic fields produced by the hot spot include the Columbia River basalt field of Oregon and Washington, the Steens Mountain basalt field of southeastern Oregon and northwestern Nevada, the northwestern Nevada volcanic field, the rhyolite and basalt field along the Snake River Plain (extending east-northeast from the McDermitt caldera complex), and the northern Nevada rift.

Throughout the region, the basal Miocene volcanic rocks largely are basaltic (alkali olivine basalt to tholeiitic basalt) in composition (Ekren et al., 1984; Johnson et al., 1998; Rytuba and McKee, 1984; Rytuba and Vander Meulen, 1991; Wallace and John, 1998). The basalts were erupted from linear dikes, largely but not completely of north-northwest orientation, and formed extensive flows. Along the northern Nevada rift, the basaltic dikes form a narrow but very elongate belt several hundred kilometers in length, and the basalt flows are constrained to the area of the magnetic anomaly (McKee and Blakely, 1990; Zoback et al., 1994; Wallace and John, 1998). Elsewhere, basalts were erupted from extensive shield volcanoes. Isotopic data from the Steens and Columbia River basalt sequences indicate magma derivation from a depleted mantle source, with variable amounts of contamination by a slightly less depleted oceanic crustal source (Hooper and Hawkesworth, 1993; Carlson and Hart, 1987). Data are consistent with those from other hot spot-related flood basalt sequences worldwide. Intercalated rhyolites are rare throughout the mafic sequence, with exceptions in northern Nevada in the Buckskin-National district (Vikre, 1985), the Snowstorm Mountains (Wallace, 1993), and the Ivanhoe district (Wallace, 2000).

Commencing with felsic volcanism at the McDermitt center and elsewhere in northwestern Nevada at about 16 Ma, the locus of magmatism migrated to the northeast as the North American plate migrated southwest across the stationary hot spot. Numerous large eruptive centers formed along this path, which is marked by the Snake River Plain (Fig. 1). These centers become younger to the northeast, culminating in the active Yellowstone volcanic complex in northwestern Wyoming. The most voluminous components of this volcanic sequence are high-temperature and areally extensive rhyolitic welded tuffs and flows with a peralkaline and anhydrous

composition. Yellowstone departs from this norm with its more hydrous composition, perhaps indicating a different crustal composition. Locally derived but thick rhyolitic volcanic centers in northern Nevada (Buckskin-National, Snowstorm Mountains, Ivanhoe, and Jarbidge) are exposed south of the Snake River Plain (Fig. 1). These range in age from about 14.5 to 13.4 Ma. They overlie the basal basalts and in turn are overlain by the extensive tuffs derived from north in the region of the Snake River Plain. Tholeiitic basalts form a relatively thin but laterally persistent veneer over the rhyolitic rocks along the plain. These basalts generally have younger ages to the northeast, ranging from about 10 Ma in the southwest to fairly recent in the northeast. Along the northern Nevada rift, dated volcanic rocks younger than about 13 Ma are uncommon south of Midas (Zoback et al., 1994; John et al., 1999).

The region is bisected in a general north-south direction by the edge of the North American craton, as evidenced by Sr, Pb, Nd, and O isotopic data (Kistler and Peterman, 1978; Farmer and DePaolo, 1983; Wooden et al., 1998). Crust east of this boundary is dominantly continental in nature, whereas crust to the west is more oceanic in composition. As noted above, isotopic data on volcanic rocks in southeastern Oregon, which is west of the craton, show no evidence of contamination by a continental crust. In contrast, rhyolites along the Snake River Plain contain both granulite xenoliths and isotopic evidence of derivation from a granulitic continental crust (Honjo and Leeman, 1987). Therefore, although the Yellowstone hot spot provided the impetus for volcanism throughout the region, the role and composition of the crust likely played a major role in the ultimate composition of the erupted volcanic materials.

## MIDDLE MIOCENE IGNEOUS ROCK TYPES, DISTRIBUTION, AND AGE

Studies of igneous rocks that are along the northern Nevada rift between the Cortez and Snowstorm Mountains indicate that there is considerable compositional variation (Struhsacker, 1980; Wallace and John, 1998; John et al., 1999). In particular, rocks with intermediate compositions (andesite and dacite) are abundant in the northernmost Shoshone Range, where they are form much of the Argenta and Malpais Rims, and in the southwestern Sheep Creek Range. Table 1 summarizes the stratigraphy of middle Miocene igneous rocks associated spatially with the northern Nevada rift from the Roberts Mountains to the Snowstorm Mountains and Table 2 lists representative chemical analyses of rocks from these areas.

### Roberts Mountains-Simpson Park Range-Sulphur Springs Range

Rocks related to the aeromagnetic anomaly in the Roberts Mountains consist primarily of north-northwest-trending basaltic dikes; a few thin flows of similar composition are present south of the dike swarm. K-Ar ages of these rocks (four dikes and four lava flows) range from 13.6±0.4 to 18.6±0.7 Ma (Zoback et al., 1994). New $^{40}Ar/^{39}Ar$ incremental heating analyses of three dikes (Table 3) range from 15.15±0.09 to 15.73±0.10 Ma, suggesting emplacement of the three dikes over a relatively short interval between about 15 and 16 Ma. The dikes are nearly vertical and the flows lie nearly horizontal; thus, they appear to post-date the approximately 20° eastward tilting of Paleozoic strata in the Roberts Mountains.

Four thin basaltic flows are exposed in the northern part of the Simpson Park Range that may be the same flows found a few kilometers north in the Cortez Mountains. These flows overlie Tertiary conglomerates that are about 125 m thick, which in turn lie on Oligocene rhyodacitic volcanic rocks (McKee and Conrad, 1994). One of these flows gave a $^{40}Ar/^{39}Ar$ plateau age of 15.67±0.09 Ma (Table 3). Both the flows and the underlying Tertiary sedimentary rocks are flat-lying to slightly east dipping.

In the Sulphur Springs Range about 15 km east of the magnetic anomaly, three basaltic flows cap a sequence of more than 100 m of Tertiary conglomeratic and tuffaceous sedimentary rocks; the base of the Tertiary section is not exposed. The middle flow gave a $^{40}Ar/^{39}Ar$ plateau age of 13.55±0.10 Ma (Table 3). In contrast to the nearly untilted late Tertiary rocks in the Roberts Mountains and northern Simpson Park Range, the basalt flows and older sedimentary rocks in the Sulphur Springs Range dip about 15 degrees to the east.

### Cortez Mountains

Middle Miocene rocks on the south side of the Cortez Mountains consist of as many as eight flows of andesite or basaltic andesite (Gilluly and Masursky, 1965; Plahuta, 1986) that locally are overlain by thin units of graben-filling sedimentary rocks (Monroe et al., 1988). The lava flows have K-Ar dates of 16.7±0.9 and 14.8±1.5 Ma (Wells et al., 1971; Armstrong, 1970). A small rhyolite flow dome intrudes and overlies the andesites along the west margin of the rift (Gilluly and Masursky, 1965) and has a sanidine K-Ar age of 15.7±0.4 Ma (Wells et al., 1971). The andesites have a total thickness of as much as 110 m. They are compositionally and petrographically similar to the andesite of Horse Heaven in the northern Shoshone Range (Table 2). On the north side of the Cortez Mountains, a swarm of north-northwest-trending "diabase" dikes are present (Gilluly and Gates, 1965; Gilluly and Masursky, 1965). These dikes are possible feeders for the lava flows, although the dikes are not in contact with the flows.

### Northern Shoshone Range

Rocks near the aeromagnetic anomaly in the northern Shoshone Range consist mostly of basaltic andesite or andesite lava flows that overlie middle Tertiary gravel deposits (Gilluly and Gates, 1965). These lava flows are

## TABLE 1. Characteristics of the central part of the northern Nevada rift.

| Location | Roberts Mountains | Cortez Mountains and northern Simpson Park Range | Northern Shoshone Range (south of 40°30'N latitude) | Mule Canyon quad and Argenta and Malpais Rims | Southwestern Sheep Creek Range | Northern Sheep Creek Range | Snowstorm Mountains |
|---|---|---|---|---|---|---|---|
| Width of "rift" (Fig. 2) | 6 km | 10 to 15 km | >10 km | 17 to 19 km | Unknown | Unknown | Unknown |
| Margins of rift | High-angle faults of uncertain age | High-angle NNW-striking fault on west side of Cortez Mountains; east side covered by younger gravels; lava flows pinch out | Middle Miocene units pinch out on west side; east side covered by younger gravels | Small displacement NNW-striking high-angle faults; rift-filling units markedly thin to east | Unknown; young NNW-striking Basin and Range fault on west side; middle Miocene volcanic and sedimentary rocks on east side | Unknown. Middle Miocene volcanic rocks pinch out on east margin | Unknown. Middle Miocene volcanic rocks pinch out on west and east margins |
| Intrarift faults | None mapped | NNW-striking | NNW-striking | NNW- and NE-striking | NNW-striking | None mapped | NNW-striking |
| Middle Miocene "rift"-related rocks | Mafic dikes | Gravels; basaltic andesite/andesite lava flows; small rhyolite flow dome; mafic dikes on north side of Cortez Mountains | Gravels; basaltic andesite/andesite lava flows; minor trachydacite | Gravels and lake sediments; basalt to trachydacite lava flows and pyroclastic rocks with local vents | Basalt to trachydacite lava flows; porphyritic dacite stock; rhyolite porphyry flow dome | Basal basaltic andesite to rhyolite lava flows; lacustrine sedimentary rocks; overlying rhyolite porphyry flow domes | Basal basaltic andesite flows and rhyolite tuffs; overlying rhyolite flows and tuffs |
| Thickness of middle Miocene rocks (max.) | — | Gravels—150 to 400 m; lava flows—110 m | Gravels—200 m; lava flows—80 to 300 m | Gravels and lake sediments—≥250 m; volcanic rocks—1200 m | Lava flows—≥1050 m | >700 m | >1000 m |
| Age of middle Miocene rocks (Ma)[1] | Dikes—15.7±0.10 to 15.15±0.09 | Gravels—<34; lava flows—approx. 15.5 | Gravels—<34; lava flows—approx. 15.5 | Gravels and lake sediments-<34; lava flows and tuffs—>15.85±0.08 to 14.7±0.2 | Lava flows—15.58±0.1 to 14.7±0.2; dacite stock—15.34±0.1; rhyolite dome—14.84±0.04 | Basaltic andesite-->15.10±0.06; tuffaceous sediments--16.5-14.41±0.04; rhyolite dome--14.92±0.05 | Lava flows—>15.2±1.6-14.7±0.5; rhyolite flows—14.3±0.8-13.4±0.4; basalt—9.8±2.5 |
| Dikes | NNW-trending basalt dike swarm, 2 to 6 km wide and 10 km long | NNW-trending diabase dike swarm, 6 km wide and 5 km long along west side of rift | None exposed | NNW-trending mafic dike swarm, 3 to 5 km wide and 15 km long along west side of rift | None exposed | NNW-trending rhyolite porphyry dike (14.92 Ma) | NNW-trending mafic and rhyolite dikes (<15.4-13.4 Ma) |
| Sedimentary deposits | None exposed | Gravels underlie middle Miocene volcanic rocks | Gravels underlie middle Miocene volcanic rocks | Gravels and lake sediments underlie middle Miocene volcanic rocks | None exposed | Lacustrine sedimentary rocks, tuffaceous (16.5-14.41±0.04 Ma) | Minor lacustrine sediments (Midas, ~15.5 Ma); extensive lacustrine sediments to north (~13.0 Ma) |
| Epithermal mineral deposits | None | Buckhorn | Fire Creek | Mule Canyon | None | Ivanhoe | Midas; Eastern Star sinters |
| Other features | | | | | | Sn deposits in rhyolite porphyry at Izzenhood | Anomalous Sn in rhyolite porphyry at Ivanhoe |
| References | Murphy et al., 1978; McKee, 1986; Zoback and others, 1994; this study | Gilluly and Masursky, 1965; Monroe et al., 1988; Jennings, 1991; McKee and Conrad, 1994; Zoback et al., 1994; this study | Gilluly and Gates, 1964; this study | Zoback, 1978; Struhsacker, 1980; John et al., 1999; this study | Wallace and John, 1998; John and Wrucke, 1999; Ramelli et al., 1999; this study | Bartlett et al., 1991; Wallace and John, 1998; this study | Wallace, 1993; Wallace et al., 1990; Wallace and McKee, 1994 |

[1]Age based on $^{40}Ar/^{39}Ar$ dates reported in Table 3 and ages discussed in text.

**TABLE 2. Representative chemical analyses of middle Miocene igneous rocks in the northern Nevada rift.**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample Number | 99-DJ-9 | 99-DJ-3 | 99-DJ-21 | 97-DJ-23 | 979-17B | 98-DJ-71 | 99-DJ-61 | 96-DJ-48B | 97-DJ-40 | 97-DJ-19 |
| Unit[1] | Tdk | Tmcb | Tmct | Tba | Thhd | Thh (MC) | Thh (CC) | Tpd (MC) | Tpd (SC) | Td |
| **Major elements (normalized to 100% volatile-free)** | | | | | | | | | | |
| $SiO_2$ | 52.60 | 50.23 | 58.02 | 50.70 | 58.72 | 56.01 | 56.19 | 68.42 | 68.21 | 64.42 |
| $Al_2O_3$ | 16.09 | 18.02 | 14.16 | 16.41 | 14.20 | 15.14 | 14.48 | 13.61 | 13.41 | 14.26 |
| $TiO_2$ | 1.12 | 0.97 | 1.76 | 1.09 | 1.58 | 1.26 | 1.60 | 0.75 | 0.75 | 0.94 |
| FeO* | 8.87 | 8.98 | 9.91 | 9.91 | 9.20 | 9.42 | 10.34 | 6.34 | 6.36 | 7.73 |
| MnO | 0.18 | 0.16 | 0.18 | 0.18 | 0.17 | 0.17 | 0.18 | 0.06 | 0.09 | 0.14 |
| CaO | 10.31 | 11.49 | 6.42 | 10.68 | 6.36 | 8.43 | 7.61 | 2.12 | 2.48 | 3.47 |
| MgO | 6.71 | 6.96 | 3.00 | 7.32 | 3.10 | 4.36 | 4.00 | 0.41 | 0.45 | 0.72 |
| $K_2O$ | 0.90 | 0.36 | 2.34 | 0.68 | 2.27 | 1.85 | 1.95 | 4.81 | 4.79 | 4.36 |
| $Na_2O$ | 2.88 | 2.57 | 3.42 | 2.72 | 2.65 | 2.95 | 3.08 | 3.25 | 3.24 | 3.70 |
| $P_2O_5$ | 0.34 | 0.26 | 0.78 | 0.30 | 0.72 | 0.40 | 0.57 | 0.22 | 0.21 | 0.25 |
| Total | 99.39 | 99.36 | 99.64 | 99.73 | 97.54 | 98.66 | 99.37 | 98.86 | 98.93 | 98.57 |
| **Trace Elements (ppm)** | | | | | | | | | | |
| Ni | 36 | 41 | 0 | 52 | 71 | 7 | 3 | 3 | 2 | 3 |
| Cr | 200 | 146 | 16 | 137 | 11 | 43 | 27 | 6 | 0 | 0 |
| Sc | 32 | 35 | 27 | 32 | 25 | 32 | 31 | 8 | 9 | 19 |
| V | 239 | 221 | 338 | 247 | 253 | 245 | 324 | 36 | 23 | 18 |
| Ba | 409 | 263 | 888 | 358 | 728 | 673 | 773 | 1658 | 1613 | 2217 |
| Rb | 22 | 10 | 60 | 11 | 78 | 46 | 48 | 151 | 151 | 129 |
| Sr | 318 | 339 | 346 | 328 | 339 | 346 | 347 | 253 | 232 | 300 |
| Zr | 111 | 83 | 204 | 94 | 213 | 154 | 175 | 386 | 388 | 444 |
| Y | 28 | 25 | 42 | 27 | 37 | 32 | 39 | 56 | 50 | 68 |
| Nb | 7 | 5 | 14 | 7 | 15 | 11 | 12 | 26 | 25 | 33 |
| Ga | 19 | 19 | 23 | 16 | 21 | 21 | 20 | 24 | 20 | 24 |
| Cu | 37 | 41 | 11 | 62 | 18 | 16 | 10 | 6 | 13 | 3 |
| Zn | 100 | 91 | 135 | 97 | 141 | 102 | 127 | 125 | 116 | 146 |
| Pb | 5 | 0 | 9 | 0 | 7 | 8 | 6 | 27 | 24 | 21 |
| La | 23 | 6 | 43 | 13 | 32 | 22 | 35 | 70 | 75 | 66 |
| Ce | 58 | 31 | 72 | 37 | 77 | 48 | 55 | 132 | 124 | 130 |
| Th | 3 | 3 | 7 | 4 | 5 | 6 | 5 | 17 | 19 | 12 |

[1]Units: Tdk, basalt dike, Mule Canyon quadrangle; Tmcb, porphyritic basalt, lower part of Mule Canyon sequence, Mule Canyon quadrangle; Tmct, andesite tuff, top of Mule Canyon Sequence, Mule Canyon quadrangle; Tba, basal basalt, southwestern Sheep Creek Range; Thhd, andesite of Horse Heaven dike, north ore zone, Mule Canyon mine; Thh (MC), andesite of Horse Heaven, Mule Canyon quadrangle; Thh (CC), andesite of Horse Heaven, Corral Canyon, northern Shoshone Range; Tpd (MC), porphyritic dacite lava flow, Mule Canyon quadrangle; Tpd (MC), vitrophyric margin of porphyritic dacite stock, southwestern Sheep Creek Range; Td, trachydacite flow, southwestern Sheep Creek Range; Trp, rhyolite porphyry flow dome, southwestern Sheep Creek Range; Tob (MC), capping olivine basalt flow, southwestern Sheep Creek Range; Trf, rhyolite flow, basal Miocene section, Ivanhoe district; Tb, basaltic andesite flow above Trf, Ivanhoe district; Tvt, vitric tuff, Ivanhoe district; Trc, Craig rhyolite, Ivanhoe district; Trp, rhyolite porphyry dome, Ivanhoe district; Tba, basaltic andesite, Snowstorm Mountains; Tep, Elko Prince rhyolite (Midas ore host), Snowstorm Mountains; Trt, rhyolite flow above rift-age rocks, Snowstorm Mountains; Trpy, rhyolite porphyry flow, Snowstorm Mountains; Tb, Big Island Basalt, northeastern Snowstorm Mountains.

compositionally and petrographically similar to the andesite of Horse Heaven exposed farther north in the Mule Canyon quadrangle (Table 2). A flow from Corral Canyon yielded a whole rock $^{40}Ar/^{39}Ar$ date of 15.8±0.8 Ma (Table 3). A thin unit of mafic tuff locally underlies the andesite and unconformably overlies the middle Tertiary gravels. East of the Muleshoe fault near the mouths of Fire Creek and Corral Canyon, small areas of trachydacite lava flows are exposed on top of the andesites. These flows appear similar to trachydacite flows that locally cap the Malpais and Argenta Rims and the southwestern Sheep Creek Range.

### Mule Canyon quadrangle and Argenta and Malpais Rims

Middle Miocene rocks near the magnetic anomaly in these areas consist of four major units: (1) Mule Canyon sequence, (2) andesite of Horse Heaven, (3) trachydacite, and

**TABLE 2. Representative chemical analyses of middle Miocene igneous rocks in the northern Nevada rift (continued).**

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|
| Sample Number | 97-DJ-7 | 96-DJ-61 | 96WC-4 | 97WC1 2 | 96WC-19 | 97WC1 3 | 97WC1 4 | 9LH25 | 8LH29 |
| Unit[1] | Trp | Tob (SC) | Trf | Tb | Tvt | Trc | Trp | Tba | Tep |
| **Major elements (normalized to 100% volatile-free)** | | | | | | | | | |
| $SiO_2$ | 73.84 | 50.29 | 72.96 | 56.42 | 70.55 | 76.92 | 77.41 | 52 | 73 |
| $Al_2O_3$ | 13.10 | 15.97 | 13.86 | 13.72 | 15.61 | 11.51 | 11.62 | 16.2 | 13.0 |
| $TiO_2$ | 0.30 | 1.52 | 0.27 | 2.24 | 0.31 | 0.13 | 0.06 | 1.0 | 0.4 |
| FeO* | 2.81 | 10.30 | 3.61 | 12.57 | 3.06 | 1.96 | 1.69 | 8.4 | 5.5 |
| MnO | 0.03 | 0.19 | 0.03 | 0.19 | 0.03 | 0.03 | 0.02 | 0.2 | 0.1 |
| CaO | 0.84 | 10.05 | 0.51 | 5.81 | 1.08 | 0.38 | 0.28 | 10.0 | 0.5 |
| MgO | 0.14 | 7.45 | 0.18 | 1.89 | 0.40 | 0.07 | 0.05 | 8.5 | 0.5 |
| $K_2O$ | 5.55 | 0.94 | 5.56 | 2.70 | 6.48 | 5.10 | 4.54 | 0.8 | 3.2 |
| $Na_2O$ | 3.29 | 2.74 | 2.96 | 3.69 | 2.38 | 3.88 | 4.29 | 2.5 | 3.8 |
| $P_2O_5$ | 0.11 | 0.55 | 0.05 | 0.77 | 0.09 | 0.03 | 0.04 | 0.3 | 0.1 |
| Total | 99.09 | 98.79 | 100.51 | 100.51 | 100.04 | 99.17 | 98.85 | 98.25 | 96.10 |
| **Trace Elements (ppm)** | | | | | | | | | |
| Ni | 7 | 63 | <10 | <10 | <10 | <10 | <10 | NA | NA |
| Cr | 0 | 179 | 1 | 5 | 4 | 7 | 6 | NA | NA |
| Sc | 2 | 28 | NA | NA | NA | NA | NA | NA | NA |
| V | 11 | 214 | 23 | 207 | 10 | 6 | 19 | NA | NA |
| Ba | 1161 | 668 | 1179 | 1269 | 977 | 90 | 134 | NA | 1700 |
| Rb | 206 | 10 | 166 | 88 | 191 | 311 | 444 | NA | 100 |
| Sr | 109 | 418 | 203 | 378 | 78 | 15 | 10 | NA | 58 |
| Zr | 347 | 155 | 218 | 306 | 431 | 252 | 173 | NA | 380 |
| Y | 83 | 33 | 33 | 51 | 65 | 76 | 121 | NA | 64 |
| Nb | 33 | 13 | 13 | 25 | 36 | 37 | 58 | NA | 33 |
| Ga | 23 | 18 | 21 | 22 | 24 | 22 | 27 | NA | NA |
| Cu | 8 | 12 | <10 | <10 | <10 | <10 | <10 | NA | NA |
| Zn | 80 | 117 | 161 | 142 | 81 | 67 | 58 | NA | NA |
| Pb | 31 | 4 | 66 | 23 | 62 | 63 | 79 | NA | NA |
| La | 99 | 30 | 76 | 50 | 92 | 80 | 34 | NA | NA |
| Ce | 207 | 54 | 104 | 109 | 118 | 173 | 80 | NA | NA |
| Th | 27 | 4 | 18 | 7 | 27 | 29 | 45 | NA | NA |

*Continued on following page*

(4) olivine basalt (John et al., 1999). These rocks unconformably overlie lower Paleozoic sedimentary rocks, the ca. 34–Ma Caetano Tuff, and early Oligocene to early Miocene sedimentary rocks. Along the west side of the rift, the Mule Canyon sequence consists of as much as 400 m of interbedded lava flows and pyroclastic rocks that had local sources. These rocks range in composition from basalt to andesite. The andesite of Horse Heaven overlies the Mule Canyon sequence and consists of several lava flows of andesite and basaltic andesite. This unit is as much as 250 m thick and thickens to more than 300 m farther south in the Corral Canyon area (Fig. 3; Gilluly and Gates, 1965). Numerous dikes that were feeders for the upper parts of the Mule Canyon sequence and for the andesite of Horse Heaven intrude these units along the west side of the rift. The dikes locally coalesce at depth forming a nested body. The andesite of Horse Heaven is overlain by a series of dacite to trachydacite lava flows. Two major units of dacite are present: an older series of porphyritic flows and an unconformably overlying series of aphyric to sparsely porphyritic flows (Fig. 4; Struhsacker, 1980; John et al., 1999). The dacites locally are more than 300 m thick and form most of the Malpais Rim and much of the Argenta Rim. The dacites are overlain unconformably by as much as 150 m of ilmenite-rich olivine basalt flows. Thin units of rhyolite airfall tuff and tuffaceous sedimentary rocks are present locally between the dacites and the olivine basalt flows.

**TABLE 2. Representative chemical analyses of middle Miocene igneous rocks in the northern Nevada rift (continued).**

| | 20 | 21 | 22 |
|---|---|---|---|
| Sample Number | 7LH40 | 5LHW90 | 5LHW94 |
| Unit[1] | Trt | Trpy | Tb |
| **Major elements (normalized to 100% volatile-free)** | | | |
| $SiO_2$ | 73 | 77 | 48 |
| $Al_2O_3$ | 13.1 | 12.7 | 15.4 |
| $TiO_2$ | 0.3 | 0.3 | 2.1 |
| FeO* | 3.8 | 0.5 | 10.3 |
| MnO | 0.0 | 0.0 | 0.2 |
| CaO | 0.6 | 0.8 | 10.8 |
| MgO | 0.0 | 0.1 | 9.5 |
| $K_2O$ | 5.6 | 5.4 | 0.3 |
| $Na_2O$ | 3.2 | 3.3 | 2.4 |
| $P_2O_5$ | 0.0 | 0.1 | 0.5 |
| Total | 98.52 | 98.50 | 99.75 |
| **Trace Elements (ppm)** | | | |
| Ni | NA | NA | NA |
| Cr | NA | NA | NA |
| Sc | NA | NA | NA |
| V | NA | NA | NA |
| Ba | 930 | 1045 | 231 |
| Rb | 220 | 176 | 11 |
| Sr | 44 | 68 | 240 |
| Zr | 505 | 436 | 146 |
| Y | 69 | 71 | 27 |
| Nb | 34 | 29 | 8 |
| Ga | NA | NA | NA |
| Cu | NA | NA | NA |
| Zn | NA | NA | NA |
| Pb | NA | NA | NA |
| La | NA | NA | NA |
| Ce | NA | NA | NA |
| Th | NA | NA | NA |

See footnote on page 144.

### Southwestern Sheep Creek Range

In the southwestern part of the Sheep Creek Range, a sequence of basalt and basaltic andesite lava flows directly overlies lower Paleozoic sedimentary rocks. Several dozen thin flows with a total thickness of about 300 m are present along the western edge of the range (John and Wrucke, 2000; Ramelli et al., 1999). These flows are compositionally and petrographically similar to the Mule Canyon sequence and to the andesite of Horse Heaven in the Mule Canyon area except that very few pyroclastic rocks are present (Wallace and John, 1998; John et al., 1999). About 600 m of trachydacite lava flows overlie the basalt and basaltic andesite sequence. A large stock of porphyritic dacite intrudes both units. The dacite units are compositionally and petrographically identical to similar units on the Malpais and Argenta Rims, and the porphyritic dacite units have nearly identical $^{40}Ar/^{39}Ar$ ages (see below). A thin, discontinuous unit of rhyolite air-fall tuff and tuffaceous sedimentary rocks unconformably overlies the trachydacite flows. Olivine basalt lava flows, which are about 150 m thick, unconformably cap the sequence. The olivine basalts are petrographically identical to flows capping the west side of the Argenta Rim and have identical 14.7±0.2 Ma $^{40}Ar/^{39}Ar$ ages (John et al., 1999). To the north, rhyolite porphyry that forms the southernmost exposures of the Izzenhood rhyolite field intrudes and unconformably overlies the trachydacite units (Fig. 3).

### Izzenhood Ranch to Midas trough

In general, middle Miocene volcanic rocks exposed in the northern Sheep Creek Range are progressively older to the east. Extensive Quaternary cover west of the Sheep Creek Range conceals whatever middle Miocene rocks may be present in that area. In the northwestern Sheep Creek Range, between the Midas trough and Izzenhood Ranch, virtually all exposed rocks are rhyolite porphyry domes of the Izzenhood rhyolite field that were emplaced between 14.9 and 13.4 Ma (Wallace and John, 1998). These domes conceal all other rock units. In the Ivanhoe district to the east, middle Miocene rocks include tuffaceous sedimentary rocks (16.5-14.4 Ma) and relatively minor interbedded basaltic andesite and rhyolite flow units that are Miocene age but older than about 15.1 Ma (Wallace, 2000). The flow units at Ivanhoe extend westward, where they are concealed by the rhyolite porphyry domes. Within the Ivanhoe district, 15.1 Ma rhyolite flows and 14.9 Ma rhyolite domes, the latter similar to those exposed to the west, overlie the tuffaceous sedimentary rocks and associated flows (Wallace and John, 1998). Post-rhyolite sedimentation continued to the east until at least 14.4 Ma (Fleck et al., 1998).

### Snowstorm Mountains

In the Snowstorm Mountains, the basal Miocene volcanic rocks include basaltic andesite flows, dikes, and sills and lesser rhyolite tuffs, flows, and dikes (Wallace, 1993). These rocks range in age from about 15.5 to 14.7 Ma based on K-Ar dating (Wallace et al., 1990; Wallace and McKee, 1994). The base of the early mafic-felsic sequence is exposed only along the western margin of the range, where basaltic andesite flows overlie Paleozoic sedimentary rocks. Flows of basaltic andesite comprise the majority of the volcanic sequence where it is exposed in the Snowstorm Mountains, whereas exploration drilling in the Midas district indicates that the majority of the mafic rocks there are dikes and sills (Casteel et al., 1999). Rhyolitic pyroclastic rocks are abundantly exposed in the Midas district, and evidence, such as mesobreccias and great thickness changes, suggest the presence of a small caldera. Rhyolitic pyroclastic rocks are present within the basaltic andesite sequence elsewhere in

**TABLE 3. New $^{40}Ar/^{39}Ar$ dates of igneous rocks from the central part of the northern Nevada rift.**

| Rock type/unit | Material dated | Age (Ma) | Comments |
|---|---|---|---|
| **Roberts Mountains, Simpson Park Range, and Sulphur Springs Range** | | | |
| Basalt dike | whole rock | 15.73±0.10 | Roberts Mountains |
| Basalt dike | whole rock | 15.48±0.11 | Roberts Mountains |
| Basalt dike | whole rock | 15.15±0.09 | Roberts Mountains |
| Basalt flow | whole rock | 15.67±0.09 | N. Simpson Park Range |
| Basalt flow | whole rock | 13.55±0.10 | Sulphur Springs Range |
| **Northern Shoshone Range** | | | |
| Olivine basalt flow | whole rock | 14.7±0.8 | capping basalt flows just east of Mule Canyon Mine |
| Porphyritic dacite | plagioclase | 15.33±0.09 | lava flow in Mule Canyon Mine |
| Andesite lava flow | whole rock | 15.86±0.12 | andesite of Horse Heaven |
| Andesite lava flow | whole rock | 15.2±0.8 | andesite of Horse Heaven |
| Andesite lava flow | whole rock | 15.8±0.8 | lava flow in Corral Canyon correlative with andesite of Horse Heaven |
| Andesite lava flow | whole rock | 15.85±0.08 | near top of Mule Canyon sequence in Mule Canyon Mine |
| Caetano Tuff | sanidine | 33.87±0.08 | oldest Tertiary unit in area |
| **Southwestern Sheep Creek Range** | | | |
| Olivine basalt | whole rock | 14.7± 0.2 | capping basalt flow |
| Rhyolite porphyry | sanidine | 14.84±0.04 | southern end of Izzenhood dome complex |
| Rhyolite tuff | sanidine | 14.94±0.04 | tuff between trachydacite and olivine basalt units |
| Porphyritic dacite | plagioclase | 15.34± 0.10 | "dogball" dacite unit; intrusive |
| Trachydacite flow | plagioclase | 15.42± 0.10 | trachydacite unit |
| Basalt flow | whole rock | 15.58± 0.10 | basal basalt flow in SW Sheep Creek Range |
| **Ivanhoe District** | | | |
| Carlin Formation | sanidine | 14.4-15.1 | Carlin Formation tuffs (SE of Ivanhoe) |
| Rhyolite porphyry | sanidine | 14.92±0.05 | Ivanhoe dome complex |
| Rhyolite flow | sanidine | 15.07±0.08 | Craig rhyolite |
| Vitric tuff | sanidine | 15.10±0.06(a) | air-fall vitric tuff |
| Air-fall tuff | plagioclase | 15.84±0.10 | air-fall tuff in basal lacustrine sediment |
| Welded tuff | sanidine | 39.22±0.10(b) | tuff of Willow Creek, oldest dated Tertiary unit in district |

All but two dates on igneous rocks determined at the geochronology labs of the U.S. Geological Survey, Menlo Park, CA. Vitric tuff (a) and welded tuff (b) from Ivanhoe district dated at the New Mexico Bureau of Mines and Geology laboratory by C.D. Henry. All dates standardized to an age of 513.9 Ma for interlaboratory standard hornblende, MMhb-1.

the Snowstorm Mountains, most notably at Snowstorm Mountain and north of Midas (Wallace, 1993).

A diverse, thick, and extensive series of rhyolitic flows and tuffs overlie and largely conceal the older volcanic sequence. The oldest dated flows were erupted at 14.3±0.8 Ma, and the youngest are 9.8±2.5 Ma (Wallace et al., 1990). These rocks were erupted from several volcanic centers in the Snowstorm Mountains, and limited field evidence suggests that most were fed by dikes. Units range from phenocryst-poor, laterally extensive flows to phenocryst-rich domes. Extensive rhyolitic, high-temperature ignimbrites were emplaced in the northern part of the Snowstorm Mountains at about 13.0 Ma (Wallace, 1993). In places, these ignimbrites were erupted across an extensive shallow lake that lapped onto and extended northwest from the northern Snowstorm Mountains. These ignimbrites were erupted from the Snake River Plain to the north (Ekren et al., 1984). The youngest major unit in the Snowstorms is a series of basalt flows that were erupted at about 9.8 Ma from numerous vents northeast of the main part of the Snowstorms.

## GEOCHEMISTRY AND PETROLOGY OF IGNEOUS ROCKS ALONG PART OF THE NORTHERN NEVADA RIFT

Middle Miocene igneous rocks along the northern Nevada rift between the Cortez and Snowstorm Mountains

form three distinct compositional groups: (1) basalt to andesite, (2) dacite-trachydacite, and (3) rhyolite and rhyolite porphyry (Fig. 7 and Table 2; Wallace and John, 1998; John et al., 1999). All these rocks have similar petrographic and compositional characteristics suggesting that they were erupted at relatively high temperatures and had low water contents and low oxygen fugacities (John et al., 1999). Basalt to andesite compositions are present in all areas except in the northwestern Sheep Creek Range, where the basal middle Miocene units are not exposed. Dacite-trachydacite compositions are limited to the southwestern Sheep Creek Range and the northern Shoshone Range. Rhyolite and rhyolite porphyry are limited mostly to the northern Sheep Creek Range and to the Snowstorm Mountains. In general, the dikes and the oldest related flow rocks have basalt to andesite compositions with the dacites and rhyolites unconformably overlying the older, more mafic rocks. Olivine basalts locally cap the middle Miocene volcanic sequence (southwestern Sheep Creek and Argenta and Malpais Rims) or younger rhyolites and sedimentary rocks (Midas trough area and northern Snowstorm Mountains).

All rocks along the magnetic anomaly between the Shoshone Range and the Snowstorm Mountains are Fe-rich and form a tholeiitic series using classification schemes of Irvine and Baragar (1971) and Miyashiro (1974) (see John et al., 1999). Intermediate-composition and silicic rocks are noteworthy for their extremely low Mg and high Fe contents, and their compositions show a strong Fe enrichment trend (Table 2; John et al., 1999). Intermediate-composition rocks also are potassium-rich but do not have alkaline compositions (John et al., 1999). Intermediate and silicic compositions are highly enriched in large ion lithophilic elements (K, Rb, Ba), Th, rare earth elements, and high field strength elements (Ti, Nb, Y, Zr). These rocks also have low Sr contents (Table 2; John et al., 1999).

Middle Miocene igneous rocks of all three compositional groups share petrographic features that are distinct from age-equivalent igneous rocks in western Nevada (John, 1999; John et al., 1999). These features include generally low phenocryst abundance, anhydrous phenocryst assemblages, and reduced mineral assemblages. Many rocks are aphyric to sparsely porphyritic suggesting that they were erupted at relatively high temperatures. Phenocrysts in mafic to intermediate composition rocks consist of plagioclase + clinopyroxene ± olivine + Fe-Ti oxide minerals. Hydrous minerals such as hornblende and biotite are notably absent. Porphyritic rhyolites also have fayalitic(?) olivine phenocrysts and lack biotite and hornblende phenocrysts.

Preliminary studies of Fe-Ti oxide minerals in the intermediate and mafic rocks from the Mule Canyon area and the southwestern Sheep Creek Range indicate that the magmas were highly reduced with oxygen fugacities between the fayalite-magnetite-quartz and magnetite-wustite oxygen buffers (D.A. John, unpub. data, 1999). Ilmenite commonly is much more abundant than magnetite and is the only Fe-Ti oxide mineral in the late olivine basalt flows. These data, petrographic features described above, and detailed petrologic studies of rocks from the McDermitt caldera complex by Conrad (1984) indicate that magmas of the northern Nevada rift were erupted at high temperatures, were relatively water poor, and had low oxygen fugacities.

Isotopic and compositional data from middle Miocene mafic rocks in northern Nevada generally suggest formation from a subduction-enriched lithospheric mantle source (Fitton et al., 1991). In contrast, isotopic data from the Steens and Columbia River basalt sequences, which do not overlie continental crust, indicate magma derivation from a depleted mantle source, with variable amounts of contamination by a slightly less-depleted oceanic crustal source (Hooper and Hawkesworth, 1993; Carlson and Hart, 1987). Rhyolites along the Snake River Plain, which are correlative with rhyolites in the Snowstorm Mountains and northern Sheep Creek Range, contain both granulite xenoliths and isotopic evidence of derivation from a granulitic continental crust (Honjo and Leeman, 1987). Dacites and trachydacites in the northern Shoshone Range and southwestern Sheep Creek Range have compositional and petrographic affinities to the rhyolites, suggesting that they also were derived largely from water-poor melts of lower crustal derivation.

## AGE CONSTRAINTS ON THE RIFT, INCLUDING NEW GEOCHRONOLOGY

New $^{40}Ar/^{39}Ar$ dates have been obtained from igneous and sedimentary rocks and epithermal gold-silver deposits from central Nevada near the northern Nevada rift. These data suggest that igneous activity and formation of epithermal gold-silver deposits associated with the rift occurred mostly between about 16 and 15 Ma. Table 3 summarizes the new geochronological data.

### IGNEOUS ROCKS

The oldest igneous rocks include mafic volcanic flows and dikes. The oldest of the volcanic rocks are more than 15.85±0.08 Ma, the age of the upper part of the Mule Canyon sequence in the northern Shoshone Range. Other new dates on the basal mafic flows are 15.67±0.09 Ma in the northern Simpson Park Range, 13.55±0.10 Ma in the Sulphur Springs Range, 15.8±0.8 Ma in Corral Canyon in the northern Shoshone Range, and 15.58±0.10 Ma in the southwestern Sheep Creek Range. Previously published K-Ar dates on the basal flows in the southern Snowstorm Mountains range from 15.2±1.6 to 14.7±0.5 Ma (Wallace and others, 1990; Wallace and McKee, 1994). Basaltic andesite flows in the Ivanhoe district underlie a 15.10±0.06 Ma tuff unit and therefore fall within the general age range of this older magmatic suite. Possible feeder dikes for the mafic flows range from 15.73±0.10 to 15.15±0.09 Ma in the Roberts Mountains, and undated dikes at the Mule Canyon Mine clearly fed flows of the Mule Canyon sequence and the overlying andesite of Horse Heaven. All these new ages, which represent the oldest volcanic sequence in the area near the anomaly range from

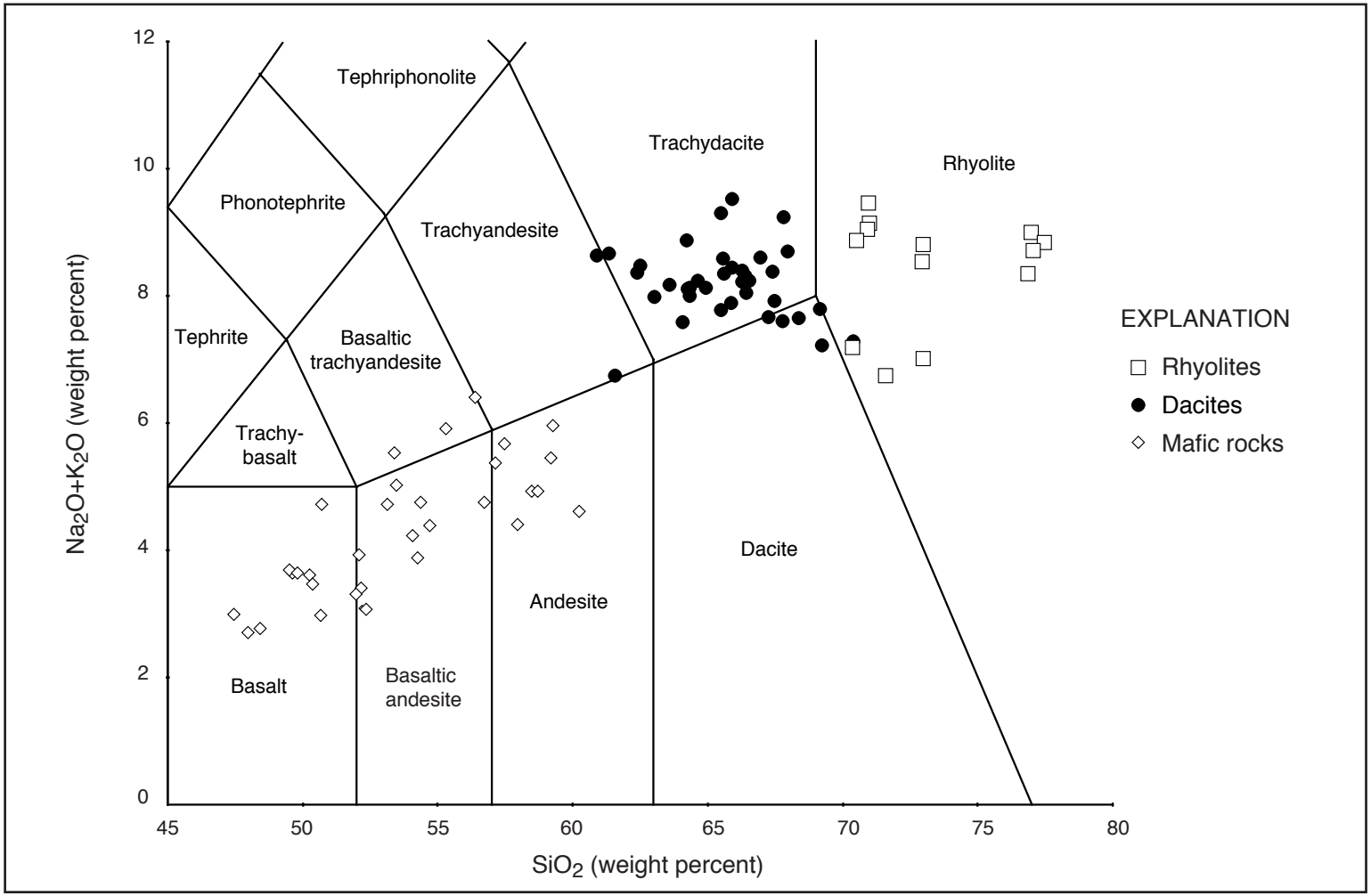


**FIGURE 7. Total alkali-silica diagram for igneous rocks from the northern Nevada rift, showing the three major groups of rocks. Rock classification from IUGS (Le Bas et al., 1986). Data from Wallace (1993), Wallace and John (1998), John et al. (1999), and Table 2.**

about 15.9 to 15.1 Ma. Using samples from the Roberts Mountains, Zoback et al. (1994) reported a somewhat larger range of ages, citing K-Ar dates of 14.1±0.4 to 17.6±1.1 Ma on basaltic dikes and 13.6±0.4 to 18.6±0.7 Ma on basaltic flows. Only one of these ages, however, is significantly older (at 2σ) than 16 Ma. In general, we prefer incremental heating $^{40}Ar/^{39}Ar$ ages of the mafic rocks, because the incremental heating technique offers higher precision than conventional K-Ar methods and because analysis of the $^{40}Ar/^{39}Ar$ age spectrum can reveal samples that give anomalous ages. Because all three of the dikes dated by $^{40}Ar/^{39}Ar$ incremental heating techniques give ages between 16 and 15 Ma, we conclude that most, if not all, of the older mafic rocks, which represent the basal volcanic sequence associated with the magnetic anomaly, formed between about 16 and 15 Ma. Although most of the mafic volcanic rocks appear to have formed during this interval, a few ages as young as about 13.5 Ma suggest that some mafic volcanism persisted for another 1.5 m.y.

Felsic rocks associated with the older mafic sequence are common in the Snowstorm Mountains and in the northern Sheep Creek Range but are absent elsewhere in the region. Extensive and thick pyroclastic rocks and rhyolite flows are interbedded with and cut by older mafic units in the Snowstorm Mountains.

Igneous rocks that are younger than the early mafic suite vary in form and composition in the region. In the Snowstorm Mountains, voluminous, locally derived rhyolite flows, domes, and tuffs were erupted between about 14.3±0.8 and 13.4±0.4 Ma. In the northern Sheep Creek Range, similar rhyolite units were emplaced between about 15.1 and 13.4 Ma. The southwestern Sheep Creek Range and the northern Shoshone Range have a wide range of igneous rocks, including trachydacite flows and intrusions that were emplaced between 15.42±0.10 and 15.33±0.09 Ma, rhyolite porphyry domes (14.84±0.04 Ma in the Izzenhood Gap area of the west-central Sheep Creek Range), and capping olivine basalt flows (14.7±0.2 Ma). South of the Shoshone Range, middle Miocene igneous rocks younger than the early mafic suite essentially are absent.

## SEDIMENTARY ROCKS

Middle Miocene sedimentary rocks are sparse to absent along the magnetic anomaly south of the southwestern part of the Sheep Creek Range. Tertiary sedimentary rocks in that area are slightly or substantially older than mafic volcanic rocks in the Cortez Mountains, Simpson Park Range, and northern Shoshone Range, or they form a thin layer on middle Miocene volcanic rocks (Buckhorn district). The most substantial middle Miocene sedimentary rocks are in the vicinity of the Midas and Ivanhoe districts, 15 to 30 km east of the magnetic anomaly, where a large, shallow lake began to form at about 16.5 Ma (Perkins et al., 1998) and sediments progressively filled the basin to at least 14.4 Ma, forming in part what is known as the Carlin Formation (Wallace and John, 1998; Fleck et al., 1998). Although the lake was contemporaneous with the mafic volcanism, the depocenter was east of the aeromagnetic anomaly. Relatively minor amounts of sediments were deposited in the southwestern Sheep Creek and northern Shoshone Ranges in the interlude between the eruptions of trachydacite and olivine basalt flows; one date from a tuff interbedded with the sediments is 14.94±0.04 Ma.

## STRUCTURAL DEVELOPMENT

As noted by Zoback and Thompson (1978), dikes related to the aeromagnetic anomaly reflect the east-northeast–west-southwest extension direction during their emplacement. The 16 to 15 Ma ages of mafic dikes provide an indication of the age of this extension, and the >15.85±0.08 Ma flows in the northern Shoshone Range indicate that the extensional event may have begun around 16 Ma. North-northwest-trending dacite and rhyolite intrusions that were emplaced from about 15.3 to 13.4 Ma indicate continued east-northeast–west-southwest extension.

Evidence for north-northwest-striking extensional faults is seen in the Mule Canyon area. Here, mafic dikes were emplaced along and are cut by high-angle normal faults. The Muleshoe fault system was active during extension and igneous activity, and it controlled both the emplacement of dikes and the distribution of the mafic flows. Because the flows are at least 15.85 Ma, the faults must have been active by that time. Similarly, the polygonal graben between the Argenta and Malpais Rims accumulated a significant thickness of Mule Canyon sequence flows (Fig. 4), indicating that it, too, was actively forming before 15.85 Ma.

Faulting continued after the formation of the early mafic sequence, as shown by fault control on younger volcanic units. Faults in the northern Shoshone and southwestern Sheep Creek Ranges, including the Muleshoe fault, controlled the distribution of dacite and 14.7 Ma olivine basalt flows. In the Snowstorm Mountains, north-northwest-trending faults controlled the emplacement of rhyolite dikes between 14.3 and 13.4 Ma, cut volcanic units as young as 13.4 Ma, and influenced the distribution of 13.0 Ma welded tuffs.

## MINERAL DEPOSITS

New $^{40}Ar/^{39}Ar$ dates, existing K-Ar dates, and geologic relations at epithermal gold-silver deposits along the rift indicate that all deposits formed in the narrow time interval of about 15.0-15.6 Ma (Table 4; John et al., 1999; John and Wallace, 2000). Ore formation took place at or slightly after the end of the early mafic phase of volcanism, and all deposits are associated spatially with that volcanic suite. Volcanic units that formed after the early mafic event are unmineralized. In places, mineralization clearly was related temporally to specific igneous events, such as the eruption of the 15.2±0.8 to 15.86±0.12 Ma andesite of Horse Heaven in the Mule Canyon area and the 15.07±0.08 Ma Craig rhyolite at Ivanhoe. Elsewhere, such as Midas and Buckhorn, a direct

**TABLE 4. Summary of $^{40}Ar/^{39}Ar$ and K-Ar ages of epithermal gold-silver deposits in the central part of the northern Nevada rift.**

| Deposit | Method/ material dated | Age (Ma) | Source of Data | Comments |
|---|---|---|---|---|
| Midas | K-Ar/adularia | 15.4±0.4 | (1) | |
| Midas | $^{40}Ar/^{39}Ar$/adularia | 15.07±0.05 | (2) | vein in Ken Snyder Mine |
| Midas | $^{40}Ar/^{39}Ar$/adularia | 15.12±0.08 | (3) | vein in Ken Snyder Mine |
| Midas | $^{40}Ar/^{39}Ar$/adularia | 15.23±0.08 | (3) | vein in Ken Snyder Mine |
| Ivanhoe | K-Ar/adularia | 15.1±0.4 | (4) | |
| Mule Canyon | $^{40}Ar/^{39}Ar$/adularia | 15.59±0.04 | this study | quartz-adularia vein from the South pit |
| Fire Creek | | <15.86±0.12 | this study | age of the host rock (andesite of Horse Heaven) |
| Buckhorn | K-Ar/adularia | 15.0±0.4 | (5) | |

All $^{40}Ar/^{39}Ar$ ages standardized to an age of 513.9 Ma for interlaboratory standard hornblende, MMhb-1. Sources of dates: (1) recalculated from McKee et al. (1976), (2) recalculated from Schmidt and Goldstrand (this volume), (3) recalculated from Leavitt et al. (2000), (4) Bartlett et al. (1991), and (5) recalculated from Wells and Silberman (1973).

temporal association with a magmatic or thermal event is not yet clear. More accurate dating of most of the ore deposits and their host rocks is needed.

## ORIGIN OF THE NORTHERN NEVADA RIFT AND COMPARISON WITH INTRA-CONTINENTAL RIFTS

Zoback and Thompson (1978) applied the term "rift" to a north-northwest-trending aeromagnetic lineament in northern Nevada and a coincident narrow zone of mafic dikes at several places along it. Building upon the plate tectonic model of Atwater (1970), Zoback and Thompson (1978) concluded that the northern Nevada rift was an indicator of west-southwest–east-northeast-directed regional extension in the middle Miocene. They concluded that later Miocene and Pliocene east-northeast-striking normal faults that cut rift-related rocks were consistent with a 45° clockwise rotation of the regional stress field to a northwest-oriented extension direction sometime after about 10 Ma and most likely by about 6 Ma (Zoback and Thompson, 1978; Wallace, 1991).

Although the mafic dikes that are presumed to create the aeromagnetic anomaly formed during the middle Miocene (roughly between about 16 and 15 Ma), the zone along which they intrude may have had a pre-Miocene precursor. Wooden et al. (1998) and Tosdal et al. (2000) noted that part of the northern Nevada rift is subparallel to the Battle Mountain-Eureka mineral belt and to a embayment in Pb isotopic isopleths. They suggested that this feature may represent an old major crustal fault largely within a region of continental crust thinned during Late Proterozoic rifting. Theodore et al. (1998) suggested that late Paleozoic, south-directed compression created major conjugate strike-slip fault zones, one of which may coincide with at least the north-central segment of the northern Nevada rift. The aeromagnetic anomaly occurs in the stable craton as well as in several terranes that were accreted to the craton in the Paleozoic (e.g., Roberts Mountains, Golconda terranes) and the Mesozoic (Jungo terrane; Lahren et al., in press). If the trend of the aeromagnetic anomaly is a true indicator of regional stress (Zoback and Thompson, 1978), then a crustal break along this trend had an orientation unrelated to the Phanerozoic geologic terranes in this part of Nevada.

Evidence for the origin of the northern Nevada magnetic anomaly as an intracontinental rift has been limited to the aeromagnetic anomaly, the dike swarms that are presumed to cause it and flow units related to the dikes, and coincident normal faults (see summary in Zoback et al., 1994). The geologic features presented in this paper permit a more definitive evaluation of the origin of this feature.

Intracontinental rifts have a wide variety of evolutionary histories and resulting morphologies. They vary considerably in size, and research generally has focused on the larger rifts, although numerous smaller rifts have been identified. Many intracontinental rifts (e.g., Rio Grande rift, East and West African rift systems; Keller et al., 1991; Chapin and Cather, 1994; Rosendahl, 1987) are composed of a series of grabens with highlands on one or both sides. The rifts typically are long (>1000 km) and wide (>50 km). The highlands can rise more than 3 km above the floor of the graben, and high-angle normal faults separate the graben and the highlands. Early extension produced broad, shallow basins; subsequent high-angle faulting generated the pronounced graben-highland pairs. Abundant clastic sediments filled the developing basins, and related volcanism was both abundant or relatively minor. Other intracontinental rifts, such as the Mid-Continent rift of North America, have a different history (Cannon, 1992). Early and extensive dike-fed mafic flows both predated and formed during fault-related basin development.

The flows extended well beyond the axis of the rift, and clastic sedimentation was minor due to the volume of volcanic material. The basins continued to form, either by down-faulting along normal faults or through crustal flexing, and were filled with mafic flows that largely were confined to the grabens. As basin filling continued, volcanism waned and eventually ceased. Thick fluvial and lacustrine sediments began to be deposited as volcanic activity decreased. Extension ceased during the sedimentation phase, and the sedimentary deposits filled and eventually extended well beyond the original central basins.

Evidence presented here suggests that the formation of the northern Nevada rift is somewhat analogous to the Mid-Continent style of rift evolution. The major features of the northern Nevada rift include the aeromagnetic anomaly, mafic dike swarms and related flow units, graben-filling to more extensive mafic to intermediate flows with limited clastic sediments (Argenta and Malpais Rim areas, and possibly the Midas area), and late lacustrine sedimentation (Cortez Mountains, northeastern Sheep Creek Range, and northern Snowstorm Mountains). The Mule Canyon/Argenta Rim/Malpais Rim area contains the best examples of the volcanic and basin-forming phases of the rift evolution, and the northeastern Sheep Creek Range and, to a limited extent, the Cortez Mountains provide examples of the later sedimentation-dominant phase.

In summary, the middle Miocene northern Nevada rift is the product of two major regional processes: (1) onset of regional west-southwest–east-northeast-directed extension, and (2) emplacement in the upper crust of magmas related to development of the Yellowstone hot spot. Extension created or reactivated linear breaks in the crust, including the structural precursor along the northern Nevada rift and two other similar but shorter zones farther to the west in northwestern Nevada (McKee and Blakely, 1990; Blakely and Jachens, 1991). The Yellowstone hot spot, which penetrated the upper crust at about 16.5 Ma, began to produce extensive dike swarms and lava flows over a very large region. Some of these magmas invaded the crustal flaw in northern Nevada, leading to magmatism and faulting along the rift. Regional west-southwest–east-northeast-directed extension continued until sometime after 10 Ma, and hot-spot-related volcanism continued to about 13 Ma over a relatively broad area that overlapped the northern part of the rift. However, magmatism along the rift declined as the hot spot progressively migrated to the northeast, and thermal uplift decreased as a result. Late Miocene to Holocene faulting, in response to a change in the regional extension direction, produced normal faults that cut and exposed the faults and igneous and sedimentary rocks that formed during the 16.5 to 15 Ma period of time.

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