Geophysical Setting of the Blue Mountain Geothermal Area, North-Central Nevada and its Relationship to a Crustal-Scale Fracture Associated with the Inception of the Yellowstone Hotspot

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Keywords

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ABSTRACT

The Blue Mountain geothermal field, located about 35 km northwest of Winnemucca, Nevada, is situated along a prominent crustal-scale fracture interpreted from total-intensity aeromagnetic and gravity data. Aeromagnetic data indicate that this feature is related to the intrusion of mafic dikes, similar to the Northern Nevada Rift (Zoback et al., 1994), and may be associated with the inception of the ~16 Ma Yellowstone Hotspot. This pre-existing large-scale crustal feature may have influenced the location of the geothermal prospect and the spatially associated epithermal gold deposit on the western flank of Blue Mountain. Other epithermal gold deposits in north-central Nevada are also strongly correlated with this and other similar crustal-scale fractures associated with the Yellowstone Hotspot (Ponce and Glen, 2002). Combined geologic and geophysical studies suggest this crustal feature may influence the migration of hydrothermal fluids and that other crustal-scale features in northern Nevada may be associated with geothermal resources.

We investigate mafic dikes exposed along the western flank of Blue Mountain, and encountered in drill-holes DB-1 and DB-2 at depths of about 500 and 750 meters, respectively. The dikes are composed of gabbro to diorite and physical-property measurements indicate they have an average saturated-bulk density of 2,852 kg/m^3 and a moderately magnetic susceptibility of about 18.0 x 10^{-3} SI. Gravity and magnetic modeling reveal that the dikes are much more extensive in the subsurface than previously thought. Geologic investigations by Wyld (2002) indicate the dikes are approximately 10 Ma and paleomagnetic investigations yield directions consistent with a mid-Miocene age, suggesting they may be related to the emergence of the Yellowstone Hotspot.

Introduction

The Blue Mountain geothermal area is situated along the western flank of Blue Mountain about 35 km west of Winnemucca, Nevada (Figure 1). The geothermal area was originally discovered during exploration of a spatially associated epithermal gold deposit (Parr and Percival, 1991), it is now the site of a

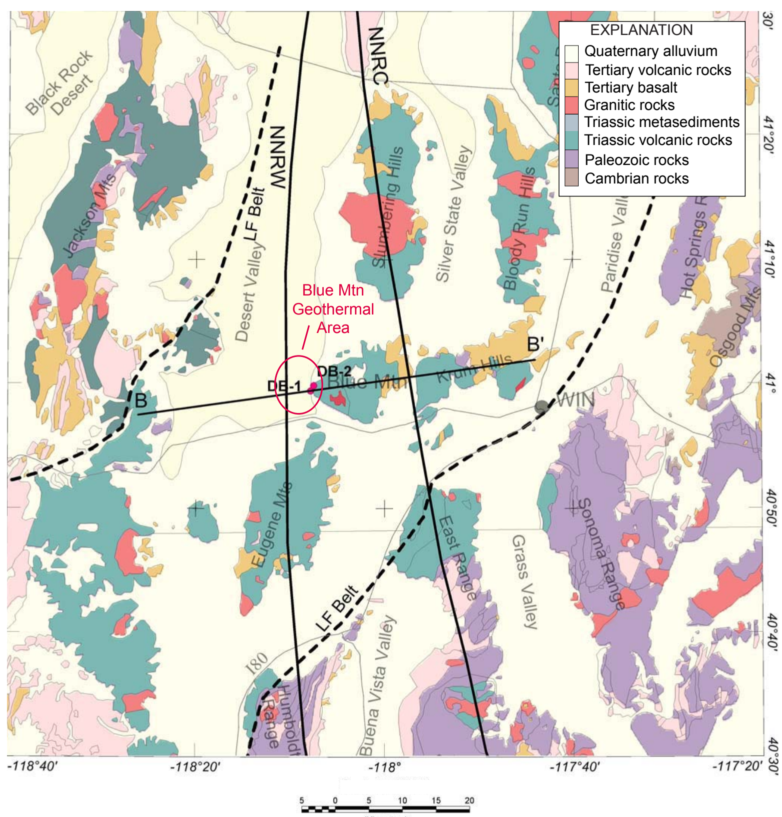


Figure 1. Simplified geologic map (modified from Stewart and Carlson, 1978) of the study area showing location of profile BB′. Bold black lines, western and central Northern Nevada Rifts (NNRW, NNRC) inferred from regional aeromagnetic data; LF Belt, Luning-Fencemaker fold and thrust belt (from Wyld, 2002); gray lines, major roads; DB-1, drill-hole DB-1; WIN, Winnemucca.

~50 megawatt geothermal facility operated by Nevada Geothermal Power.

Blue Mountain is located in the central part of the late Mesozoic Luning-Fencemaker fold and thrust belt of north-central Nevada (Figure 1) that was responsible for the closing of a Late Triassic back arc basin in the Jurassic (e.g., Oldow, 1984; Wyld, 2002). Although the geology of Blue Mountain was first described by Wilden (1964), more recent studies by Wyld (2002) indicate that Blue Mountain is composed of three Triassic metasedimentary stratigraphic units that have a combined structural thickness of more than 6 km. And in particular, geologic studies show that the originally mapped Jurassic diorite stock (Wilden, 1964), is instead a north-trending mafic dike swarm (Wyld, 2002). The mafic dikes are subvertical, range in thickness from 1 to 200 m, and composed of diorite to gabbro (Wyld, 2002). Although the dike swarm is undated, $^{40}Ar/^{39}Ar$ analyses of Triassic metasedimentary rocks from Blue Mountain indicate a prominent episode of Ar loss in the late Tertiary at about 10 Ma that could be due to a thermal event associated with the intrusion of the dikes (Wyld, 2002; Wyld et al., 2003). Continuing detailed geologic studies of the Blue Mountain geothermal area show that it occurs at the intersection of a NNE-trending normal fault system along the western flank of Blue Mountain and Eugene Mountains, and a WNW-trending fault system on the southwest side of Blue Mountain that may represent a dilational step in the fault system (Faulds and Melosh, 2008).

We use gravity and magnetic methods to further investigate the regional geophysical setting of the Blue Mountain geothermal area as an aid in assessing the regional geothermal resource potential in northern Nevada. In particular, we explore the relationship of the Blue Mountain geothermal area and a crustal-scale fracture possibly associated with the inception of the Yellowstone Hotspot (Ponce and Glen, 2008)

Geophysical Data and Methods

Gravity and Magnetic Data

An isostatic gravity map of the study area (Figure 2) was derived from a statewide gravity data compilation of Nevada (Ponce, 1997) that was augmented with new gravity stations collected by the U.S. Geological Survey throughout northern Nevada, including over 500 gravity stations that we collected in the vicinity of Blue Mountain during 2008 and 2009 (Figure 2). All gravity data were reduced using standard gravity methods (e.g.,

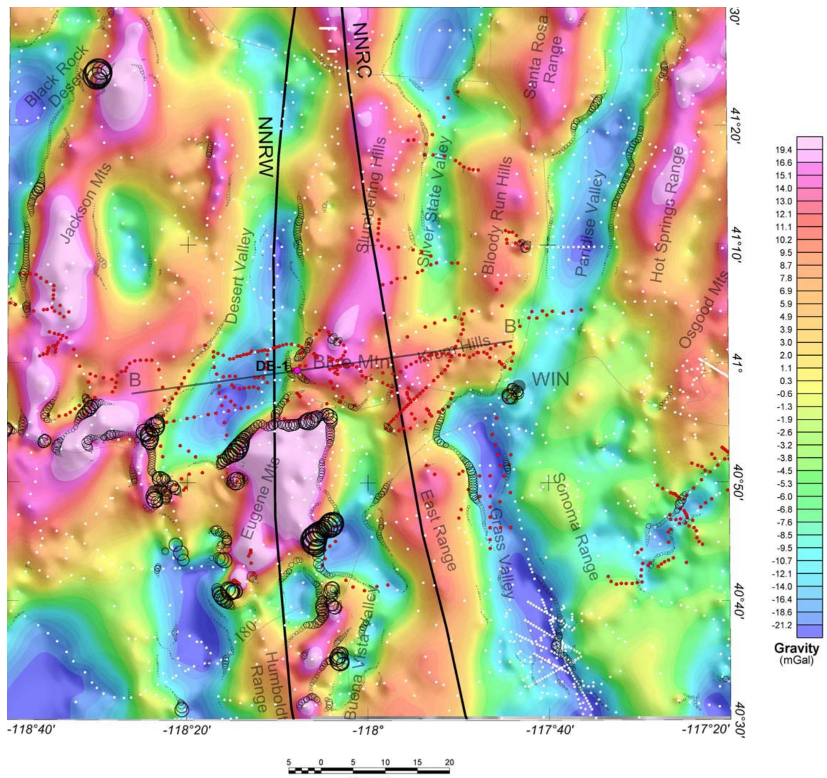


Figure 2. Isostatic gravity map of the study area. Black circle, proportionally-sized maximum horizontal gradient location; red dot, new gravity station; white dot, pre-existing gravity station. See Figure 1 for additional explanation.

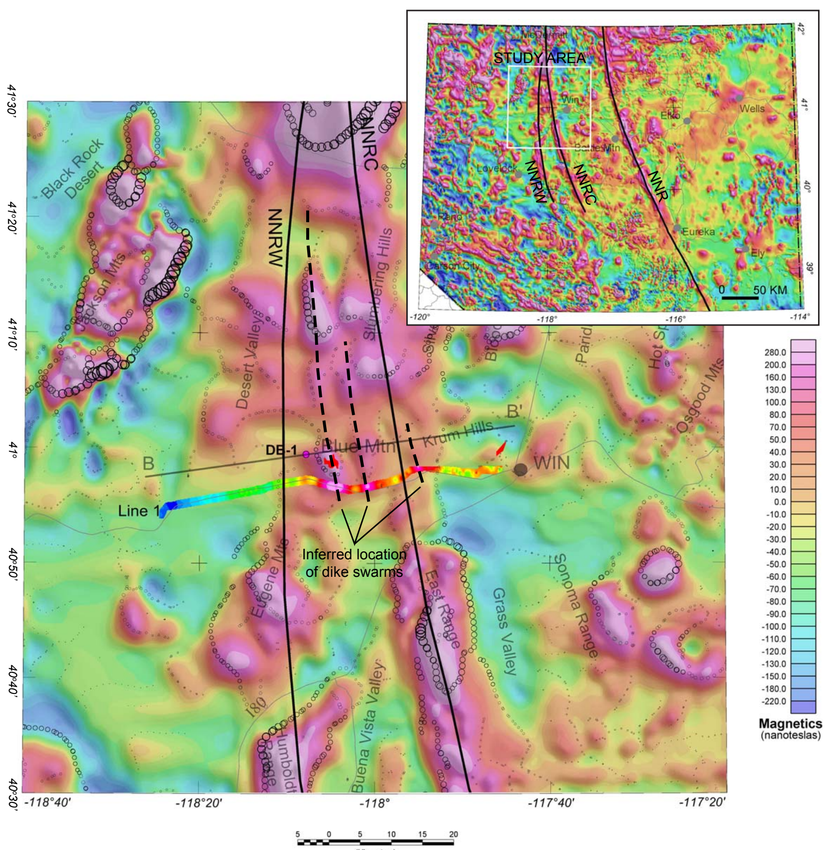


Figure 3. Aeromagnetic map of the study area (from Kucks et al., 2006) with overlay of truck-towed magnetic data along Jungo Road (Line 1). Dashed lines, inferred location of mafic dike swarms; black circle, proportionally-sized maximum horizontal gradient location. Inset: Aeromagnetic map of northern Nevada (from Kucks et al., 2006) showing the three-main Northern Nevada Rifts. See Figure 1 for additional explanation.

Dobrin and Savit, 1988; Blakely, 1995) and include an isostatic gravity correction. The resulting isostatic anomaly is particularly useful because it emphasizes features in the mid to upper crust by removing long-wavelength variations in the gravity field related to the isostatic compensation of topography (e.g., Jachens and Roberts, 1981; Simpson and others, 1986). Gravity values are reported in milligals (mGal), where 1 mGal is equivalent to an acceleration of 10^{-5} m/s^2.

An aeromagnetic map of the study area (Figure 3) was derived from an updated statewide compilation of Nevada by Kucks et al. (2006). Aeromagnetic data were corrected by Kucks et al. (2006) for diurnal variations of the Earth's magnetic field, upward or downward continued to a constant elevation of 305 m above the ground, adjusted to a common datum, and merged to produce a uniform map with a grid spacing of 500 m. This improved compilation, although composed of surveys acquired with different specifications, allows interpretation of magnetic anomalies across survey boundaries.

Aeromagnetic surveys in the study area have a range in flight-line spacing from 400 m to 3.2 km, and a range in flight-line altitude from 150 m above ground to 2.7 km barometric elevation. However, most of the study area has a poor spatial resolution with flight-line spacing of 1.6 to 3.2 km and a flight-line altitude of 2.7 km barometric elevation. Because of the widely spaced surveys flown at high flight-line altitudes, shallow magnetic sources may not be well resolved in parts of the aeromagnetic map. However, these issues are not significant for the regional-scale magnetic interpretations presented here.

Boundary Analysis

A directional derivative technique was used to locate maximum horizontal gradients of gravity data (R.W. Simpson, oral commun., 2006), which often occur over abrupt lateral changes in the density of the underlying rock units, especially for shallow sources with steep edges (e.g., Cordell and Grauch, 1985; Blakely and Simpson, 1986; Blakely, 1995). Because the regional magnetic field and the direction of magnetizations are seldom vertical, magnetic anomalies are commonly laterally displaced from their sources and often have a more complex shape than gravity anomalies. For these reasons, magnetic data were first transformed into their magnetic potential (or pseudogravity) (e.g., Blakely, 1995) prior to horizontal gradient analysis. As a consequence, locations of maximum horizontal gradients of the magnetic data shown in Figure 3 are shifted with respect to the apparent edges of the non-transformed magnetic anomalies. Alignments of maximum horizontal gradient locations obtained from both gravity and magnetic data (open circles, Figures 2 and 3) were used as a proxy for lineaments, faults, and boundaries of geologic features or geophysical terranes.

Regional Geophysical Discussion

The isostatic gravity map of the study area (Figure 2) is dominated by a series of gravity highs and lows that in general, reflect dense pre-Cenozoic rock outcrops and low-density basin fill deposits, respectively. Gravity highs occur over Blue Mountain, Slumbering Hills, Bloody Run Hills, Eugene Mountains, and the East Range and reflect Paleozoic rocks and Triassic to Jurassic metasedimentary rocks. Relatively lower-amplitude gravity highs over parts of the Slumbering Hills and the Bloody Run Hills reflect lower-density plutonic rocks that compose the central parts of the ranges (Figures 1 and 2). The lowest gravity values are associated with the surrounding valleys and reflect moderately deep sedimentary basins. Based on the amplitude of the gravity lows, these basins reach depths of up to at least 2 km, which is typical of most basins in Nevada.

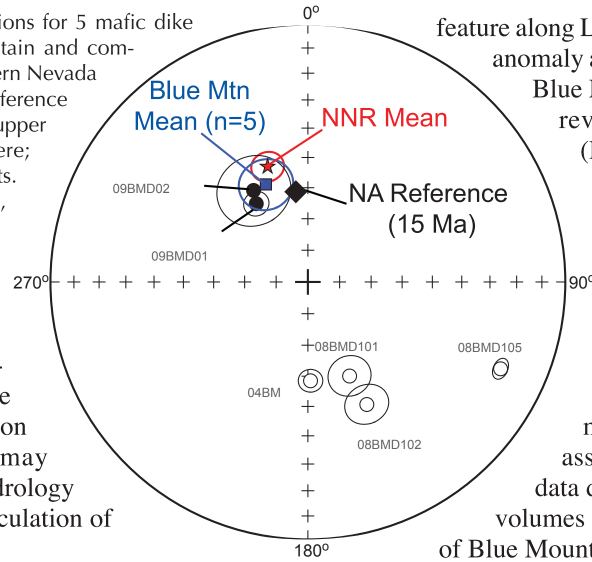
The aeromagnetic map of the study area (Figure 3) is dominated by broad long-wavelength high-amplitude anomalies associated with moderately magnetic plutonic rocks mapped throughout the area (Stewart and Carlson, 1978). High-amplitude, short-wavelength anomalies such as in the northwest corner of the map are associated with volcanic rocks. Magnetic anomalies are particularly useful for delineating the subsurface extent of plutonic rocks, because plutons are often more magnetic than the basement rocks they intrude. For example, the pluton in the central block of the Slumbering Hills may extend well beyond the range and beneath Desert Valley. In addition to these features, prominent arcuate aeromagnetic anomalies referred to as the western and central Northern Nevada Rifts (NNRW, NNRC, Figure 3), that are similar to the Northern Nevada Rift (NNR, inset, Figure 3) east of Battle Mountain, reflect crustal-scale mafic-dike intrusions that occurred during the inception of the Yellowstone Hotspot (Zoback et al., 1994; Ponce and Glen, 2008). Indeed, the mafic dike swarm along the western flank of Blue Mountain with its associated magnetic anomaly is the surface manifestation of one of these rift zones.

Detailed Discussion

Density and susceptibility data from drill holes DB-1 and DB-2 (Ponce et al., 2008) indicate that Blue Mountain mafic dikes are relatively dense (2,852 kg/m^3) and moderately magnetic (18.0 x 10^{-3} SI). In contrast, Triassic metasedimentary rocks have a density of about 2,700 kg/m^3 and are essentially nonmagnetic. Physical property measurements on core samples from DB-1 and DB-2 reveal a high porosity and a relatively flat susceptibility zone from a depth of about 250 to 400 m that probably represents a highly-fractured and altered zone within the Triassic metasedimentary rocks. Paleomagnetic sampling from 5 sites show that the mafic dike swarm at Blue Mountain correlates well with the mean direction of mafic dikes associated with the Northern Nevada Rift and the mid-Tertiary (15 Ma) reference direction of North America (Figure 4). Paleomagnetic data reveal that the Blue Mountain dikes have normal, reversed, and transitional polarities (Figure 4), suggesting that they have recorded a magnetic reversal as have the dikes along the Northern Nevada Rift (Zoback et al., 1994). These paleomagnetic results suggest that the Blue Mountain dikes have a similar origin and age as the Northern Nevada Rift and are probably associated with large-scale fracturing of the earth's crust that occurred during the inception of the Yellowstone Hotspot at about 16 Ma.

Isostatic gravity data indicate that Desert Valley, a *dogleg* shaped basin on the west flank of Blue Mountain (Figure 2), abruptly changes its direction from north-northwest to north along a possible extension of a NNW-trending fault at the southwest boundary of Blue Mountain (Faulds and Melosh, 2008). Such

Figure 4. Stereonet of paleomagnetic directions for 5 mafic dike sites along the western flank of Blue Mountain and comparisons to the mean directions of the Northern Nevada Rift (NNR) and the mid-Tertiary (15 Ma) reference direction for North American. Open circles, upper hemisphere; solid circles, lower hemisphere; and ellipses, cones of 95% confidence limits. Sample sites indicate normal (09BMD01, 02), reversed (04BM, 08BMD101, 102), and transitional polarities (08BMD105).



changes in the trend of sedimentary basins are common along the Northern Nevada Rift, suggesting that these rift-like features may resist deformation (Blakely and Jachens, 1991) and may influence basin development and hydrology (Ponce and Glen, 2008), including circulation of hydrothermal fluids.

A truck-towed magnetic profile along Jungo Road (Line 1, Figure 5A) reveals a number of magnetic anomalies, some of which appear to be related to moderately magnetic normal and reversely polarized volcanic rocks. However, the most prominent feature along Line 1 is a broad, high-amplitude magnetic anomaly associated with the exposed mafic dikes at Blue Mountain (Figure 3). Here, magnetic data reveal a *double-humped*-shaped anomaly (Figure 5A) associated with the exposed dikes that likely represents the regionally defined crustal-scale fracture NNRW (Ponce and Glen, 2008). In addition, the magnetic profile images a prominent anomaly that may be associated with another regionally defined fracture NNRC (Figures 3 and 5). Because of the absence of high-amplitude and short-wavelength magnetic anomalies, except for those associated with the dike swarm, magnetic data do not indicate the presence of significant volumes of volcanic rocks along the western flank of Blue Mountain.

A two-dimensional (2D) gravity and magnetic model across Blue Mountain (Figure 5B), constrained by surface geology and physical property measurements, indicate that the Blue Mountain dike swarm is much more extensive in the subsurface than previously thought. The amplitude of the gravity high over Blue Mountain and the relatively high density of the dikes (2,852 kg/m^3), suggests that the modeled dike body underlying Blue Mountain contains only about 1/3 dike material. In addition, the mafic dike swarm probably extends to at least mid-crustal depths (Figure 5B). Not surprisingly, these modeling results are quite similar to those found along the NNR, east of Battle Mountain (Zoback et al, 1994; Watt et al., 2007), including the *double-humped*-shaped magnetic anomaly and the signature of the gravity high. In addition, the 2D gravity model indicates that Desert Valley reaches a depth of at least 2 km along profile BB' (Figure 5B), assuming a density contrast of 500 kg/m^3 between basin fill deposits (2200 kg/m^3) and basement rocks (2700 kg/m^3). However, the depth to basement estimate depends on the density of the basin fill deposits and its variation with depth, which is poorly constrained and may improve with more detailed drill-hole information.

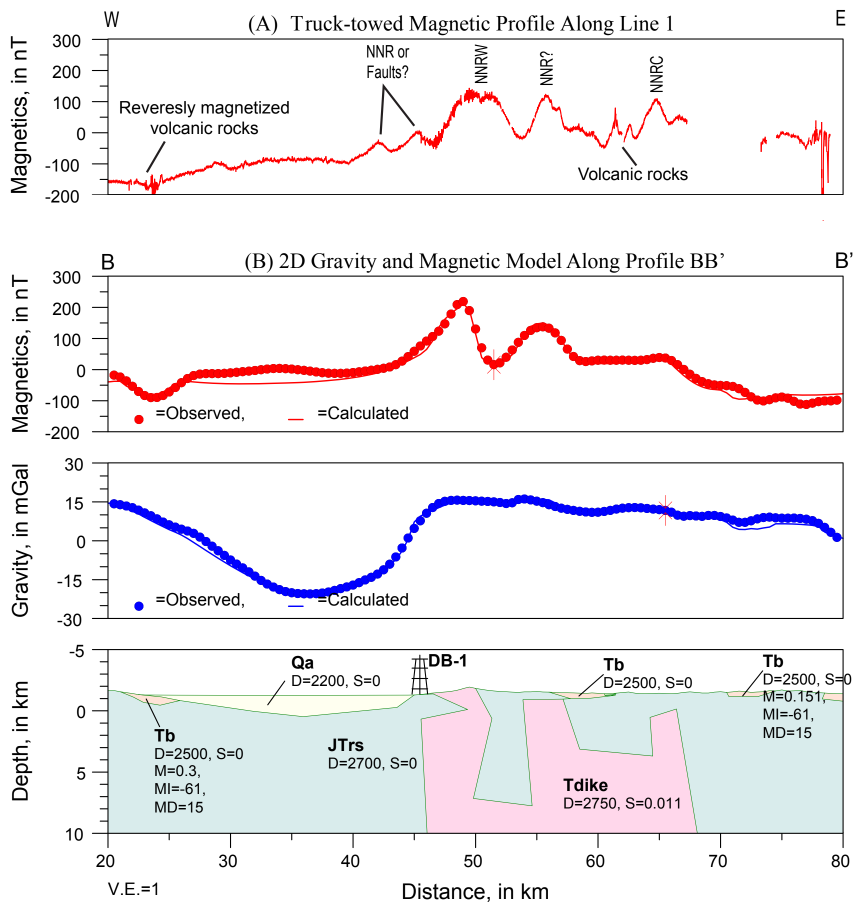


Figure 5. (A) Truck-towed magnetic profile along Line 1 (see Figure 3), about 5-km south of profile BB'. (B) Two-dimensional gravity and magnetic model along profile BB'. Qa, alluvium; Tb, Tertiary basalt; Tdike; Tertiary diorite to gabbro dikes; JTRs, Jurassic to Triassic metasedimentary rocks. D, density in kg/m^3; S, susceptibility in SI units; M, remanent magnetization in A/m; MI, magnetic inclination in degrees; MG, magnetic declination in degrees. See Figure 1 for additional explanation.

Conclusions

The Blue Mountain geothermal field appears to be situated along a prominent crustal-scale fracture interpreted from total-intensity aeromagnetic and gravity data. Aeromagnetic data indicate that this fracture is composed of mafic dikes, similar to the Northern Nevada Rift. The dikes are composed of gabbro to diorite and have an average saturated-bulk density of 2,852 kg/m^3 and a moderate magnetic susceptibility of about 18.0 x 10^{-3} SI. Paleomagnetic investigations indicate the dikes have a direction consistent with a mid-Miocene age, suggesting they may be related to the inception of the Yellowstone Hotspot. This pre-existing fracture may influence the migration of hydrothermal fluids, and suggests that other crustal-scale features in northern Nevada may be associated with geothermal resources as well.

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