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Relationship of Epithermal Gold Deposits to Large-scale Fractures in Northern Nevada

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Abstract

Geophysical maps of northern Nevada reveal at least three and possibly six large-scale arcuate features, one of which corresponds to the northern Nevada rift that possibly extends more than 1000 km from the Oregon-Idaho border to southern Nevada. These features may reflect deep discontinuities within the earth's crust, possibly related to the impact of the Yellowstone hotspot. Because mid-Miocene epithermal gold deposits have been shown to correlate with the northern Nevada rift, we investigate the association of other epithermal gold deposits to other similar arcuate features in northern Nevada. Mid-Miocene and younger epithermal gold-silver deposits also occur along two prominent aeromagnetic anomalies west of the northern Nevada rift. Here, we speculate that mid-Miocene deposits formed along deep fractures in association with mid-Miocene rift-related magmatism and that younger deposits preferentially followed these pre-existing features. Statistical analysis of the proximity of epithermal gold deposits to these features suggests that epithermal gold deposits in northern Nevada are spatially associated with large-scale crustal features interpreted from geophysical data.

Introduction

RECENT gravity and magnetic studies of northern Nevada have spawned new data and insights into the origin and character of large-scale geologic features and their relationship to gold mineralization in northern Nevada. Major lithologic or structural discontinuities in the crust that may, in part control ore-forming environments, commonly correspond to prominent lateral variations in density and magnetization, expressed in gravity and magnetic maps, respectively. One of the most prominent of these features is the northern Nevada rift [NNRE (northern Nevada rift-east), Fig. 1].

Previous studies indicate that the NNRE is related to a mid-Miocene (17-14 Ma) mafic dike swarm that is defined by a narrow (4-7 km), north-northwest trending, linear magnetic anomaly (Zoback and Thompson, 1978; Zoback et al., 1994). Based on an analysis of aeromagnetic flight-line profiles spaced 5 km (3 mi) apart, the rift extends over 500-km from the Nevada-Oregon border to southern Nevada (Blakely and Jachens, 1991). In addition, aeromagnetic and topographic data suggest that it may extend to the Nevada-Arizona border (Ponce and Glen, unpub. data, 2001). Geophysical studies also extend both the NNRE and similarly related fractures NNRW (northern Nevada rift-west) and NNRC (northern Nevada rift-central) (Fig. 1) northward over 200 km beyond the Nevada-Oregon border (Glen and Ponce, 2000). Combined, these studies suggest that the total extent of the NNRE may exceed 1000 km.

Several workers have suggested that the NNRE may be related to a mantle plume associated with the Yellowstone hotspot originating near the McDermit caldera (Zoback and Thompson, 1978; Zobak et al., 1994; Camp, 1995; Pierce et al., 2000). However, we speculate that all these large-scale fractures formed as a result of the impact of the Yellowstone hotspot on the earth's crust along the Oregon-Idaho border (Glen and Ponce, 2000; 2001).

Stewart and others (1977) suggested that aeromagnetic anomalies and mineral deposits are associated with patterns of Cenozoic igneous rocks, especially along the NNRE (Fig 2). Although, the correlation of the western two anomalies (NNRW, NNRC) with mid-Miocene igneous rocks is not as prominent (Fig. 2), paleomagnetic investigations indicate that numerous mid-Miocene mafic dikes may be present along these two features as well (Glen and Ponce, 2000; 2001). More recent geologic studies by John and Wallace (2000) indicate that mid-

Miocene epithermal gold-silver deposits in northern Nevada are associated with the NNRE. They show that several epithermal deposits are spatially and temporally associated with rift-related magmatism and faulting in the north-central part of the NNRE.

Epithermal gold-silver deposits in Nevada are typically hosted in volcanic rocks that range in age from about 43 Ma to present (Cox et al., 1991). These deposits form in near surface environments (less than about 1-2 km) in the distal parts of igneous systems where gold deposition is related to low temperature (150-300ºC) hydrothermal processes. Here, we speculate that mid-Miocene epithermal gold-silver deposits formed along large-scale fractures that acted as conduits for ore-forming solutions in northern Nevada during mid-Miocene rift-related magmatism and that younger epithermal deposits preferentially formed along these pre-existing features.

Gravity and Magnetic Methods

Gravity

Gravity data for northern Nevada were derived from a statewide compilation by Ponce (1997) and supplemented by additional gravity data in northern Nevada (Ponce, 2001). The study area includes over 30,000 gravity stations that were reduced to a common datum using standard reduction methods that included terrain and isostatic gravity corrections. The isostatic gravity corrections were based on an Airy-Heiskanen model of local isostatic compensation that enhances sources within the shallow- to mid-crust by removing long-wavelength variations in the gravity field that arise from the isostatic compensation of topography (Jachens and Roberts, 1981; Simpson et al., 1986).

Because many of the features on the isostatic gravity map are obscured by the effect of low-density poorly to unconsolidated sedimentary deposits in Cenozoic basins, their effects were minimized by using an iterative gravity inversion technique developed by Jachens and Moring (1990). This was accomplished by separating the gravity field into two components: the field caused by pre-Cenozoic or 'basement' rocks and the field caused by overlying younger Cenozoic basin deposits. An initial basement gravity field was calculated by using just those gravity stations located on pre-Cenozoic basement outcrops. The initial basement gravity field was only approximate because stations located on pre-Cenozoic basement rocks were influenced by the gravity effect of low-density deposits in nearby basins, especially for those stations near the edge of adjoining basins. The difference between the isostatic gravity and basement gravity fields provided a first estimate of the basin gravity field, which was inverted to provide the first estimate of the basin depth and shape. The gravitational effects of the basins were then subtracted from each basement station, and an improved basement gravity field was calculated. This process was repeated until successive iterations converged.

Inherent limitations in the inversion process included: gravity data coverage (especially for stations on basement outcrops), assumptions regarding concealed geology, and distribution of pre-Cenozoic basement outcrops. A more detailed discussion of the limitations and accuracy of the method was given by Jachens and Moring (1990). The basement gravity map (Fig. 4) reflects lateral density variations in pre-Cenozoic basement rock.

Magnetics

An aeromagnetic map of northern Nevada (Fig. 4) was derived from a statewide compilation by Hildenbrand and Kucks (1988). Aeromagnetic survey specifications in this compilation vary, but most of the surveys were flown at a flight-line spacing of 1.6-3.2 km (1-2 mi) and a barometric flight-line altitude of 2.7 km (9,000 ft) or higher. The northeastern part of the map is covered by NURE (National Uranium Resource Evaluation) aeromagnetic surveys flown at a coarse flight-line spacing of 4.8 km (3 mi) and a nominal flight-line elevation of 120 m (400 ft) above ground. Some parts of the map were flown at a flight-line spacing of 1.6 km (1 mi) and a nominal flight-line elevation of 152-610 m (500-2,000 ft) above ground. Residual magnetic anomalies were calculated by subtracting an International Geomagnetic

Reference Field (Langel, 1992) appropriate for the year of the survey. Individual aeromagnetic surveys were normalized (upward or downward continued), if necessary, to a flight-line elevation of 305 m (1,000 ft) above ground, adjusted to a common datum, and merged to produce a uniform map that allows interpretations across survey boundaries (Fig. 4).

In order to enhance magnetic anomalies caused by sources in the mid-crust, a filtering technique was used to separate intermediate- from short- and long-wavelength anomalies. This was accomplished by using a match filter (Syberg, 1972; Phillips, 2001) that models the power spectrum of observed anomalies as originating from horizontal layers of varying depth. The intermediate-depth layer (Fig. 5) reflects sources in the mid-crust essentially deeper than approximately 5 km. An inherent limitation in any wavelength filtering process is that the separation is not complete, because, for example, shallow sources produce anomalies that contain intermediate wavelengths, as well as short and long wavelengths.

Regional Fracture Patterns

An updated isostatic gravity map, incorporating more than 2,000 recently collected gravity stations in north-central Nevada, supports the interpretation that a steep isostatic gravity gradient is associated with the NNRE (Blakely and Jachens, 1991). Isostatic gravity anomalies (not shown) are also associated with the two sub-parallel NNRE-like features to the west (NNRW, NNRC, Fig. 1). A prominent 'V'-shaped basement gravity anomaly (Fig. 3) probably reflects a density discontinuity in the basement rocks of northern Nevada, possibly part of the Precambrian to mid-Paleozoic continental margin of North America. Much of the NNRE corresponds to the western margin of the 'V'-shaped basement gravity anomaly. Although not conclusive, this geometry implies that the NNRE was partly controlled by a pre-existing basement structure. The western leg of the 'V'-shaped basement gravity high is over 250-km long and 40-km wide and is oriented 15-20^0 clockwise with respect to the Battle Mountain-Eureka mineral trend (Roberts, 1966), a NNW-trending alignment of base and precious metal deposits. The Battle Mountain-Eureka mineral trend may also be related to a pre-existing crustal feature described by Grauch et al. (1995, 1998), based on gravity and magnetelluric data.

Aeromagnetic compilations in the 1960s (Philbin et al., 1963; Mabey, 1966) allowed only a piecemeal view of the magnetic expression of Nevada. A more complete view was not widely available until a statewide aeromagnetic compilation was released by Hildenbrand and Kucks (1988). These data reveal several prominent and arcuate magnetic highs that traverse most of northern Nevada (Fig. 4). Although, these features are delineated by their centerlines, they range in width from about 4-7 km. (Fig. 4). The most prominent of these anomalies is the NNRE, originally defined on the basis of aeromagnetic data and interpreted as a mid-Miocene mafic dike swarm that reflects the mid-Miocene stress direction (Zoback, 1978; Zoback et al., 1994). Intermediate-wavelength magnetic sources (Fig. 5) indicate that these anomalies extend well beyond the Nevada-Oregon border and converge at a point along the Oregon-Idaho border at lat 44°N.

Glen and Ponce (2000, 2001) describe these features in more detail and speculate on their origin and relationship to the emergence of the Yellowstone hotspot. Presumably, the mid-Miocene emergence of the Yellowstone hotspot and associated topographic uplift (Pierce et al., 2000) and dike injection led to regional fracturing of the crust, resulting in a pervasive structural fabric throughout northern Nevada. Because the magnetic anomaly signatures are only slightly asymmetrical, the causative feature is nearly vertical. However, the NNRE may dip steeply to the east (John et al., 2000), based on its magnetic signature. Geophysical modeling of the NNRE (Robinson, 1971; Zoback, 1978; Zoback et al., 1994) and the basement gravity feature associated with it (Ponce and Glen, 2000) indicate that mafic rocks extending to a depth of about 15 km can account for the observed gravity and magnetic anomalies.

Relationship to Mineral Resources

Previous studies have shown that the NNRE is characterized by an alignment of middle Miocene intrusive rocks and epithermal gold deposits hosted in middle Miocene intermediate to felsic volcanic rocks (Wallace and John, 1998; John et al., 2000; John and Wallace, 2000). These deposits formed as the result of hydrothermal activity along the rift during middle Miocene volcanism. Recent $^{40}Ar/^{39}Ar$ dates, existing K-Ar dates, and geologic information along the rift indicate that the epithermal deposits formed in a short time interval from about 15.6-15.0 Ma at the end of early rift-related magmatic activity and are commonly associated with NNW-striking high-angle faults (See John et al., 2000; John and Wallace, 1999; 2000). In addition to the regional association with the NNRE, local- or deposit-scale features may also play an important role in localizing epithermal gold deposits such as NNW-trending normal faults and NE-trending faults (Seedorff, 1991; John and Wallace, 2000). Because known epithermal gold-silver mineral deposits are spatially and temporally associated with the NNRE, we speculate that these deposits might be present along other parts of the NNRE and along other proposed fractures to the west of the NNRE.

About 75 epithermal gold-silver deposits (Fig. 4) occur throughout northern Nevada and most of the volcanic-hosted deposits (which include epithermal vein and hot-spring deposits) occur in rocks that range in age from 43 Ma to present. Most epithermal vein deposits formed between 27 and 5 Ma and most hot-spring epithermal gold deposits are related to a bimodal basalt-rhyolite assemblage and range in age from 17 Ma to present (Cox et al., 1991; Seedorff, 1991; John and Wallace, 2000; John et al., 2000; Wallace et al., 2001). Deposits older than rift-related mid-Miocene deposits are associated with the southwest progression of continental arc volcanic rocks that preceded the NNRE, whereas post middle Miocene deposits are associated with the Cascade magmatic arc of southeast Oregon (John et al., 2000; Steve Ludington, oral commun., 2001).

The distribution of epithermal gold deposits in northern Nevada is also, in part, a function of areas of exposed geology. Because about 80 percent of Nevada is covered by Cenozoic deposits, areas along these fractures that are covered by alluvium may be more prospective for undiscovered deposits than exposed areas. In addition, information such as the thickness of Cenozoic deposits derived from gravity data (Blakely and Jachens, 1991) could play a role in eliminating prospective areas that are too deep for deposits to be mined economically.

Middle Miocene and younger epithermal gold-silver deposits also occur along the western two aeromagnetic anomalies in northern Nevada (NNRW, NNRC, Fig. 4). At least three other arcuate, but less prominent magnetic features, two west of the NNRW and one between the NNRE and NNRC also correlate spatially with known epithermal gold-silver deposits (F1-F3, Fig. 4). We speculate that these less prominent features could also be related to the inception of the Yellowstone hotspot based on geophysical evidence that indicates that these fractures converge along the Oregon-Idaho border and point to a common source (Glen and Ponce, 2000).

Proximity Analysis

The association of epithermal gold deposits with north-northwest-trending arcuate features in northern Nevada is apparent in figure 4. To investigate this further, the statistical proximity of known epithermal gold deposits to large-scale features derived from magnetic data was compared to the proximity of 100 trials of randomly generated deposit locations. The comparison was made within a subset of the study area (black rectangle, Fig. 4) to remove vast regions that have no interpreted lineations, and to more accurately represent the statistics for randomly generated deposits. The analysis excluded clusters of deposits that could be part of the same mineralizing system, one mid-Miocene deposit in the north-easternmost part of the study area that could be related to an as yet undefined lineament, and the deposits within the Walker Lane geophysical terrane (southwest of bold black line, Fig. 4) that are unrelated to these crustal features.

The resulting 23 mid-Miocene deposits (red circles, Fig. 4) range from 0.2 to 32.3 km away from the nearest large-scale feature and have a mean distance of 8.7 km and a standard deviation of 8.7 km, whereas the randomly generated deposits have a mean distance of 20.9 km and a standard deviation of 18.8 km. Of the 100 simulations, all of the mean distances of the random set were greater than the known deposits, and 86 percent were found to be statistically different at the 95 percent confidence level.

A proximity analysis that includes all mid-Miocene and younger epithermal deposits and deposits of unknown age (32 deposits, all red symbols, Fig. 4) yields similar results. The resulting 32 deposits have a mean distance from the large-scale features of 9.3 km and a standard deviation of 8.1 km, whereas the randomly generated deposits have a mean distance of 20.8 km and a standard deviation of 18.8 km. Of the 100 simulations, all of the mean distances of the random set were greater than the known deposits, and 96 percent were found to be statistically different at the 95 percent confidence level.

A histogram of the number of deposits within 4-km intervals from the large-scale features indicates a preference for these epithermal gold deposits to be associated with large-scale geophysical features (Fig. 6). Of the 23 mid-Miocene deposits, 10 (43%) are within 4 km of a large-scale fracture and 17 (74 percent) are within 12 km. Of the 32 mid-Miocene and younger deposits, 10 (31 percent) are within 4 km of a large-scale fracture and 24 (75%) are within 12 km (Fig. 6).

Although, the mean distance from the centerline of the curvilinear features is large (~9 km), this does not account for the width of these features that, in the case of the NNRE, varies from about 4 to 7 km. This would reduce the mean distance to the margins of these features to about 4 to 5 km. Although there are a number of caveats in the proximity analysis, including geologic factors (Blakely et al., 1990), sampling bias, areal extent, and width of the features, the overall results suggest that mid-Miocene epithermal gold deposits in northern Nevada are spatially and temporally associated with large-scale features interpreted from geophysical data. These deposits probably formed as a result of formation of a rift possibly related to the inception of the Yellowstone hotspot. In addition, deposits younger than mid-Miocene are spatially associated with these large-scale features suggesting that they may have been influenced by the presence of these pre-existing features. These pre-existing crustal fractures may have acted as a conduit for ore-bearing solutions.

Conclusions

Geophysical investigations in northern Nevada reveal the presence of several large-scale arcuate features, some of which correlate to the northern Nevada rift and to two similar fractures to the west. These features are particularly evident in the magnetic data, but some are also prominently expressed in gravity data. These geophysical lineaments represent major crustal discontinuities within the earth that are interpreted to have formed as a result of mid-Miocene rift-related magmatism. Furthermore, the convergence of these features along the Oregon-Idaho border suggest that they originate from a common source, possibly the impact of the Yellowstone hotspot at the base of the earth's crust during the middle Miocene (Glen and Ponce, 2002).

Regardless of their origin, these large-scale features may have served as conduits for ore-forming hydrothermal solutions. These large-scale features are both spatially and temporally associated with mid-Miocene epithermal gold-silver deposits. The statistical proximity of these features to mid-Miocene and younger epithermal gold-silver deposits further suggests that they may serve as a guide to future epithermal mineral exploration in Nevada, Oregon, and Idaho.

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Alan Wallace, Dave John, and Steve Ludington provided valuable discussions and information on epithermal mineral deposits in northern Nevada. Rick Blakely developed and provided the proximity analysis software. Earlier versions of this paper benefited from reviews by Rick Blakely, Tom Hildenbrand, Dave John, and Steve Ludington of the U.S. Geological Survey, and by two *Economic Geology* referees Shane Ebert and Lewis Teal.

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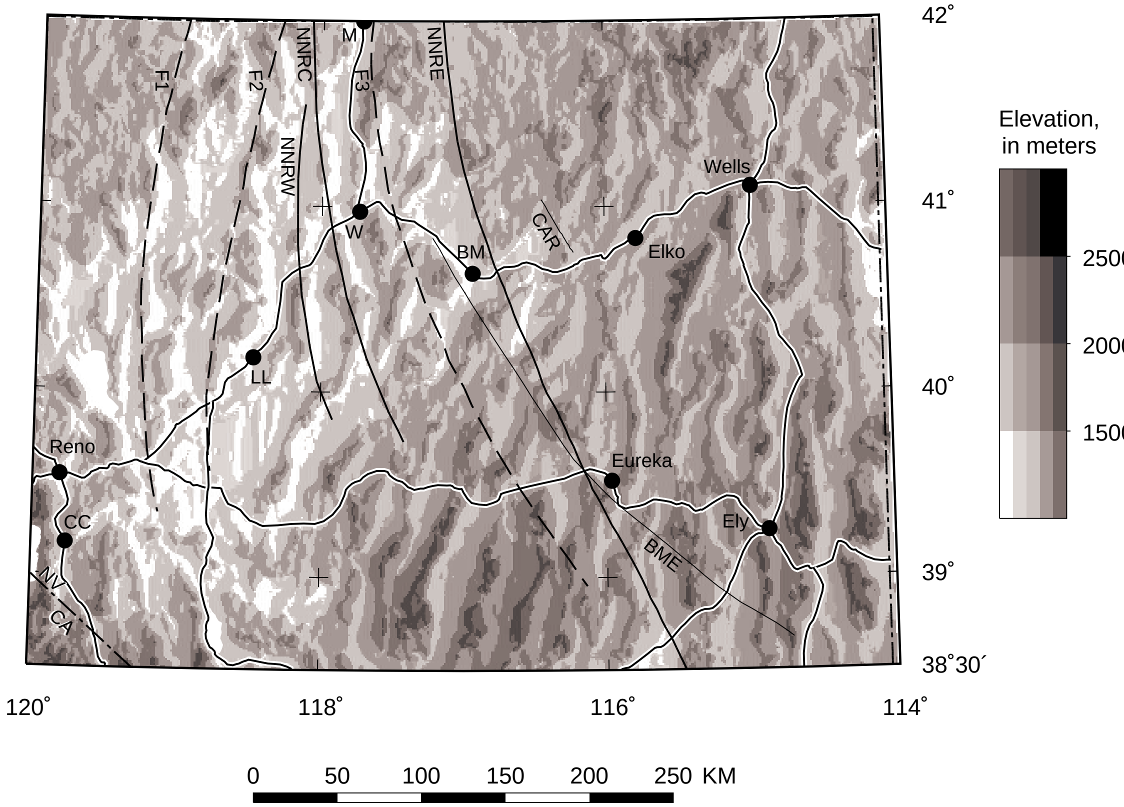

Fig. 1. Shaded-relief terrain map of northern Nevada showing location of the northern Nevada rift (NNRE), two parallel features to the west (NNRW, NNRC), and other less prominent large-scale features (F1-F3) derived primarily from magnetic data. BM, Battle Mountain; BME, Battle Mountain-Eureka mineral trend; CA, California; CC, Carson City; CAR, Carlin mineral tend; LL, Lovelock; M, McDermitt; NV, Nevada; W, Winnemucca.

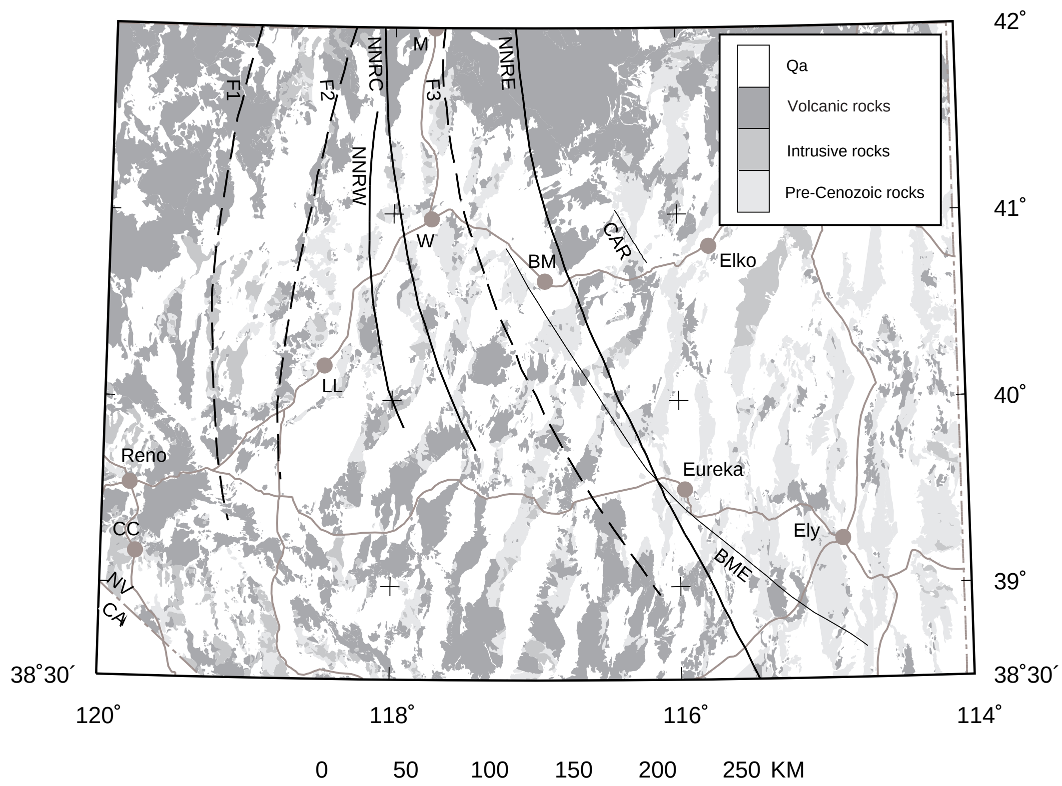

Fig. 2. Simplified geologic map of northern Nevada showing the association of Tertiary volcanic rocks with the mid-Miocene northern Nevada rift (NNRE) and associated features (NNRW, NNRC). Modified from Stewart and Carlson (1978). Explanation as in Figure 1.

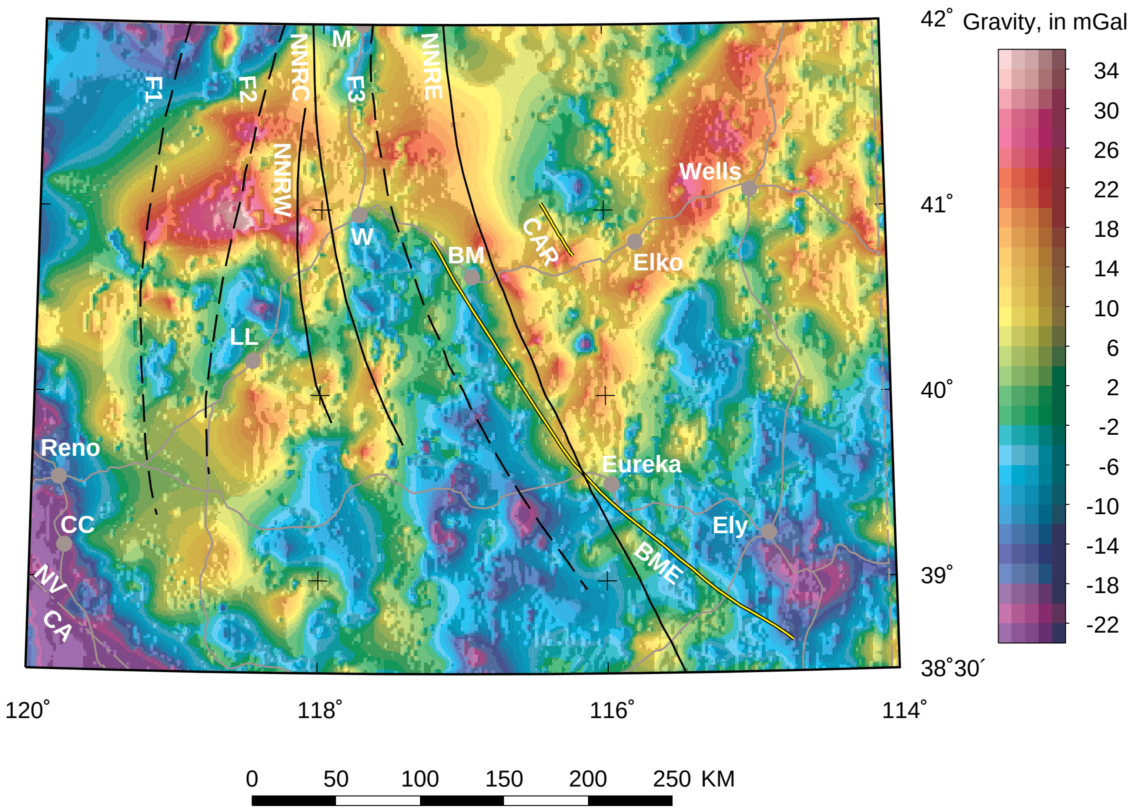

Fig. 3. Basement gravity map of northern Nevada derived by removing the gravity effect of Cenozoic basins from isostatic gravity anomalies. Prominent 'V'-shaped basement gravity anomaly transects northern Nevada. Explanation as in Figure 1.

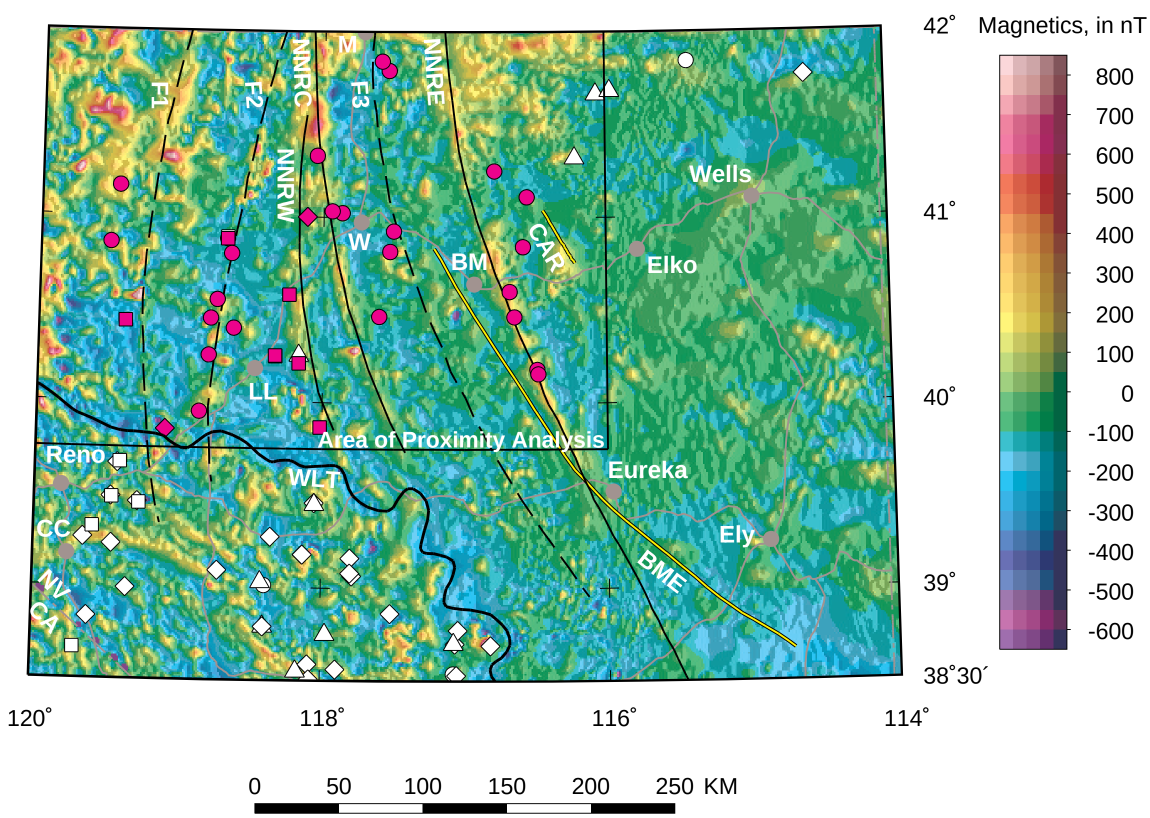

Fig. 4. Aeromagnetic map of northern Nevada showing the magnetic expression of large-scale features. Especially prominent are the northern Nevada rift (NNRE) and two parallel features to the west (NNRW, NNRC). Bold black line (WLT), northeast boundary of the Walker Lane geophysical terrane; black rectangle, area of proximity analysis. Deposits: triangle, epithermal deposits older than mid-Miocene; circle, mid-Miocene epithermal deposits; square, epithermal deposits younger than mid-Miocene; diamond, epithermal deposits of uncertain age or age range that spans across Mid-Miocene; red, epithermal deposits used in the proximity analysis (modified from Seedorff, 1991; John et al., 2000; Wallace et al., 2001). Explanation as in Figure 1.

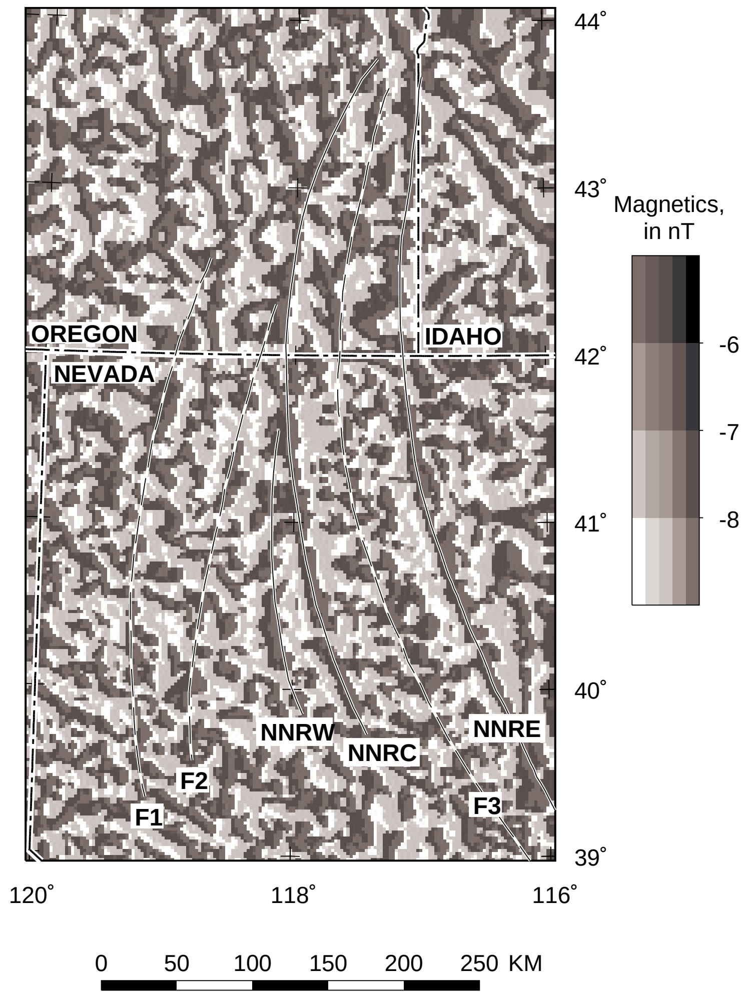

Fig. 5. Intermediate-wavelength magnetic map of northern Nevada and parts of Oregon and Idaho derived by applying a match filter to aeromagnetic data to remove the effects of both shallow and deep magnetic sources. Explanation as in Figure 1.

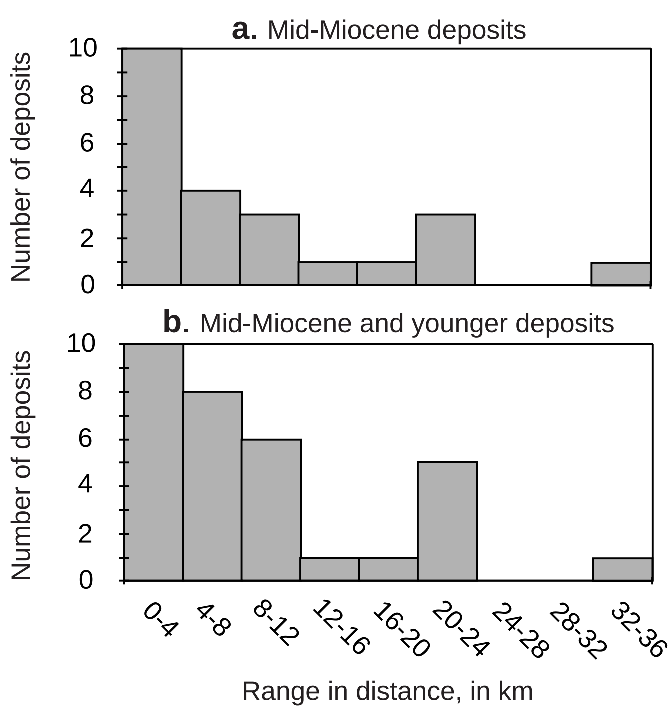

Fig. 6. Histogram showing number of epithermal gold deposits and their distances from large-scale features derived from geophysical data. a. Mid-Miocene deposits (n=23). b. Mid-Miocene and younger deposits (n=32).