PROGRESS ON UNDERSTANDING THE CRUSTAL STRUCTURE NEAR THE BATTLE MOUNTAIN-EUREKA MINERAL TREND FROM GEOPHYSICAL CONSTRAINTS

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ABSTRACT

Information from magnetic, gravity, seismic-reflection, and MT data were integrated along a southwest-northeast profile crossing the Battle Mountain-Eureka trend to better understand crustal structure related to the trend. Most importantly, the mineral trend coincides with a change in density and resistivity of upper crustal rocks from high-density, high-resistivity rocks on the east to lower density, less resistive rocks on the west. An electrically conductive zone separates the areas of different resistivities and corresponds in part to the mineral trend. The observations are consistent with an interpretation that carbonate rocks with some igneous intrusion dominate the upper crust on the east and that on the west consists primarily of volcanic and clastic sedimentary rocks. We infer that the two regions are separated by a deeply penetrating crustal fault, of unknown slip. The fault may be a multiply reactivated rift-basin margin, related to Late Proterozoic rifting of North America, that represents a long-lived crustal conduit for mineralizing fluids. Many questions remain about the tectonic origin of the fault zone, its activity throughout geologic history, the relation to other tectonic features such as the northern Nevada rift, the source of fluids, and the source of gold.

INTRODUCTION

Roberts (1966) first pointed out and named alignments of geologic structures and mineral deposits in north-central Nevada. Since then, mining geologists have used the alignments as exploration guides for discovering new precious-metal deposits, with most success along the parallel Battle Mountain-Eureka and Carlin trends (fig. 1). Buried crustal structures that helped localize mineralization were usually invoked to explain the alignments (e.g., Shawe, 1991), although evidence for them was only conjectural.

We seek to explain the origin of the Battle Mountain-Eureka trend by examining geophysical data for evidence of buried crustal features that correspond to the trend. We focus on gravity, magnetic, seismic, and new magnetotelluric data. Based on preliminary examination, we propose that the mineral trend follow a deep and long-lived crustal zone of enhanced permeability that has served as a conduit for mineralizing fluids.

GEOPHYSICAL DATA

Regional structures and major differences in lithology, porosity, or pore fluid composition are commonly reflected in contrasts in physical properties of the crust. Therefore, geophysical techniques, which are sensitive to certain physical properties of the subsurface, can be used to infer crustal structure. However, each geophysical method resolves different aspects of geologic features. Therefore, an understanding of the subsurface comes from the integrated application of several different geophysical methods, combined with constraints from geologic maps and isotopic data that reflect crustal chemistry. Geophysical data discussed in this report include gravity, magnetic, magnetotelluric (MT), and seismic-reflection data.

Variations in gravity are caused by lateral variations in crustal density. Gravity anomalies occur over volumes of rock having densities that contrast with the surrounding rock. Gravity measurements are useful for detecting geologic features such as near-vertical faults that juxtapose rock types of contrasting density, and anticlines or folds containing layers of contrasting density.

A technique developed by Jachens and Moring (1990) isolates gravity anomalies due to density variations in underlying rocks (basement gravity data) from the gravity signature of shallower, younger, basin features. To a first order, the resulting basement gravity map expresses major density variations within the pre-Tertiary basement, including younger intrusions within the basement (fig. 2) (Jachens and others, 1996). Jachens and Moring's method focuses on the gravity effects of sources within the top 10 km of the crust. Its accuracy and resolution are limited by the distribution of pre-Tertiary basement outcrops, gravity station coverage, and

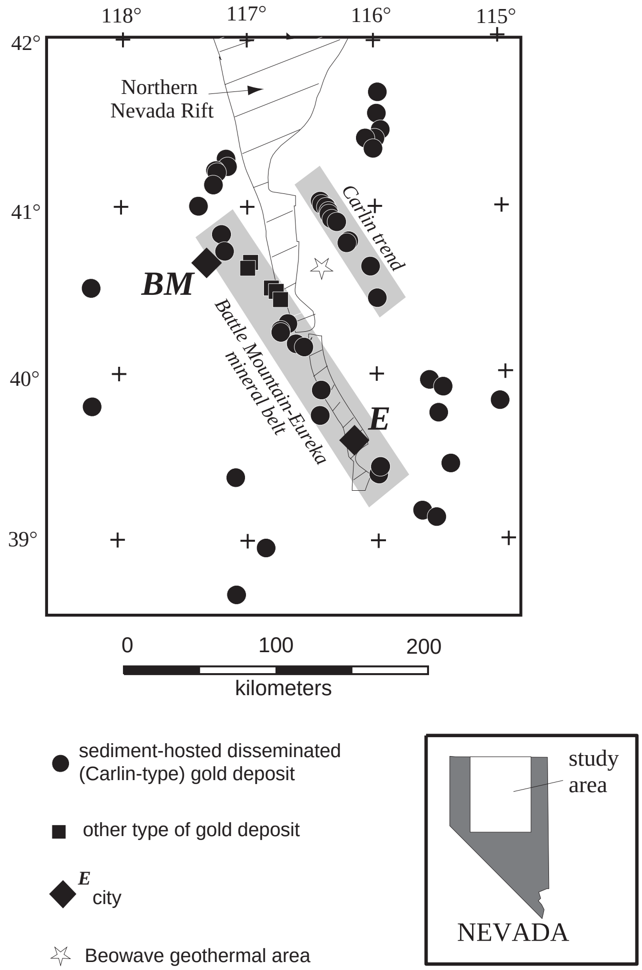

Figure 1. Location of mineral trends and other geologic and geographic features in the study area. Locations of sediment-hosted, disseminated ("Carlin-type") gold and other deposits that help define the trends are also shown. The northern Nevada rift (Zoback and others, 1994) is delineated by its magnetic expression. The cities of Battle Mountain (BM) and Eureka (E) are located by solid diamonds; Beowawe geothermal area by a star.

simplifying assumptions about density and rock type within basins and volcanic areas (Jachens and Moring, 1990; Jachens and others, 1996; Saltus and Jachens, 1995).

With the new view of pre-Tertiary basement provided by the basement gravity map, Grauch and others (1995) recognized a major gravity gradient associated with the alignment of sediment-hosted, disseminated gold ("Carlin-type") deposits along the Battle Mountain-Eureka trend (fig. 2). The gradient separates lower gravity values on the southwest from higher values on the northeast, indicating an abrupt change in crustal density. This density contrast is an expression of a crustal boundary, such as a significant lateral offset of the crust, vertical uplift, or a suture between different types of crust. The boundary's correspondence to the alignment of deposits, geologic structures, and intrusions along the Battle Mountain-Eureka trend suggests it controlled their spatial distribution as they formed and is at least Jurassic in age (Grauch and others, 1995). The basement gravity gradient has provided the focus for investigations using other geophysical methods.

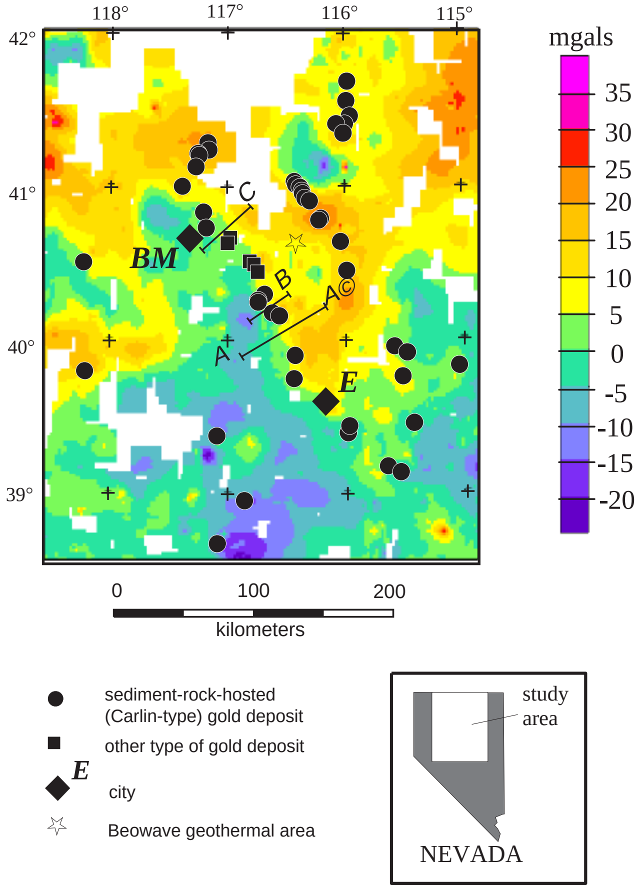

Figure 2. Basement gravity map for the study area from Jachens and Moring (1990), with gold deposits and geographic features of Figure 1. The location of gravity gradients generally can be resolved to within 2 to 10 km; blank areas show where information required to construct the map was inadequate. Data for profile A-A' are shown in subsequent figures; profiles B and C indicate MT profiles that have been collected but are not presented in this report.

Magnetic map

Magnetic methods conventionally measure variations in the strength of the earth's magnetic field produced by the magnetization of rocks containing significant amounts of magnetic minerals (commonly magnetite). The most common rock types containing a significant quantity of magnetite are igneous rocks and certain metamorphic rocks. Magnetic data for Nevada were pieced together from individual aeromagnetic surveys (Hildenbrand and Kucks, 1988). The resulting data set gives a coherent picture for regional interpretation of volcanic rocks, intrusions, and related tectonic features, especially within the top 10 km of the crust. Magnetic data for north-central Nevada are dominated by the signature of shallow igneous rocks (Blakely and Jachens, 1991). One of the most prominent magnetic features is a linear high associated with the mid-Miocene northern Nevada rift (fig. 1), an alignment of dikes, intrusions, and graben-filling lava flows extending for at least 250 km in north-central Nevada (Zoback and others, 1994). The alignment follows a trend east of and slightly divergent from the Battle Mountain-Eureka mineral trend (fig. 1). Although the proximity of the rift to the Battle Mountain-Eureka mineral trend suggests a cause-and-effect relation between them, most of the gold deposits along the trend were formed earlier than the mid-Miocene rifting, during Late Cretaceous to Oligocene time (Maher and others, 1993; Seedorff, 1991).

Seismic-Reflection Profile

Seismic-reflection data, collected as part of the Consortium for Continental Reflection Profiling (COCORP) program, are available corresponding to most of profile A-A’ (figs. 2 and 3) (Potter and others, 1987). Seismic-reflection methods induce acoustic or sonic waves into the ground and observe the arrival times of waves returning from reflectors in the subsurface. “Reflectors” occur at semi-horizontal contrasts in elastic properties of the Earth, which are commonly associated with interfaces between layered rock units of contrasting lithologies.

COCORP deep seismic-reflection data were designed to provide cross-sectional information about the crust to depths of 35-40 km (Allmendinger and others, 1987). In a segment of COCORP data corresponding to profile A-A’ (fig. 2), Potter and others (1987) observed a pronounced zone of subhorizontal reflectors 18-33 km (fig. 3*B*), which they interpreted as mafic intrusions related to the northern Nevada rift. The layering of this zone is considered to be a better-developed portion of a more widespread, mid- to lower-crustal reflective zone observed across northern Nevada (Allmendinger and others, 1987; Holbrook and others, 1991; Hyndman and others, 1991). Potter and others (1987) also interpreted several reflectors between depths of 8-15 km (fig. 3*B*), which probably originate near the top of crystalline basement or within the overlying sedimentary rocks. They suggest reflector Y (fig. 3*B*) may represent either an inclined feeder to the northern Nevada rift, a Mesozoic thrust fault, or in conjunction with reflector Z (fig. 3*B*) the upper boundary of a lens produced by irregular extension of the mid-crust.

Magnetotelluric Profiles

The magnetotelluric (MT) method (Vozoff, 1991) measures the natural, time-varying electric and magnetic fields at the surface of the Earth to yield information on the patterns of electrical resistivity (the inverse of conductivity) in the subsurface. Sources of natural magnetic and electric fields are lightning and ionospheric electrical currents found across the globe at a range of frequencies. The range of frequencies produced by the fields allows experimental design to adjust the depths of investigation from tens of meters to tens of kilometers.

Laboratory studies have shown that factors that affect resistivity in the Earth’s crust are the composition and temperature of pore-fluids, melting, and the presence of clay minerals, graphite, or certain metallic minerals (Keller, 1989). Any of these factors can measurably decrease the resistivity of carbonate and silicate rocks that constitute most of the crust, and thus allow certain inferences on lithology and structure.

Previous MT investigations were conducted as part of geothermal exploration in central Nevada near the northwestern and the southeastern part of the basement gravity gradient. Swift (1979) and Park (1985) regarded MT measurements in the Beowawe geothermal area (fig. 1) as consistent with a north-northwest trending zone of electrically conductive and anisotropic rocks extending to depths of about 6 km. The zone is associated with the northern Nevada Rift in this area (fig. 1; Zoback and others, 1994). Chau (1989) and Chau and Park (1990) evaluated MT observations across the gravity gradient to the northwest of Eureka (fig. 1). Two-dimensional analysis of the data (Chau, 1989) suggested a conductive zone similar to that in the Beowawe geothermal area that trends north-northwest in the vicinity of the gravity gradient and the northern Nevada Rift. However, in the final three-dimensional analysis, Chau and Park (1990) concluded that this zone is confined to the upper two kilometers of the crust and related to contrasts between bedrock and alluvial fill within valleys.

Magnetotelluric experiment

An electromagnetic experiment using the magnetotelluric (MT) method was conducted in 1994 to characterize the crustal resistivity across the basement gravity gradient. The initial objective was to establish whether crustal resistivity could identify resistivity contrasts associated with the tectonic feature inferred from the gradient. MT observations were established near profile A-A’, corresponding to the COCORP deep seismic-reflection data (Potter and others, 1987) and along profile B (fig. 2). Based on preliminary analysis of the MT observations, we concluded that resistivity structure might

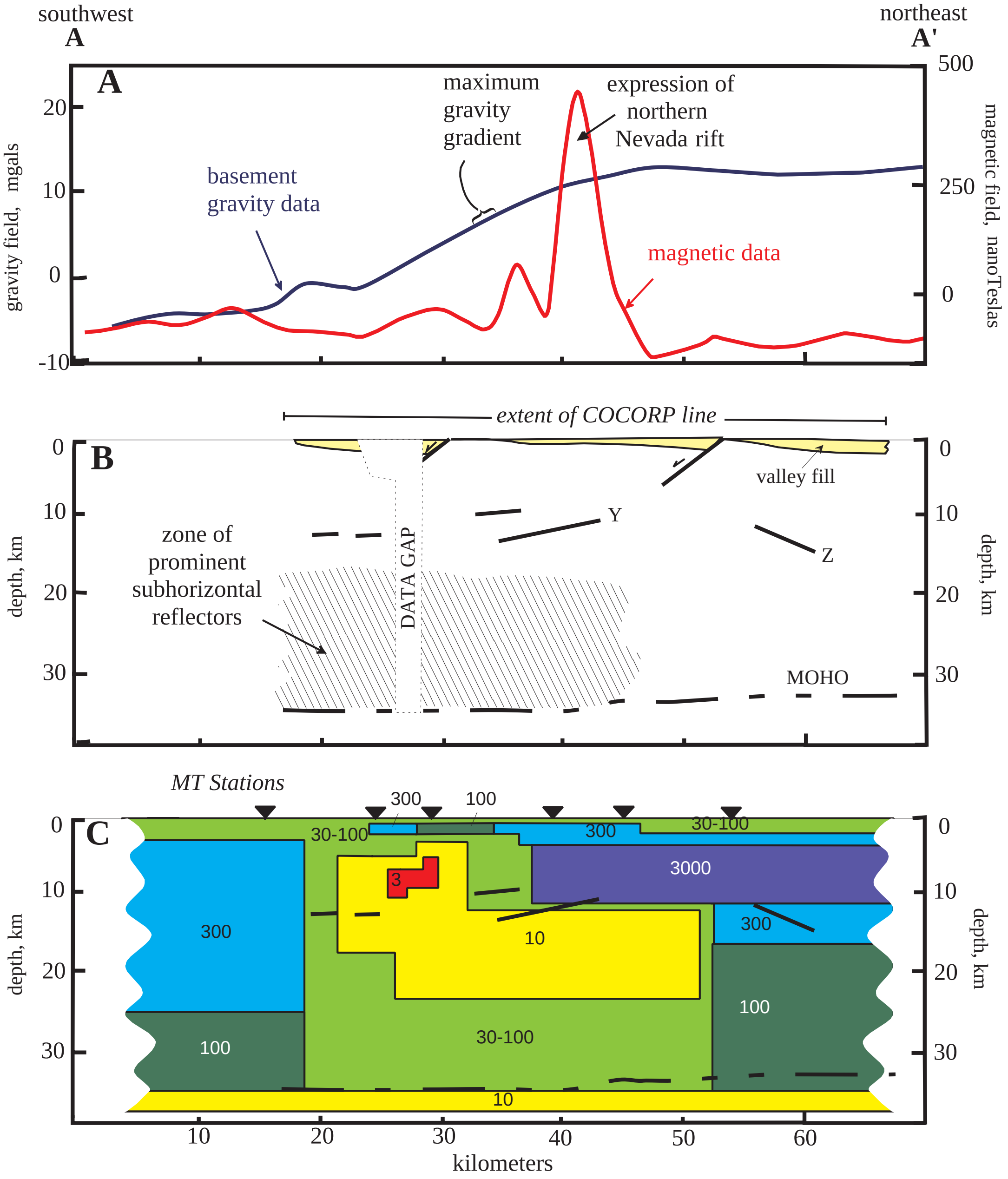

Figure 3. Basement-gravity, magnetic, and seismic-reflection data and MT model for profile A-A' located on Figure 2. For simplicity, topography is not shown. (***A***) Basement gravity and magnetic profiles extracted from Jachens and Moring (1990) and Hildenbrand and Kucks (1988), respectively. Basement gravity does not contain the effects of shallow basins and deep sources (>10 km). Noted are the magnetic high associated with the northern Nevada rift (Zoback and others, 1994) and the maximum gravity gradient that locates the inferred crustal boundary coinciding with the Battle Mountain-Eureka mineral trend (Grauch and others, 1995). (***B***) Interpreted depth section from COCORP seismic-reflection data modified from Potter and others (1987) and projected to the profile. Interpreted basin and range features are shown schematically. Solid black lines are reflectors of Potter and others (1987); Y and Z are discussed in the text. The dash-dot-dot line indicates the Moho. The zone of prominent subhorizontal reflectors was considered by Potter and others (1987) to be a better-developed portion of a more widespread lower-crustal reflective zone. (***C***) Diagram of the result of two-dimensional MT modeling, projected to the profile and overlain by seismic reflectors and the Moho as shown in ***B*** MT stations are located by inverted triangles. Resistivities of model layers are shown in units of ohm-m. The change in basement gravity values in ***A*** corresponds to a change in the upper crust from high-resistivity rocks on the east to less resistive rocks on the west, with an intervening electrically conductive zone. We interpret the conductive zone to represent a crustal fault or fault zone that may have been a long-lived crustal conduit for mineralizing fluids.

provide useful constraints for understanding the other geophysical data. Additional observations across the gravity gradient north of the initial experiment were acquired in 1997 (profile C, fig. 2). Discussion of these latter observations will be reported elsewhere.

A 2-D model of MT observations corresponding to profile A-A' was created using the inversion algorithm of Smith and Booker (1991). This algorithm results in models showing slow changes, representing average resistivity, as opposed to abrupt resistivity contrasts. Results of the 2-dimensional inversion for profile A-A' are summarized in figure 3*C*, a schematic view of the important aspects of the model.

Although the model may share features in common with the Earth, several criteria of dimensionality in the data and misfit statistics of the model indicate that a two-dimensional representation may not be adequate. The effects of three-dimensional bodies at shallow depths (upper 1-3 km) could account for some two-dimensional representation of contrasts extending into the lower crust, as shown by Chau and Park (1990) elsewhere. Moreover, studies of shallow, rectangular conductive bodies similar in dimensions to the basins of the present study area (Wannamaker and others, 1984) have demonstrated that the basin configurations are an important influence on MT data in Basin and Range Province.

Thus, with caveats that the 2-dimensional model (fig. 3*C*) is a rough representation of the resistivity structure along profile A-A' the main features and suggested origins are as follows:

1. A conductive zone is located near the gravity gradient and penetrates from near surface to mid-crustal depths. The zone could be associated with intrusion and alteration associated with a crustal suture or fault zone.
2. A high-resistivity (about 3000 ohm-m) upper crust borders the conductive zone on the east. It may represent resistive carbonate shelf rocks or unaltered intrusions.
3. A moderate-resistivity (several hundred ohm-m) upper crust borders the conductive zone on the west. It may signify a larger portion of volcanic and clastic sedimentary rocks in the upper crust compared to crust on the east.
4. A moderately-conductive (30-100 ohm-m) lower crust seems to extend across the profile. It is similar to a conductive zone inferred further east near the Ruby Range that may represent small percentages (<5%) of high-temperature, metamorphic-derived brines (Wannamaker and others, 1997).

CONCLUSIONS

Magnetic, gravity, seismic-reflection, and MT information along profile A-A' have been combined onto one cross-section on figure 3. Integrating this information helps constrain different aspects of the subsurface in the vicinity of the Battle Mountain-Eureka trend. Preliminary conclusions about the relations between these data sets follow.

A major change in gravity values originating in upper crustal rocks corresponds to the Battle Mountain-Eureka mineral belt, as discussed by Grauch and others (1995). Along profile A-A' the change in gravity values corresponds to a change from high-resistivity rocks on the east to less resistive rocks on the west, with an intervening electrically conductive zone that penetrates from near surface to mid-crustal depths (fig. 3). In addition, the magnetic data indicate igneous rocks at depth coinciding with the northern Nevada rift (Zoback and others, 1994). These observations are consistent with an interpretation that the upper crust on the east is dominated by carbonate rocks, intruded by igneous rocks in the vicinity of the northern Nevada rift, whereas the upper crust on the west consists primarily of volcanic and clastic sedimentary rocks. The intervening conductive zone and the steepness and linearity of the gravity gradient in map view (fig. 2; Grauch and others, 1995) are evidence for a deeply penetrating crustal fault, which offsets crust of different composition either vertically, laterally, or both. The fault may be a multiply reactivated rift-basin margin, related to Late Proterozoic rifting of North America, as suggested for this and other areas in northern Nevada from isotopic evidence (Wooden and others, 1997). This scenario is also consistent with paleo-carbonate basin escarpments interpreted in the subsurface along the Carlin trend (Teal and Jackson, 1997). The conductive fault zone encompasses a larger area than known geothermal activity at the surface, which leads us to suggest it may represent a long-lived crustal conduit for mineralizing fluids.

The MT model and seismic-reflection depth-section show several commonalties in the picture of the mid- to lower crust (below about 10 km) along profile A-A' (fig. 3*C*), but their significance is unclear. COCORP reflectors Y and Z (fig. 3*B*; Potter and others, 1987) generally coincide with large vertical contrasts in resistivity at about 12 km depth in the MT model. The zone of prominent reflectors and the conductive zone (less than 100 ohm-m) in the middle of profile A-A' coincides for the most part. The reflection Moho apparently corresponds to the top of extensive conductive zone at about 33-35 km depth. However, the resistivity distribution at these depths has not been sufficiently evaluated to warrant further discussion.

The current state of our study has produced some encouraging leads that point to an explanation of the alignment of mineral deposits along the Battle Mountain-Eureka trend. A crustal fault or fault zone generally coincident with the trend may have developed as a system of deep faults and fractures that enhanced permeability and allowed magmatic, metamorphic, or deeply penetrating surface fluids to circulate upward, resulting in a locus of mineralization along the boundary. Many questions remain about the tectonic origin of the fault zone, its activity throughout geologic history, the relation to other tectonic features such as the northern Nevada rift, the source of fluids, and the source of gold.

Our focus for the near future is to test and expand our geophysical models. The current MT model has to be evaluated for its sensitivity to data noise and against the possible influence of the 3-D basin configuration. Additional MT profiles will help establish a consistent resistivity signature at several points along the basement gravity gradient. We have recently acquired the additional profile C-C' in the Battle Mountain area (fig. 2), and our current priority is to develop a model for this new data. Gravity models must be revised in light of constraints provided by the new MT data, by exposed and inferred geology, and by isotopic information. Eventually, we must look to other disciplines, such as geology and geochemistry, to constrain these tectonic questions and to make a connection between mineralizing fluids and the crustal fault.

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