DEEP REGIONAL RESISTIVITY STRUCTURE ACROSS THE BATTLE MOUNTAIN-EUREKA AND CARLIN TRENDS, NORTH-CENTRAL NEVADA

by

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ABSTRACT

Magnetotelluric data collected along four, regional scale, southwest-to-northeast profiles show deep resistivity structures beneath the Battle Mountain-Eureka and Carlin gold trends in north-central Nevada, which appear consistent with tectonic breaks in the crust that possibly served as channels for hydrothermal fluids. It seems likely that gold deposits along these linear trends were, therefore, controlled by deep regional crustal fault systems.

Two-dimensional resistivity modeling of the magnetotelluric data generally show resistive (30 to 1,000 ohm-m) crustal blocks broken by narrow, sub-vertical, two-dimensional, conductive (1 to 10 ohm-m) zones that are indicative of large-scale crustal fault zones. These inferred fault zones are regional in scale, trend southeast-to-northwest, and extend to mid-crustal (20 km) depths. The conductors are about 3 to 15 km wide, extend from 1 to 8 km below the surface to about 20 km depth, and show two-dimensional electrical structure with general north to northwesterly strikes. From connecting the locations of the conductors together, a single regional crustal fault zone can be inferred that is about 10 km wide within the upper crust and about 150-km long. It coincides with the Battle Mountain-Eureka mineral trend. The images also show regional changes in the resistive crust from north to south. Most of Reese River Valley and Boulder Valley are underlain by a thick (20 km) southwest-to-northeast section of conductive (1 to 10 ohm-m) rock, suggesting that high-temperature fluids are more pervasive in this area (Battle Mountain Heat-Flow High), which implies that the crust beneath these valleys is more fractured than in the areas surveyed to the south.

INTRODUCTION

Many sediment-hosted gold deposits occur along linear trends in northern Nevada. The distribution and genesis of these deposits along the Battle Mountain-Eureka (BME) and Carlin gold trends is not fully understood. In general, most models agree that regional structures played an important role in the spatial distribution of these deposits (e.g. Arehart and others, 1993; Ilchik and Barton, 1997; Radtke, 1985; Shawe, 1991; Sillitoe and Bonham, 1990; Tosdal, 1998). To investigate crustal structures that may be related to the genesis of gold deposits along these trends, four regional southeast-to-northwest profiles of magnetotelluric (MT) soundings were acquired in 1996, 1997, 1999, and 2000 (lines MT1 to MT4, Figure 1). Resistivity modeling of the MT data can be used to infer the deep resistivity structure of the crust. Such structures may reflect possible tectonic controls on the emplacement of mineral deposits along these linear trends, and so may be used to help improve critical gold endowment estimates in the Humboldt River Basin.

MAGNETOTELLURIC METHOD

The magnetotelluric (MT) method is a passive surface geophysical technique, which uses the earth's natural electromagnetic fields to investigate the electrical resistivity structure of the subsurface. The resistivity of geologic units is largely dependent upon their fluid content, porosity, degree of fracturing, temperature, and conductive mineral content (Keller, 1989). Saline fluids within the pore spaces and fracture openings can reduce resistivities in a resistive rock matrix. Also, resistivity can be lowered by the presence of conductive clay minerals, carbon, and metallic mineralization. It is common for altered volcanic rocks to contain authigenic minerals that have resistivities ten times lower than those of the surrounding rocks (Nelson and Anderson, 1992). Increased temperatures cause higher ionic mobility and mineral activation energy, reducing rock resistivities significantly. Unaltered, unfractured igneous rocks are normally very resistive (typically 1,000 ohm-m or greater), whereas fault zones will show low resistivity (less than 100 ohm-m) when they are comprised of rocks fractured enough to have hosted fluid transport and consequent mineralogical alteration (Eberhart-Phillips and others, 1995). Carbonate rocks are moderately to highly resistive (hundreds to thousands of ohm-m) dependent upon their fluid content, porosity, fracturing, and impurities. Marine shales, mudstones, and clay-rich alluvium are normally very conductive (a few ohm-m to tens of ohm-m). Unaltered, metamorphic rocks (non-graphitic) are moderately to highly resistive (hundreds to thousands of ohm-m). Tables of electrical resistivity for a variety of rocks, minerals and geological environments may be found in Keller (1987) and Palacky (1987).

The MT method can be used to probe the crust from depths of tens of meters to depths of tens of kilometers (Vozoff, 1991). Natural variations of the Earth's magnetic and electric field are measured and recorded at each MT station. The main frequency bands used by the MT method are 10,000 Hz to 1 Hz from worldwide lightning activity and 1 Hz to 0.0001 Hz from geomagnetic micro-pulsations. The natural electric and magnetic fields propagate vertically in the earth because the very large resistivity contrast between the air and the earth causes a vertical refraction of both fields transmitted into the earth (Vozoff, 1972).

The natural electric and magnetic fields are recorded in two orthogonal, horizontal directions. The vertical magnetic field ("tipper") is also recorded. The resulting time-series signals are used to derive earth tensor apparent resistivities and phases by first converting them to complex cross-spectra using FFT (fast-Fourier-transform) techniques. Least-squares, cross-spectral analysis (Bendat and Piersol, 1971) is used to solve for a tensor-transfer function that relates the observed electric fields to the magnetic fields under the assumption that the Earth consists of a two-input, two-output, linear system with the magnetic fields as input and the electric fields as output (Rodriguez and others, 1996). Prior to conversion to apparent resistivity and phase, the tensor is normally rotated into principal directions that correspond to the direction of maximum and minimum apparent resistivity. For a two-dimensional (2-D) Earth, the MT fields can be de-coupled into transverse electric (TE) and transverse magnetic (TM) modes; 2-D modeling is generally done to fit both modes. When the geology satisfies the 2-D assumption, the MT data for the TE mode is assumed to represent the situation when the electric field is along the geologic strike, and the data for the TM mode is assumed to represent the situation when the electric field is across strike. The MT method is well suited for studying complicated geological environments because the electric and magnetic relations are sensitive to vertical and horizontal variations in resistivity. The method is capable of establishing whether the electromagnetic fields are responding to subsurface terranes of effectively 1-, 2-, or 3-dimensions. An introduction to the MT method and references for a more advanced understanding are contained in Dobrin and Savit (1988) and Vozoff (1991).

MAGNETOTELLURIC SURVEYS

Sixty-nine MT soundings were located along four regional southwest-to-northeast profiles (MT1 to MT4, Figure 1) of varying lengths (40 to 110 km) with spacing that varied from 1.3 to 19.5 km. The profile orientations are roughly perpendicular to the BME and Carlin gold trends. The MT soundings span as far northwest as Reese River Valley and Boulder Valley near Battle Mountain and as far southeast as Long Valley, east of the Alligator Ridge mine.

The following table lists the MT station locations in the four regional southwest-to-northeast profiles (Figure 1). These locations were found using either on-site GPS measurements or digitized from 100,000 scale field maps (Williams and Rodriguez, 2000; Williams and Rodriguez, 2001; Williams and others, 2001a; Williams and others, 2001b; Williams and others, 2001c). Coordinates are referenced to the 1866 Clarke spheroid and North

American 1927 Western United States datum. Longitude and latitude format below is decimal degrees. Elevation is in meters.

Station	Longitude	Latitude	Elev(m)
	MT4		
98	-117.23117	40.44410	1440
12A	-117.12441	40.44999	1430
13A	-117.05447	40.46508	1420
14A	-116.98314	40.49695	1390
16A	-116.94524	40.51559	1360
19A	-116.89245	40.51839	1390
20A	-116.86685	40.52878	1350
22A	-116.84852	40.55662	1340
23A	-116.82223	40.56811	1350
24A	-116.79907	40.58977	1340
25A	-116.78090	40.61226	1400
71	-116.76773	40.69609	1350
26A	-116.70164	40.66617	1450
27A	-116.54826	40.73778	1410
28A	-116.44901	40.78003	1420
9	-116.36060	40.76114	1490
1	-116.33037	40.79034	1550
2	-116.31374	40.80459	1650
24	-116.29118	40.79805	1650
25	-116.25092	40.79475	1770
26	-116.22477	40.82100	1600
27	-116.18810	40.80681	1600
28	-116.15437	40.80115	1600
	MT3		
16	-117.03204	40.03355	1740
15	-116.92586	40.06778	1595
1A	-116.84890	40.15161	1590
2A	-116.75097	40.20433	1500
5A	-116.66432	40.23551	1475
3A	-116.58452	40.27633	1445
4A	-116.57803	40.29375	1445
14	-116.55498	40.35025	1445
13	-116.56650	40.43708	1460
12	-116.46765	40.55145	1495
19	-116.41989	40.59568	1445
11	-116.40231	40.67147	1525
10	-116.36736	40.73788	1490
9	-116.36060	40.76114	1490
1	-116.33037	40.79034	1550
2	-116.31374	40.80459	1650
3	-116.30656	40.82193	1700
4	-116.30516	40.84248	1800
5	-116.29302	40.85368	1730

6	-116.27523	40.86021	1660
7	-116.26662	40.87744	1640
8	-116.25457	40.89239	1645
20	-116.22196	40.93338	1675
21	-116.18823	40.95701	1675
22	-116.16402	41.00800	1710
29	-116.09901	41.03600	1840
23	-116.03185	41.10000	1900
54	-116.38179	41.44002	2130
	MT2		
17	-116.83356	39.96701	1950
11A	-116.73088	39.94657	1770
10A	-116.65782	40.03011	1790
6A	-116.58502	40.03230	1720
9A	-116.48118	40.06390	1790
8A	-116.42011	40.08985	1725
7A	-116.32249	40.09119	1725
18	-116.16121	40.09325	1840
	MT1		
88	-116.47773	39.52744	1890
87	-116.27814	39.55249	1850
86	-116.15948	39.60576	1870
85	-116.04913	39.62802	1820
89	-115.97073	39.75141	1780
109	-115.87795	39.70953	1870
83	-115.80588	39.73506	2050
82	-115.71711	39.79929	1780
81	-115.63851	39.79379	1810
108	-115.53142	39.76552	2120
79	-115.47101	39.80462	2020
77	-115.39775	39.81638	1870
78	-115.32175	39.83858	1910

MAGNETOTELLURIC DATA

Frequencies sampled ranged from 0.002 to 300 Hz using single station recordings of both orthogonal horizontal components of the electric and magnetic fields, along with the vertical magnetic field at stations 12A to 28A, 1, 11, 14, 71, 77, 79 to 89, 98, 108, and 109 (Williams and Rodriguez, 2000; Williams and Rodriguez, 2001; Williams and others, 2001a; Williams and others, 2001b; Williams and others, 2001c). Sampling this frequency range in previous areas of widely varying geology has allowed us to probe the crust from depths of hundreds of meters to depths of tens of kilometers (Rodriguez and others, 1996). The recorded time-series data were transformed to the frequency domain and Fourier analyzed to determine a two-dimensional apparent resistivity and phase tensor at each site. The data were rotated to maximum and minimum apparent resistivity directions so that propagation modes for the signals were decoupled into TE and TM modes.

A measure of the dimensionality for MT data is provided by the impedance skew of the impedance tensor (Vozoff, 1972) and the impedance polar plots (Reddy and others, 1977). By examining the tensor impedances, the dimensionality (2- or 3-D) of electrical structures and the general strikes of 2-D structures were determined for different frequencies. MT stations whose impedances were 3-D in the lower frequencies (Williams and Rodriguez, 2000; Williams and Rodriguez, 2001; Williams and others, 2001a; Williams and others, 2001b; Williams and others, 2001c) are indicated with triangle symbols in Figure 1. Predicted values of the electric field can be computed from the measured values of the magnetic field (Vozoff, 1991). The coherence of the predicted electric field with the measured electric field is a measure of the signal-to-noise ratio provided in the multiple coherency plot. Values are normalized between 0 and 1, where values at 0.5 signify signal levels equal to noise levels. For this data set, coherencies were generally at an acceptable level, except at times in the "dead band" (0.1 to 1 Hz) and at times in the lower frequencies (0.002 to 0.1). Overall data quality was fair to good for profiles MT1, MT2, and MT4, and fair to poor for MT3 (Williams and Rodriguez, 2000; Williams and Rodriguez, 2001; Williams and others, 2001a; Williams and others, 2001b; Williams and others, 2001c). The worst data points were ignored and the data used in the modeling generally had predicted coherencies above 90% and 60% for the higher and lower quality data, respectively.

In the Appendix, observed data of each MT sounding for each profile (MT1 to MT4) are represented by descrete values (circle and x symbols) of the TE and TM modes from the raw data curves (Williams and Rodriguez, 2000; Williams and Rodriguez, 2001; Williams and others, 2001a; Williams and others, 2001b; Williams and others, 2001c). Calculated data for each profile are represented by solid (TE mode) and dashed (TM mode) lines interpolated from the descrete values output from the 2-D finite element model (Figure 2).

RESISTIVITY MODELS

Wannamaker (1983) found that MT responses in the northern Basin and Range are fundamentally 3-D in nature. However, because 3-D modeling is very time-consuming, 2-D modeling was used to construct the preliminary resistivity cross-sections shown in Figure 2. Wannamaker and others (1984) have demonstrated in 3-D resistivity (MT) modeling that approximating 3-D structure beneath a centrally located profile with 2-D modeling is best achieved when fitting the TM curve even at the expense of fitting the TE curve. However, because TM data are quite insensitive to the depth extent of a subsurface body (Eberhart-Phillips and others, 1995), the depths to the base of the bodies in the model are not well constrained. Clarifying the limits of the model structures with 3-D resistivity modeling is needed.

Resistivity models (Figure 2) assuming a 2-D earth were constructed for each profile using the forward modeling finite element algorithm of Wannamaker and others [1987]. The resistivity models generally fit the TM data better than the TE data (see Appendix A, B, C, and D), although fits to the TE data were generally satisfactory for stations where 2-D structure was indicated (Figure 2). However, because of the widespread 3-D character of the results, we focus only on the gross structure determined by the models.

The variable-dimension finite-element grid cells used for our models had 77x38, 127x38, 136x36, and 125x38 horizontal and vertical nodes for profiles MT1, MT2, MT3, and MT4, respectively. The edges of the model were extended to 900-, 980-, 550-, and 890-km horizontally and 450-, 450-, 200-, and 450-km vertically for profiles MT1, MT2, MT3, and MT4, respectively, so as to minimize edge effects. The resolution of the resistivity boundaries used for each model is somewhat subjective. If different resistivities are used, then boundary positions and layer depths would have to be adjusted to achieve similar fits to the observed data. The extreme case would be to use a model with a "continuous" resistivity gradient from low to high resistivities. The resolution of the resistivity boundaries is also, in part, a function of our model grid mesh design. We have attempted to keep each model simple. The MT profile models (Figure 2) are stacked as though viewed from the southeast end of the BME trend (Figure 1). The model depths are relative to the surface.

DISCUSSION

The resistivity model for profile MT4 (Figure 2) shows high crustal resistivity (300 to 1,000 ohm-m) beneath the Carlin trend, characteristic of carbonates or intruded rock, although significant portions of the model below 5 to 10 km depth beneath the Carlin trend is poorly defined because of poor data quality. The narrow, sub-vertical, 2-D, low resistivity (1 to 10 ohm-m) zone beneath stations 20A to 24A that penetrates to mid-crustal depths (from 5 to 20 km depth) is hard to explain other than by a major crustal-dimension fault or fracture zone (Eberhart-Phillips et al., 1995). The low resistivities are likely caused by material associated with faulting or fracture filling, such as mylonitic breccia, brine-filled fractures, argillaceous alteration from hydrothermal fluids, substantial graphitic carbon associated with shearing, or a combination of these (Eberhart-Phillips et al., 1995). Additional support for a fault zone interpretation is the 2-D electrical structure. In the upper 8 km, the resistive (30 to 1,000 ohm-m) crustal blocks near Battle Mountain (beneath station 16A, Figure 1) appear to be broken by a southwest-to-northeast fault zone. Other conductive zones in this model are 3-D in character and so are not interpreted as crustal fault zones, however, the large 3-D conductive (1 ohm-m) zone from 1 to 12 km depth between stations 27A and 28A is characteristic of a geothermal resource area (GRA).

The resistivity model for profile MT3 (Figure 2) also shows a high crustal resistivity (300 to 1,000 ohm-m) beneath the Carlin trend, characteristic of carbonates or intruded rock. Exposures of Cretaceous quartz monzonite near MT station 4, Tertiary granodiorite about one mile southeast of station 2, widespread re-crystallized carbonates in these areas (Evans, 1980), and a broad magnetic high (Grauch, 1996) support the presence of a large, concealed, pluton. Most of the MT sites inside the Carlin trend indicate 3-D resistivity structure at depth (Williams and Rodriguez, 2000). The narrow, sub-vertical, 2-D, low resistivity (1 to 10 ohm-m) zone, extending to about 20 km depth beneath station 8 is interpreted as a crustal fault zone. The moderately resistive (30 to 300 ohm-m) rocks in the upper 5 km northeast and southwest of the Carlin trend probably correspond to carbonates in the near surface where local outcrops exist (stations 11, 10, 9, 1, 5, 29, and 23) or other unknown volcanic and/or clastic sedimentary rocks at depth (Grauch and others, 1998). The low resistivity (3 ohm-m) zone beneath stations 12 and 19 correlates with a known geothermal resource area (Beowawe KGRA, Figure 1). The narrow, sub-vertical, 2-D, low resistivity (3 to 10 ohm-m) zone, extending to about 20 km depth beneath station 5A is interpreted as a crustal fault zone. Significant portions of the model below 5 to 10 km depth at the southwest and northeast sections are poorly defined because of poor data quality. Other conductive zones in this model are 3-D in character and so are not interpreted as crustal fault zones.

Crustal resistivity for profile MT2 (Figure 2) across the eastern part of the BME trend (1,000 ohm-m, between stations 7A and 9A) is also characteristic of carbonates or intruded rocks. Southwest of this high resistivity body, a narrow, sub-vertical, 2-D, low resistivity (1 to 10 ohm-m) zone, extending to about 20 km depth is interpreted as a crustal fault zone. The inferred crustal fault zone is more resistive (from 1 ohm-m to 10 ohm-m) near 15-km depth, where it intersects the top of the brittle-ductile transition (Holbrook and others, 1991). Grauch and others (1998) show that sub-horizontal seismic reflectors from COCORP seismic-reflection data (Potter and others, 1987) in this depth range occur near a horizontal resistivity boundary near 15-km depth (brittle-ductile transition) that shows a change to lower resistivity (from 1,000 ohm-m to 100 ohm-m). Potter and others (1987) suggested the west-dipping reflection might be an inclined magma feeder for the Northern Nevada rift, whose magnetic-high expression is between stations 9A and 8A (Grauch and others, 1998). Another horizontal resistivity boundary that shows a general change to lower resistivity (from 100 ohm-m to 30 ohm-m) occurs below 20 km depth, where Holbrook and others (1991) suggested that rising basaltic magmas intrude the ductile lower crust with mafic sills.

The resistivity model for profile MT1 (Figure 2) shows high crustal resistivity (300 ohm-m), characteristic of carbonates or intruded rock, beneath Alligator Ridge (station 108, Figure 1) that is in-line with a southeast extension of the Carlin trend. The narrow, sub-vertical, 2-D, low resistivity (3 to 10 ohm-m) zone, extending to about 20 km depth beneath station 79 is interpreted as a crustal fault zone. The resistive crustal blocks near Alligator Ridge (station 79) appear to be broken by a south-to-north fault zone in the upper 5 to 10 km. The narrow, sub-vertical, 2-D, low resistivity (3 ohm-m) zone, extending to about 20 km depth beneath station 87 is interpreted as a crustal fault zone. Other conductive zones in this model are 3-D in character and so are not interpreted as crustal fault zones.

The crustal conductors, in general, are not well constrained laterally due to wide station spacing, giving 3 to 15 km as the overall range of widths. The images also show regional changes in the resistive crust from north to south. Most of Reese River Valley and Boulder Valley are underlain by a thick (20 km) southwest-to-northeast section of conductive (1 to 10 ohm-m) rock, suggesting that high-temperature fluids are more pervasive in this area (Battle Mountain Heat-Flow High, MT4, Figure 2). In turn, this implies that the crust is more highly fractured in the vicinity of profile MT4 than in the areas surveyed to the south.

SUMMARY

Strengthening the suggestion of Shawe (1991), MT data collected along four, regional scale, southwest-to-northeast profiles show deep resistivity structures beneath the Battle Mountain-Eureka (BME) and Carlin gold trends in north-central Nevada, which appear consistent with tectonic breaks in the crust that possibly served as channels for hydrothermal fluids. It seems likely that gold deposits along these linear trends were, therefore, controlled by deep regional crustal fault systems.

Two-dimensional resistivity modeling of the MT data was used to image the deep resistivity structure in the study area. The models generally show resistive (30 to 1,000 ohm-m) crustal blocks broken by narrow, sub-vertical, two-dimensional, conductive (1 to 10 ohm-m) zones that are indicative of large-scale crustal fault zones. These inferred fault zones are regional in scale, trend southeast-to-northwest, and extend to mid-crustal (20 km) depths. The conductors are about 3 to 15 km wide, extend from 1 to 8 km below the surface to about 20 km depth, and show two-dimensional electrical structure with general north to northwesterly strikes. From connecting the locations of the conductors together, a single regional crustal fault zone can be inferred that is about 10 km wide within the upper crust and about 150-km long. It coincides with the BME mineral trend.

The interpreted structure from these profiles should provide constraints for future geologic interpretations of the genesis of gold deposits along the Carlin and BME trends. The deep regional resistivity structure across the Carlin and BME trends has huge implications for large gold resources in northeastern Nevada, because it reveals major crustal structures that were probably responsible for the deformation and shattering of upper crustal rocks providing local permeable zones favorable for fluid flow and precipitation of gold ores. This implies that the potential for many additional undiscovered deeper-level deposits in the Carlin trend is large.

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Figure 1. Index map. Magnetotelluric (MT) transects (MT1 to MT4) acquired in 1996, 1997, 1999, and 2000. Hatched zones are two northwest-trending mineralized belts in north-central Nevada, the well-known Carlin trend and the less well-defined Battle Mountain-Eureka trend. MT stations are grey circles and triangles (three-dimensional character in the lower frequency MT data), strikes are two-dimensional (2-D) conductors about 1-km (grey arrows) and 10-km (black arrows) below the ground surface, resistivity model profile locations (MT1 to MT4) are black lines, and interpreted crustal fault zone is 10 km-wide gray swath based on locations and extents of the sub-vertical 2-D conductors. MT strike resolution is about ±20 degrees. Base map adapted from Struhsacker and others (1996).

Figure 2. Magnetotelluric (MT) profile, two-dimensional, resistivity models (MT1 to MT4) stacked in relative positions along a northwest-to-southeast line (Figure 1). Depths are from ground surface. White arrows mark interpreted crustal fault zones. Black squares show stations whose MT data indicated three-dimensional character in the lower frequencies. Black and white solid lines on MT2 are COCORP seismic reflectors (Potter and others, 1987).

Question marks indicate poor model definition from poor data quality.
Vertical exaggeration is 1.4.

APPENDIX A

OBSERVED AND CALCULATED DATA – PROFILE MT4

Magnetotelluric (MT) observed (circle and x symbols) and calculated (solid and dashed lines are TE and TM modes, respectively) resistivity and phase data for profile MT4. See the "Magnetotelluric Data" section of this report for a description of the observed data and the "Resistivity Models" section for a description of the calculated data.

APPENDIX B

OBSERVED AND CALCULATED DATA – PROFILE MT3

Magnetotelluric (MT) observed (circle and x symbols) and calculated (solid and dashed lines are TE and TM modes, respectively) resistivity and phase data for profile MT3. See the "Magnetotelluric Data" section of this report for a description of the observed data and the "Resistivity Models" section for a description of the calculated data.

APPENDIX C

OBSERVED AND CALCULATED DATA - PROFILE MT2

Magnetotelluric (MT) observed (circle and x symbols) and calculated (solid and dashed lines are TE and TM modes, respectively) resistivity and phase data for profile MT2. See the "Magnetotelluric Data" section of this report for a description of the observed data and the "Resistivity Models" section for a description of the calculated data.

APPENDIX D

OBSERVED AND CALCULATED DATA – PROFILE MT1

Magnetotelluric (MT) observed (circle and x symbols) and calculated (solid and dashed lines are TE and TM modes, respectively) resistivity and phase data for profile MT1. See the "Magnetotelluric Data" section of this report for a description of the observed data and the "Resistivity Models" section for a description of the calculated data.