Magnetotelluric Survey to Locate the Archean/Proterozoic Suture Zone In North-Central Elko County, Nevada

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Introduction

It is important to know whether major mining districts in the Northern Nevada Gold Province are underlain by rocks of the Archean Wyoming craton, known to contain large orogenic gold deposits (Cameron, 1988), or by accreted rocks of the Paleoproterozoic Mojave province (Whitmeyer and Karlstrom, 2004). It is also important to know the location and orientation of the Archean/Proterozoic suture zone between these provinces and of major basement structures within them because these features may affect subsequent patterns of sedimentation, deformation, magmatism, and hydrothermal activity (Grauch, and others, 2003).

In eastern Utah and western Wyoming, the Archean/Proterozoic suture zone is exposed and has an east-west strike (Reed, 1993). In the Great Basin, the strike of the Archean/Proterozoic suture zone is poorly constrained because it is largely concealed below a Neoproterozoic-Paleozoic miogeocline and basin fill. East-west and southwest strikes have been inferred on the basis of strontium (Sr), neodymium (Nd), and lead (Pb) isotopic compositions of granitoid intrusions (Tosdal, and others, 2000). To better constrain the location and strike of the Archean/Proterozoic suture zone below cover, a regional south-north magnetotelluric (MT) sounding profile was acquired in north-central Nevada (fig. 1) to track the suture zone from western Utah (Williams and Rodriguez, 2003) and eastern Nevada (Williams and Rodriguez, 2004). Resistivity modeling of the MT data can be used to investigate buried structures or sutures that may have influenced subsequent regional fluid flow. The purpose of this report is to release the MT sounding data collected in north-central Nevada in September 2004; no interpretation of the data is included.

Magnetotelluric Method

The MT method is a passive surface-geophysical technique that 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. Resistivity also can be reduced by the presence of conductive clay minerals, carbon, and metallic mineralization. It is common for altered volcanic rocks to contain authigenic minerals that have resistivity values one tenth as great as those of the host rocks (Nelson and Anderson, 1992). Increased temperatures cause higher ionic mobility and mineral activation energy, which reduce rock resistivities significantly. Unaltered, unfractured igneous rocks are moderately to highly resistive (hundreds to thousands of ohm-meters [ohm-m]), whereas fault zones will show low resistivity (less than 100 ohm-m) when they consist of rocks that are 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) depending upon their fluid content, porosity, fracturing, and impurities. Marine shales, mudstones, and clay-rich alluvium normally are 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 are included in Keller (1987) and Palacky (1987).

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

The natural electric and magnetic fields are recorded in two orthogonal, horizontal directions. The vertical magnetic field “tipper” also is recorded. The resulting time-series signals are used to derive the tensor apparent resistivities and phases. First, the signals are converted to complex cross-spectra using Fast-Fourier-Transform (FFT) techniques. Then, least-squares, cross-spectral analysis (Bendat and Piersol, 1971) is used to solve for a transfer function that relates the observed electric fields to the magnetic fields with 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. Prior to conversion to apparent resistivity and phase, the tensor is normally rotated into principal directions that correspond to the directions 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 generally is done to fit both modes. When the geology satisfies the 2-D assumption, the MT data for the TE mode are for the electric field parallel to geologic strike, and the data for the TM mode are for the electric field across the geologic 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 MT method is capable of establishing whether the electromagnetic fields are responding to subsurface terrain in effectively one, two, or three dimensions. An introduction to the

MT method and references for a more advanced understanding are described in Dobrin and Savit (1988) and Vozoff (1991).

Magnetotelluric Survey

Data were collected at 19 stations in 2004 to represent the area of study. The profile location was selected to cross the Archean/Proterozoic suture zone on the basis of projections from MT data to the east (Williams, and Rodriguez, 2004). Stations 130 and 131 represent previously published MT data that were collected to resolve ambiguity in electrical strike directions. (Williams, and others, 2001a; Williams, and others, 2001b). Station locations were chosen for proximity to roads and to avoid electrical noise such as power lines. All data at the stations were collected with a portable Electromagnetic Instruments, Inc. (EMI) MT-1 system (EMI, 1996). Horizontal electric fields were sensed using copper sulfate porous pots placed in an L-shaped, three-electrode array with dipole lengths of 30 meters (m). The orthogonal, horizontal magnetic fields in the direction of the electric-field measurement array were sensed using high magnetic permeability, mu-metal-cored induction coils. Frequencies were sampled from 0.009 to 70Hz, using single-station recordings of the orthogonal, horizontal components of the electric and magnetic fields and the vertical magnetic field.

The following table lists the 19 MT station locations as recorded using a global positioning system during field acquisition. Coordinates are referenced to the 1866 Clarke spheroid and North American 1927 Western United States datum. Longitude and latitude format is degrees:minutes:seconds. Universal Transverse Mercator (UTM) units and station elevations are in meters. The accuracy of the *x*, *y*, *z* component is ±5 m.

Table 1

Station	Longitude	Latitude	North(m)	East	Elevation
129	-115:52:26	40:38:40	4,499,674	11,595,228	1654
128	-115:49:30	40:45:03	4,511,553	11,599,183	1672
127	-115:50:55	40:50:48	4,522,161	11,597,053	1728
126	-115:53:20	40:56:15	4,532,209	11,593,543	1930
125	-115:52:33	41:00:06	4,539,354	11,594,544	1894
124	-115:53:25	41:06:22	4,550,916	11,593,190	1865
123	-115:49:18	41:12:16	4,561,911	11,598,794	1821
122	-115:46:15	41:16:35	4,569,954	11,602,946	1808
121	-115:48:25	41:21:33	4,579,105	11,599,786	1824
120	-115:46:50	41:25:37	4,586,674	11,601,903	1854
119	-115:47:56	41:29:39	4,594,099	11,600,272	1992
118	-115:49:32	41:35:03	4,604,074	11,579,907	1950
117	-115:45:39	41:39:02	4,611,525	11,603,179	1939
116	-115:44:05	41:44:15	4,621,179	11,605,217	2119
115	-115:42:09	41:48:33	4,629,181	11,607,771	1858
114	-115:39:19	41:54:52	4,640,931	11,611,511	1758
113	-115:42:41	41:59:41	4,659,782	11,606,731	1803
130	-116:35:06	40:01:55	4,431,163	11,535,405	1720
131	-116:39:26	40:14:05	4,453,639	11,529,155	1466

Magnetotelluric Data

The recorded time-series data were converted to the frequency domain and processed to determine a 2-D apparent resistivity and phase tensor at each site. Rotation of the impedance tensor to maximum and minimum directions allowed for decoupling into the TE and TM modes.

Although true remote reference techniques were not used in the study, cross-power files were sorted to select optimal signal-to-noise time-series data sets (see Appendix at the back of the report).

The effects of near-surface resistivity anomalies caused “static shifts” in the data (Sternberg and others, 1988). Static shifts were significant at stations 125, 123, 117, 116, 115, and 114. Cultural features can affect the response of the MT system. Fences, pipelines, communication lines, railways, and other manmade conductors can contaminate the responses.

The figures in the Appendix represent the field-processed MT data for each station after the time-series data were converted to the frequency domain, and after the tensor-transfer function was rotated into principal directions as described in the “Magnetotelluric Method” section of this report.

For each station, nine separate plots are given:

1. Apparent Resistivity(x and o symbols are xy and yx components)
2. Impedance Phase (x and o symbols are xy and yx components)
3. Rotation Angle
4. Impedance Skew
5. Multiple Coherency(x and o symbols are xy and yx components)
6. Impedance Polar Plots
7. Tipper Magnitude
8. Tipper Strike
9. HzHx (x symbol) and HzHy (o symbol) Coherency

Error bars (],[) on the Apparent Resistivity, Impedance Phase, Skew, Tipper Magnitude, and Tipper Strike plots represent probable errors within one standard deviation of the sample variance (Gamble and others, 1979).

Apparent resistivity is the ratio of the electric field strength magnitude over the magnetic-field strength magnitude for a given frequency. The impedance phase is proportional to the slope of the apparent resistivity curve on a log-log plot, but from a baseline at -45 degrees (Vozoff, 1991). A measure of the dimensionality for MT data is provided by the impedance skew of the impedance tensor (Vozoff, 1972). If the effective, measured resistivity response to the geology beneath an MT station is truly one- or two-dimensional, then the skew will be zero. Both instrument and environmental sources of noise contribute to non-zero skew values but are typically small (about 0.1) for relatively low-noise-level recordings. Higher skews (more than 0.2) are an indication of either the resistivity response to 3-D geology or higher levels of noise. Man-made electrical noise, such as power lines, power generators,and moving vehicles and trains, can have a negative effect on MT data quality. All of these local disturbances produce an incoherent noise mainly affecting frequencies greater than 1 Hz. Other man-made electrical noise, such as direct current electric trains and active cathodic protection of pipelines, produce coherent electromagnetic signals mainly affecting frequencies less than 1 Hz.

In the study area, noise from a number of small power lines and small moving vehicles was negligible at distances of 0.4 km and farther from the noise source. Power-line signal levels were measured at each site and were typically less than 20 percent of the maximum recordable signals. Noise from larger power lines, power generators, pipelines, and trains was negligible at distances more than 5 km. Local lightning, wind, and rainstorms also can degrade data quality, but these were avoided by not recording during active thunderstorm periods. Burying the magnetic induction coils and keeping the electric dipole wires flat on the ground surface minimize wind noise.

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 plots. Values are normalized between 0 and 1, where values at 0.5 signify signal levels equal to noise levels. For this data set, coherencies generally were at an acceptable level, except at times in the frequency range “dead band” (0.01 to 5 HZ).

The figures in the Appendix represent the field-processed MT data at each station, and include some data scatter and poor signal-to-noise ratios. The only effort aimed at removing noisy data points was to visually inspect and select the best signal-to-noise field data to combine into the final data plots.

The impedance polar plots provide a measure of the MT data dimensionality (Reddy and others, 1977). For 1-D resistivity structures, the principal impedance polar diagram (dashed line) is a circle. For 2-D or 3-D resistivity structures, the principal impedance polar diagram (dashed line) elongates either parallel or perpendicular to strike direction. Over resistors, the principal impedance polar diagram elongates perpendicular to strike direction, and over conductors, the principal impedance polar diagram elongates parallel to strike direction. For 2-D resistivity structures, the additional impedance polar diagram (solid line) attains the shape of a symmetric clover leaf. For 3-D resistivity structures, the additional impedance polar diagram (solid line) elongates in one direction, and its amplitude is comparable to that of the principal impedance polar diagram (dashed line). The polar plots computed for our data show station 127 was 3-D below 10 Hz. Stations 128, 117, 114, and 113 were 3-D below 1 Hz. Station 131 was 3-D below 0.2 Hz. Stations 125, 123, 118, and 116 were 3-D below 0.1 Hz. Station 130 was 3-D below 0.01 Hz. Station 115 was 3-D over all frequencies.

The tipper can be calculated when the vertical component of the magnetic field is measured. The tipper magnitude is a measure of the tipping of the magnetic field out of the horizontal plane (Vozoff, 1991). The magnitude is zero for the 1-D case, typically increases between 0.1 to 0.5, and rarely is as great as 1 as it responds to vertical and subvertical structures. The tipper strike typically is used to help resolve the 90-degree ambiguity in the impedance rotation angle. The tipper magnitude of these stations typically ranged between 0.1 and 0.6 over the lower frequencies, indicating some vertical structure at depth. The HzHx and HzHy coherency is a measure of the signal-to-noise ratio of the vertical magnetic field with respect to each of the orthogonal, horizontal magnetic-field directions. Values are normalized between 0 and 1, where values at 0.5 signify signal levels equal to noise levels. These three-components of magnetic-field coherence provide a check on the signal-to-noise ratio of the measured values in the tipper magnitude and tipper strike plots.

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Appendix
Magnetotelluric Data Plots

There are nine separate plots for each station:

1. Apparent Resistivity for the unrotated xy (x symbol) and yx (o symbol) modes
2. Impedance Phase for the unrotated xy (x symbol) and yx (o symbol) modes
3. Rotation Angle for the impedance tensor (corresponds to the direction of xy component)
4. Impedance Skew for the impedance tensor
5. Multiple Coherency for the xy (x symbol) and minimum (o symbol) modes of the electric field
6. Impedance Polar Plots (at 12 selected frequencies)
7. Tipper Magnitude for the vertical magnetic field
8. Tipper Strike for the vertical magnetic field
9. HzHx (x symbol) and HzHy (o symbol) Coherency

Refer to the "Magnetotelluric Data" section in this report for an explanation of these plots.

Figure 1. Index map of magnetotelluric (MT) survey area in north-central Nevada. Numbered labels are MT stations acquired in 2004.