MAGNETOTELLURIC DATA ACROSS THE BATTLE MOUNTAIN-EUREKA AND CARLIN TRENDS, NORTH OF CORTEZ, NEVADA

by

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INTRODUCTION

Genesis of gold deposits along the Battle Mountain-Eureka and Carlin trends in northern Nevada is not fully understood and subject to conflicting models (e.g. Arehart and others, 1993; Ilchik and Barton, 1997; Radtke, 1985; Shawe, 1991; Sillitoe and Bonham, 1990; Tosdal, 1998). A general consensus among these models is that regional structures somehow controlled the spatial distribution of the deposits. To investigate crustal structures that may be related to the genesis of gold deposits along these trends, a regional southwest-northeast profile of magnetotelluric (MT) soundings was acquired in 1994, 1996, 1997, and 2000 (line MT3-MT3’, Figure 1). Resistivity modeling of the MT data can be used to infer the deep resistivity structure of the crust to help investigate possible tectonic controls on the emplacement of mineral deposits along these linear trends.

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, 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 faults 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 et al., 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 allows us 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. Frequencies of 10,000 Hz to 1 Hz from worldwide lightning activity and 1 Hz to 0.0001 Hz from geomagnetic micro-pulsations are the main frequency bands used by the MT method. 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 usually 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 excellent introduction to the MT method and references for a more advanced understanding are contained in Dobrin and Savit (1988) and Vozoff (1991).

MAGNETOTELLURIC SURVEY

Eighteen MT soundings were located along or near profile MT3-MT3' (Figure 1) with spacing that varied from 1.5 to 14.0 kilometers. The profile orientation is roughly perpendicular to the Battle Mountain-Eureka and Carlin trends. Stations 1-5, 15, and 16 were collected with our U.S. Geological Survey truck-mounted MT system (Stanley, 1978). Stations 30, 31, 35, and 99-106 were collected with our portable EMI MT-1 system (EMI, 1996). Horizontal electric fields were sensed using an L-shaped, three-electrode array with dipole lengths of 30 m except for stations 1-5, 15, and 16 where a dipole length of 37.5 m was used with our truck-mounted MT system. The orthogonal, horizontal magnetic fields in the direction of the electric-field measurement array were sensed using permalloy-cored induction coils (Stanley and Tinkler, 1983). Frequencies sampled ranged from 300 to 0.004 Hz using single station recordings of both orthogonal horizontal components of the electric and magnetic fields, along with the vertical magnetic field at stations 30, 31, 35, and 99-106. 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.

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. Local reference sensors to help reduce bias in the impedance determinations due to instrument or environmental noise (Gamble and others, 1979a; Clarke and others, 1983) were used at stations 30, 31, and 35. Although true remote reference techniques were not used in our survey, we did sort cross-power files to select optimal signal-to-noise data sets (Appendix).

The effects of near-surface resistivity anomalies cause "static shifts" (Sternberg and others, 1988) in the data. Static shifts of this data set ranged from 0.0 to 1.3 of a log decade. Only stations 4, 16, 30, 31 and 105 had static shifts larger than one-third of a log decade, 1.3, 0.7, 0.5, 0.4, and 0.8, respectively. The remainder of the stations had an average of 0.1 of a decade static shift. The larger static shifts should be accounted for in any subsequent modeling of the data.

MAGNETOTELLURIC DATA

The following table shows eighteen magnetotelluric (MT) station locations (from southwest to northeast). 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)
16	-117.03204	40.03355	1740
106	-116.99012	40.02843	1571
15	-116.92586	40.06778	1595
1	-116.84890	40.15161	1590
2	-116.75097	40.20433	1500
105	-116.77233	40.21090	1560
5	-116.66432	40.23551	1475
3	-116.58452	40.27633	1445
4	-116.57803	40.29375	1445
99	-116.59627	40.32478	1475
100	-116.44335	40.35050	1475
101	-116.32823	40.39182	1550
102	-116.25280	40.48377	1640
103	-116.10717	40.48735	1600
104	-115.98703	40.53218	1950
30	-116.81659	40.26598	1740
31	-116.80054	40.31094	1870
35	-116.64283	40.39057	1580

The figures in the Appendix represent the raw field MT data for each station after the time series data was converted to the frequency domain and least-squares, cross-spectral analysis (Bendat and Piersol, 1971) was used to solve for a tensor-transfer function. This tensor transfer function was used to rotate the tensor into principal directions that correspond to the direction (rotation angle) of maximum and minimum apparent resistivity. Apparent resistivity and impedance phase were then calculated.

For each station, nine separate graph plots are given:

- Apparent Resistivity for two modes,
- Impedance Phase for two modes,
- Rotation Angle for the impedance tensor,
- Impedance Skew for the impedance tensor,
- Multiple Coherency for two modes of the electric field,
- Impedance Polar Plots (at 12 selected frequencies),
- Tipper Magnitude for the vertical magnetic field,
- Tipper Strike for the vertical magnetic field, and
- HzHx (x symbol) and HzHy (o symbol) Coherency.

Each of these graphs plots the above quantity versus frequency. The Apparent Resistivity, Impedance Phase, and Multiple Coherency plots use x and o symbols to distinguish the two tensor modes. When inverting or modeling the data, these modes will be identified as TE and TM. The x and o symbols on the HzHx and HzHy Coherency plot represent HzHx and HzHy coherency, respectively. Error bars are probable errors within one standard deviation of the sample variance (Gamble and others, 1979b).

Apparent resistivity is a measure of the magnitude of the electric field strength over the magnetic field strength for a given frequency. The impedance phase is proportional to the slope of the apparent resistivity curve on a log-log scale, 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 a MT station is truly 1-D or 2-D, 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 (above 0.2) are an indication of either 3-D resistivity responses to the geology or higher levels of noise. Man-made electrical noise, such as power lines, power generators, moving vehicles and trains can have a negative effect on MT data quality. All these local disturbances produce an incoherent noise mainly affecting higher frequencies, usually above 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 below 1 Hz.

In the survey area, noise from a number of small power lines and small moving vehicles was negligible at distances of 0.4 km and greater. Power line levels were measured at each site and were typically less than 20% of the maximum recordable signals. Noise from larger power lines, power generators, pipelines, railroads, and steam-driven trains, mostly near mining operations, was negligible at least 5 km from them. Recordings were not made when noise from moving vehicles affected the magnetic signals. Local lightning, wind, and rainstorms can also degrade data quality, but these were avoided by not recording during active thunderstorm periods. Wind noise was minimized by burying the magnetic induction coils.

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 (0.004 to 0.1). The lower frequency ionospheric signals are related to sunspot activity whose levels typically follow an 11-year cycle. The sunspot activity was near the lowest level of the cycle during the 1994, 1996, and 1997 surveys, and was near the highest level in the 2000 survey.

The figures in the Appendix represent the raw field MT data at each station, which includes some data scatter and poor signal-to-noise ratios. Our only effort 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 diagrams are circles. For 2-D or 3-D resistivity structures, the principal impedance polar diagrams (dashed lines) elongate either parallel or perpendicular to strike direction. Over resistors, the principal impedance polar diagrams elongate perpendicular to strike direction and over conductors, the principal impedance polar diagrams elongate parallel to strike direction. Also, for 2-D resistivity structures, the additional impedance polar diagrams (solid lines) attain the shape of a symmetric clover leaf. For 3-D resistivity structures, the additional impedance polar diagrams elongate in one direction and their amplitudes are comparable to those of principal impedances. Sites whose polar plots indicated 3-D character in the lower frequencies were MT stations 3, 4, 100, and 101 (Figure 1).

The tipper can be solved for 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 and typically increases between 0.1 to 0.5, and rarely as great as 1, as it responds to vertical and sub-vertical structures. The tipper strike is typically used to help resolve the 90-degree ambiguity in the impedance rotation angle. The vertical component of the magnetic field was measured at MT stations 30, 31, 35, and 99-106. The tipper magnitude of these stations was typically 0.1 to 0.4 over the lower frequencies indicating 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-component magnetic field coherencies 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

For stations 30, 31, 35, and 99-106, there are nine separate graph plots:

- Apparent Resistivity for two modes,
- Impedance Phase for two modes,
- Rotation Angle for the impedance tensor,
- Impedance Skew for the impedance tensor,
- Multiple Coherency for two modes of the electric field,
- Impedance Polar Plots (at 12 selected frequencies),
- Tipper Magnitude for the vertical magnetic field,
- Tipper Strike for the vertical magnetic field, and
- HzHx (x symbol) and HzHy (o symbol) Coherency.

Stations 1-5, 15, and 16, only have the first six graph plots above, since the vertical magnetic field data (Tipper, Hz) was not acquired. Refer to the "Magnetotelluric Data" section in this report for an explanation of these plots.

Figure 1.   Index map. Magnetotelluric transect (MT3-MT3') acquired in 1994, 1996, 1997, and 2000 in northeastern Nevada. Shaded zones are two northwest-trending mineralized belts in northeastern Nevada, the well-known Carlin trend and the Battle Mountain-Eureka trend. Base map adapted from Struhsacker and others (1996).