DEEP ELECTRICAL GEOPHYSICAL MEASUREMENTS ACROSS THE CARLIN TREND, NEVADA

by

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INTRODUCTION

Genesis of gold deposits along the Carlin trend 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 the Carlin trend, a regional southwest to northeast profile of magnetotelluric (MT) soundings was acquired in 1996 (line MT-MT’, figure 1). Resistivity modeling of the MT data can be used to derive the deep resistivity structure and investigate its implication on possible tectonic controls on the linear distribution of mineral deposits.

MAGNETOTELLURIC METHOD

The magnetotelluric (MT) method is a passive surface geophysical technique that uses the earth's natural electromagnetic fields to investigate the 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 and Frischknecht, 1966). 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, graphitic 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 unaltered 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 thousands to tens of thousands of ohm-m), whereas fault zones will show low resistivity (less than 100 ohm-m) when rocks in the zones are fractured enough to have hosted fluid flow and consequent mineralogical alteration. 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). 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). The Earth’s natural electromagnetic fields that are measured include the magnetic and electric field due to world-wide lightning activity at frequencies of 10,000 Hz to 1 Hz and geomagnetic micro-pulsations at frequencies of 1 Hz to 0.0001 Hz. 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 method can determine resistivity variations at different depths because the different frequency fields propagate to different depths (Vozoff, 1972).

Using a computer-based data-acquisition and processing system, the natural electric and magnetic fields are recorded in two orthogonal, horizontal directions (the vertical magnetic field is sometimes recorded as well). The recorded time-series signals are used to derive earth tensor apparent resistivities and phases. This is achieved 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 their 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 rock bodies of effectively 1-, 2-, or 3-dimensions (Appendix). 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

Twenty-one MT soundings were located along profile MT-MT' (figure 1) with spacing that varied from 1.6 to 12.4 kilometers. The profile orientation is oblique to the mineral trends on the southwest end of the profile. Station locations were chosen to take advantage of previously collected data (Grauch and others, 1998), to have good road access, as required by our U.S. Geological Survey truck-mounted MT system (Stanley, 1978), and to avoid electrical noise, such as power lines. Horizontal electric fields were sensed using an L-shaped, three-electrode array with dipole lengths of 37.5 m except for stations 11, 13, and 14 where a dipole length of 75 m was used to increase the recorded magnitudes of the low electric field encountered at those stations. 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. 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 analyzed using Fourier methods to determine a two-dimensional apparent resistivity and phase tensor at each site. The data for each frequency were freely rotated to maximum and minimum apparent resistivity directions so that propagation modes for the signals were de-coupled 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, 1979; Clarke and others, 1983) were not used at stations 1-10, 12, 19-23, and 29, because the additional magnetic field sensors required for use as reference sensors were not available. 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 0.1 to 0.7 of a log decade. Only stations 12, 3, and 23 had static shifts larger than one-third of a log decade, 0.5, 0.7, 0.4, respectively. The remainder of the stations had an average of 0.2 of a decade static shift.

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APPENDIX

MAGNETOTELLURIC DATA

The following table represents digitized magnetotelluric (MT) station locations in decimal degrees taken from 100,000 scale maps of Battle Mountain, Crescent Valley, Elko, and Tuscarora, Nevada.

Station	Longitude	Latitude
14	-116.55498	40.35025
13	-116.56650	40.43708
12	-116.46765	40.55145
19	-116.41989	40.59568
11	-116.40231	40.67147
10	-116.36736	40.73788
9	-116.36060	40.76114
1	-116.33037	40.79034
2	-116.31374	40.80459
3	-116.30656	40.82193
4	-116.30516	40.84248
5	-116.29302	40.85368
6	-116.27523	40.86021
7	-116.26662	40.87744
8	-116.25457	40.89239
20	-116.22196	40.93338
21	-116.18823	40.95701
22	-116.16402	41.00800
29	-116.09901	41.03600
23	-116.03185	41.10000
54	-116.38179	41.44002

The figures that follow 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 used in the conversion to **apparent resistivity** and **impedance phase** after the tensor was rotated into principal directions that correspond to the direction (**rotation angle**) of maximum and minimum apparent resistivity. **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 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 large moving vehicles affected the magnetic signals. Noise from local lightening, wind, and rainstorms was avoided by ceasing to record during active thunderstorm periods. Wind noise was minimized by burying the magnetic induction coils.

A measure of the signal-to-noise ratio is provided by the **mult**iple **coherency**. 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 this survey. Data scatter and poor point-to-point continuity indicate stations affected by poor signal-to-noise ratios.

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 elongate either parallel or perpendicular to strike direction. Over resistors, the principal impedance polar diagrams are elongate perpendicular to strike direction and over conductors, the principal impedance polar diagrams are elongate parallel to strike direction. Also, for 2-D resistivity structures, the additional impedance polar diagrams attain the shape of a symmetric cloverleaf. For 3-D resistivity structures, the additional impedance polar diagrams become 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 14, 13, 19, 9, 1, 2, 3, 4, 5, 6, 20, 21, 22, 29, and 54 with the bulk of the sites inside and northeast of the Carlin trend (figure 1).

A solution for the tipper can be computed from the vertical component of the magnetic field. 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 only at MT stations 14 and 11. The **tipper magnitude** of these stations was 0.3 or less at the lower frequencies indicating vertical structure at depth.