MAGNETOTELLURIC DATA IN THE MIDDLE RIO GRANDE BASIN, RIO RANCHO, NEW MEXICO

by

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U.S. DEPARTMENT OF THE INTERIOR
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INTRODUCTION

The population in the Albuquerque-Santa Fe region of New Mexico is rapidly growing. The Santa Fe Group aquifer in the Middle Rio Grande Basin is the main source of municipal water for the greater Albuquerque metropolitan area. The capacity of this aquifer is more limited than previously thought (Thorn et al., 1993). The Middle Rio Grande Basin, as defined hydrologically and used here, is the area within the Rio Grande Valley extending from Cochiti Dam downstream to the community of San Acacia (Figure 1). Because approximately 600,000 people (40 percent of the population of New Mexico) live in the study area (Bartolino, 1999), water shortfalls could have serious consequences for the state. Future growth and land management in the region depends on accurate assessment and protection of the region's groundwater resources. An important issue in defining the ground water resources is a better understanding of the hydrogeology of the Santa Fe Group and the other sedimentary deposits that fill the Rio Grande rift.

The U.S. Geological Survey (USGS) is currently conducting a series of studies of the Middle Rio Grande Basin in north-central New Mexico to address this issue. One objective of these studies is to improve the hydrogeologic models of the Middle Rio Grande Basin to help land managers plan the development of water supplies. These studies involve a multi-disciplinary approach to better understand the critical aquifers in what is considered to be an intracontinental rift environment. Detailed geologic mapping, high-resolution airborne magnetic surveys, lithologic and geophysical logging of wells, surface-based electrical and magnetic surveys, enhanced satellite imagery, as well as hydrologic and hydrogeochemical data are being used to refine understanding of the aquifer systems in the Middle Rio Grande Basin (Cole et al., 1999). An airborne time domain electromagnetic (TEM) survey was flown for the USGS as part of this work. The primary purpose of the TEM survey was to map changes in electrical resistivity with depth that are related to lithologic variations important to the critical aquifers. However, typical conversion of recorded signal to resistivities obtained from TEM surveys are not unique and depend on proprietary algorithms used by the various companies that collect airborne TEM data. Even though the airborne TEM method has been used for many years as a geophysical prospecting tool, its use in hydrogeological mapping is recent. Therefore, before making maps of resistivity, we first evaluated how deep the TEM inversions were reliable to, based on correlation with well logs and ground electromagnetic surveys (magnetotellurics). This report presents a description of the magnetotelluric (MT) soundings that were used to help calibrate the results of the airborne TEM survey. The purpose of this report is to release the magnetotelluric sounding data; no interpretation of the data is included.

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) depending 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 primary 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 the tensor apparent resistivities and phases. First, the signals are converted to complex cross-spectra using FFT (fast-Fourier-transform) 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 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. 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 for the electric field parallel to geologic strike, and the data for the TM mode is for the electric field 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 SURVEY

Fourteen MT soundings were acquired in May of 1997 and May of 1998 in the Rio Rancho subdivision of Albuquerque, New Mexico (Figure 1). The station locations were chosen to help calibrate the inversion of the airborne time domain electromagnetic data in areas that had locally 1-D electromagnetic response and for proximity to roads and avoidance of electrical noise, such as power lines. All stations were collected with a portable EMI MT-1 system (EMI, 1996). Horizontal electric fields were sensed using titanium electrodes placed in an L-shaped, three-electrode array with dipole lengths of 30 m. The orthogonal, horizontal magnetic fields in the direction of the electric-field measurement array were sensed using permalloy-cored induction coils. Frequencies sampled ranged from 20,000 to 1 Hz using single station recordings of both orthogonal horizontal components of the electric and magnetic fields, along with the vertical magnetic field.

The following table shows the fourteen 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 below is decimal degrees. Universal Transverse Mercator units below are in meters. Elevation below is in meters.

Station	Longitude	Latitude	North(m)	East(m)	Elev
1	-106.92200	35.34817	3,906,969	13,326,034	1775
2	-106.77783	35.34733	3,912,809	13,338,440	1829
3	-106.67917	35.29967	3,907,400	13,347,300	1700
4	-106.49917	35.29400	3,906,493	13,363,686	1720
6	-106.75667	35.17600	3,894,901	13,339,108	1719
12	-106.81327	35.17281	3,893,712	13,334,876	1781
10	-106.84378	35.23374	3,900,523	13,332,222	1847
11	-106.82655	35.23480	3,900,611	13,333,792	1823
13	-106.80202	35.23152	3,900,205	13,336,018	1804
14	-106.78210	35.23149	3,900,170	13,337,831	1756
16	-106.74807	35.23171	3,900,139	13,340,928	1689
15	-106.73068	35.23316	3,900,273	13,342,514	1701
5	-106.68654	35.22695	3,899,515	13,346,519	1609
7	-106.68118	35.22522	3,899,314	13,347,004	1606

MAGNETOTELLURIC DATA

The recorded time-series data were transformed to the frequency domain and processed to determine a two-dimensional apparent resistivity and phase tensor at each site. Rotation of the impedance tensor to maximum and minimum directions allows for decoupling into the 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 all stations. 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 (see Appendix).

The effects of near-surface resistivity anomalies cause "static shifts" (Sternberg et al., 1988) in the data. Static shifts are significant for half of this data set. Rio Rancho stations 5, 7, 10, 11, 13, 14 and 16 had a static shift larger than one-third of a log decade. The remainder of the stations had minor static shifts, ranging from 0.0 to less than 0.3 of a log decade. Cultural features can affect the response of the MT system. Fences, pipelines, communication lines, railways and other man-made conductors can contaminate the responses. Cultural noise appeared to severely affect Rio Rancho stations 5, 6, and 7.

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 the tensor-transfer function was rotated into principal directions as described above in the "Magnetotelluric Method" section.

For each station, nine separate plots are given:

1. Apparent Resistivity for the rotated maximum (x symbol) and minimum (o symbol) modes
2. Impedance Phase for the rotated maximum (x symbol) and minimum (o symbol) modes
3. Rotation Angle for the impedance tensor (corresponds to the direction of maximum apparent resistivity)
4. Impedance Skew for the impedance tensor
5. Multiple Coherency for the rotated maximum (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, and
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, 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 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 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 the resistivity response to 3-D 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 frequencies 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 from the noise source. 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, and trains 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 high frequency "dead band" (1,000 to 5,000 Hz).

The figures in the Appendix represent the field-processed 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 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. Also, 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 only site whose polar plots indicated 3-D character was Rio Rancho station 7.

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 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 all stations. The tipper magnitude of these stations was typically 0.1 to 1.2 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

There are nine separate plots for each station:

1. Apparent Resistivity for the rotated maximum (x symbol) and minimum (o symbol) modes
2. Impedance Phase for the rotated maximum (x symbol) and minimum (o symbol) modes
3. Rotation Angle for the impedance tensor (corresponds to the direction of maximum apparent resistivity)
4. Impedance Skew for the impedance tensor
5. Multiple Coherency for the rotated maximum (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
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Refer to the "Magnetotelluric Data" section in this report for an explanation of these plots.

Figure 1. Index map of the Rio Rancho survey area, north of Albuquerque, in the Middle Rio Grande Basin (Albuquerque Basin Boundary), New Mexico. Solid triangles are magnetotelluric stations acquired in 1997 and 1998. Base map modified from Bartolino (1999).