Magnetotelluric Data Across the Pajarito Fault, West of Santa Fe, New Mexico

By Jackie M. Williams and Brian D. Rodriguez

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Introduction

The Santa Fe region is rapidly growing. The Santa Fe Group aquifer, east of the Pajarito Fault, in the Española Basin is the main source of municipal water for the region (fig. 1), and water shortfalls could have serious consequences. Future growth and land management in the region depend on accurate assessment and protection of the region's ground-water resources. An important issue in managing the ground-water resources is a better understanding of the hydrogeology of the Santa Fe Group, the sedimentary deposits that fill the Rio Grande rift and contain the principal ground-water aquifers.

The U.S. Geological Survey (USGS) is doing a series of multidisciplinary studies of the Española Basin in northern New Mexico. Detailed geologic mapping, high-resolution airborne magnetic surveys, electromagnetic surveys, and hydrologic, lithologic, and hydrogeochemical data are being used to better understand the aquifer systems. A magnetotelluric (MT) survey was done as part of these studies. The primary purpose of the MT survey was to map changes in electrical resistivity with depth that are related to lithologic variations important to the critical aquifers across the Pajarito Fault. The purpose of this report is to release the MT sounding data; no interpretation of the data is included.

Magnetotelluric Method

The magnetotelluric (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 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 10 times less 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 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 are composed 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 are normally conductive (a few ohm-m to tens of ohm-m). Unaltered, metamorphic rocks (nongraphitic) 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 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 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 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. 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 decoupled 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 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 terranes of effectively one, two, or three-dimensions. An introduction to the MT method and references for a more advanced understanding are in Dobrin and Savit (1988) and Vozoff (1991).

Magnetotelluric Survey

Data were collected at 11 stations in 2004 to represent the area of this study. The station locations were chosen for constraining gravity modeling along the Pajarito Fault and for proximity to roads, and for avoidance of electrical noise such as power lines. All data at the stations were collected with a portable 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 permalloy-cored induction coils. Frequencies sampled ranged from 4 to 23,000 Hz (4.394, 7.324, 12.21, 19.04, 28.32, 41.50, 60.06, 79.00, 85.94, 100.0, 122.1, 150.0, 172.4, 210.0, 270.0, 340.0, 460.0, 580.0, 720.0, 885.0, 1170, 1500, 1870, 2200, 2730, 3550, 4900, 6500, 9000, 11590, 15290, 19500, 23370) and 0.009 to 70 Hz (0.0088, 0.0146, 0.0244, 0.0381, 0.0566, 0.0830, 0.0879, 0.1201, 0.1465, 0.1719, 0.2441, 0.3447, 0.3809, 0.5664, 0.8301, 1.201, 1.758, 2.441, 2.920, 3.447, 4.883, 7.617, 11.328, 16.602, 24.023, 34.375, 48.828, 68.945) 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 11 MT station locations 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 are in meters. Station elevation is given in meters. The accuracy of the *x*, *y*, *z* component is about ±5meters.

Station	Longitude	Latitude	UTM North(m)	UTM East(m)	Elevation(m)
35m	-106:28:31	35:49:35	3,965,476	13,366,739	2776
34m	-106:26:18	35:49:38	3,965,540	13,370,093	2709
33m	-106:25:26	35:47:56	3,962,360	13,371,350	2632
32m	-106:24:45	35:47:02	3,960,693	13,372,338	2538
31m	-106:24:37	35:43:50	3,954,777	13,372,461	2273
30m	-106:23:37	35:42:52	3,952,970	13,373,947	2093
36m	-106:23:00	35:42:40	3,952,577	13,374,863	2008
15	-106:13:43	35:44:37	3,956,023	13,388,902	2047
28m	-106:13:38	35:42:09	3,951,444	13,388,978	2037
14	-106:13:31	35:40:20	3,948,096	13,389,104	2100
29m	-106:13:34	35:38:09	3,944,059	13,388,978	1989

Magnetotelluric Data

The recorded time-series data were transformed 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 allows for decoupling into the TE and TM modes. All data were rotated to 47 degrees.

Although true remote reference techniques were not used in the survey, 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 in the MT stations 32 and 29, although the static shift is resolved in the AMT data for station 32. 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 the tensor-transfer function was rotated into principal directions as described in the "Magnetotelluric Method" section.

For each station, eight 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. Impedance Skew
4. Multiple Coherency for the rotated maximum (x symbol) and minimum (o symbol) modes
5. Impedance Polar Plots
6. Tipper Magnitude
7. Tipper Strike
8. 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 a 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 (above 0.2) are an indication of either the resistivity response to 3-D geology or higher levels of noise. Manmade 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 above 1 Hz. Other manmade 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 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 greater 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 minimized 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 were generally at an acceptable level, except at times in the "dead band" frequency ranges (0.01 to 5 Hz and 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. The 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. 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). Station 35 indicates a minor 3-D response over all of the frequencies recorded. Stations 34 and 36 indicate a 3-D response below 0.05 Hz. Stations 30 and 33 indicate a 3-D response below 0.172 Hz. Stations 31 and 32 indicate a 3-D response below 0.1 Hz.

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 typically is used to help resolve the 90-degree ambiguity in the impedance rotation angle. The tipper magnitude of these stations typically was 0.1 to 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-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 eight 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. Impedance Skew for the impedance tensor
4. Multiple Coherency for the rotated maximum (x symbol) and minimum (o symbol) modes of the electric field
5. Impedance Polar Plots (at 12 selected frequencies)
6. Tipper Magnitude for the vertical magnetic field
7. Tipper Strike for the vertical magnetic field
8. 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 and AMT) survey area, west of Santa Fe, in the Española Basin, northern New Mexico. Stations acquired in 2004 are the numbered labels. Base map modified from US Geological Survey, Albuquerque, New Mexico 250,000 scale topographic map.