Applications of Controlled Source and Natural Source Audio-frequency Magnetotellurics to Groundwater Exploration

by
Norman R. Carlson, Zonge Engineering & Research Organization, Inc., Tucson, AZ
Phillip M. Paske, HydroSystems, Inc., Tempe, AZ
Scott A. Urquhart, Zonge Engineering & Research Organization, Inc., Tucson, AZ

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Abstract

Audio-frequency magnetotellurics (AMT), using either a controlled source (CSAMT) or natural source (NSAMT), has become an efficient, cost-effective tool for groundwater exploration. Advancements in field equipment have improved data quality and increased data acquisition speed, and the availability of 2D inversion modeling has significantly improved data interpretation. Since depth of investigation is not related to the receiver electric field dipole size, AMT can be used as either a high-resolution tool (using short dipoles) or as a reconnaissance tool (using large dipoles).

Several recent field examples are presented, including fractured bedrock targets, in which lateral resolution is important, as well as reconnaissance-style basin mapping, in which speed and economic efficiency is critical. In one project, located in Tule Desert, Nevada, CSAMT was used successfully to map an undeveloped basin, and was instrumental in subsequent court hearings to support water right applications to develop groundwater resources from this basin.
APPLICATIONS OF CONTROLLED SOURCE AND NATURAL SOURCE AUDIO-FREQUENCY MAGNETOTELLURICS TO GROUNDWATER EXPLORATION

Norman R. Carlson, Zonge Engineering & Research Organization, Inc., Tucson, AZ
Phillip M. Paski, HydroSystems, Inc., Tempe, AZ
Scott A. Urquhart, Zonge Engineering & Research Organization, Inc., Tucson, AZ

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Introduction and Background

Several geophysical methods can validly be proposed for subsurface mapping in groundwater exploration projects, including seismic, gravity, magnetics, and various electrical/electromagnetic methods. Each method has advantages and disadvantages, of course, based on specific survey needs and site characteristics. One survey technique which we have been using on an increasing basis is audio-frequency magnetotellurics (AMT), in both the controlled source mode (CSAMT) and natural source (NSAMT). CSAMT in particular has seen widespread use in the minerals exploration industry since 1978 when the first commercial system became available, but until recent years, has only occasionally been applied to groundwater exploration. Advances in field equipment have reduced survey costs, and improved interpretational methods have increased the confidence of the method results. In our experience, AMT often provides more cost-effective, higher lateral and vertical resolution resistivity data at greater depths than other electrical and electromagnetic techniques, particularly in areas of difficult terrain, restricted access, or environmentally sensitive areas.

Briefly, AMT is a surface-based electromagnetic sounding technique that uses a fixed grounded dipole as a signal source (CSAMT), or alternatively, the naturally-occurring fields of the earth/atmosphere system (NSAMT). AMT can be considered a subset of the magnetotellurics (MT) method, first described in detail by Cagniard (1953); MT using a controlled signal source was developed later by Goldstein and Strangway (1975). In the case of CSAMT, the transmitter signal source usually consists of a grounded electric dipole, typically 1,200 to 1,800 meters (approximately 4,000 to 6,000
feet) in length, located 3,500 to 9,000 meters (11,500 to 29,500 feet) from the area where the measurements are recorded. In the case of NSAMT, naturally-occurring electromagnetic fields are used as the signal source.

At the receiver site, grounded dipoles detect the electric field (parallel to the transmitter if one is being used) and magnetic coil antennas sense the perpendicular magnetic field. The ratio of orthogonal, horizontal electric and magnetic field magnitudes (e.g. \( E_x \) and \( H_y \)) yields the apparent resistivity (in ohm-meters):

\[
\rho_a = \frac{1}{5f} \left| \frac{E_x}{H_y} \right|
\]

where \( f \) is frequency in hertz of the measurement, \( E_x \) is the electric field in mV/km along the observation line, and \( H_y \) is the magnetic field in gammas or nanoteslas perpendicular to the line.

The difference between the phase of the electric and magnetic fields yields the impedance phase, which is often called the phase or phase difference:

\[
\varphi = \varphi(E_x) - \varphi(H_y)
\]

Varying the frequency of the observations controls the depth of investigation using the CSAMT method. A concept used extensively in electromagnetic geophysics is the skin depth, which is the depth at which the amplitude of the field decays to 37 percent of the original value. The skin depth, \( \delta \), in meters is given by the equation:

\[
\delta = 503 \sqrt{\frac{\rho_a}{f}} \text{ meters;}
\]

where \( \rho_a \) = apparent (measured) resistivity in ohm-meters, and \( f \) = signal frequency in hertz. An estimate of the total depth of investigation is given by \( D \), which is:

\[
D = \delta/\sqrt{2} \text{ or } 356 \sqrt{\frac{\rho_a}{f}} \text{ meters.}
\]

Therefore, depth sections can be generated using the AMT method by measuring the electric and magnetic fields over a range of frequencies. The ratio of the measured electric and magnetic fields provides information about the resistivity at depth and by making measurements at lower frequencies greater depths of penetration can be attained.

Of particular importance here is the fact that depth of investigation is dependent on frequency and resistivity, but not on geometry. In other resistivity methods, including Schlumberger, gradient, dipole-dipole, transient electromagnetics (TEM), etc., the depth of investigation is related to the size of the transmitter dipole (or loop) and/or the transmitter-receiver separation. As a result, as the depth of investigation increases, the survey geometry often becomes large and unwieldy, particularly for limited-access sites. In the case of CSAMT, no changes in size or location of the transmitter or receiver dipoles
are necessary to increase depth of investigation, and the same transmitter dipole can be used for either reconnaissance surveys (larger receiver dipoles) or high-resolution surveys (small receiver dipoles).

Logistically, AMT is a very efficient survey method; the field crews usually consist of only three or four people using one or two pick-up trucks, and a typical crew is often able to acquire data at 35 to 45 stations per day. Depending on the station spacing (which depends on the resolution required by the survey), this equates to 1,750 feet (533 meters) per day (for high resolution) to as much as 12,000 feet (3658 m) per day (for lower resolution, reconnaissance-style mapping).

AMT data can be acquired as a scalar measurement (an electric-field measurement and perpendicular magnetic-field measurement), vector (two orthogonal electric-field measurements and the perpendicular magnetic-field measurements), or tensor (two orthogonal e-fields, three magnetic fields, all from two orthogonal transmitters in the case of CSAMT). The choice of scalar, vector, or tensor is usually made on the basis of survey budget and complexity of the survey area. For a more complete description of the methods, see Zonge, et. al., 1985, and Zonge and Hughes, 1991. In the examples below, all data were acquired in the scalar CSAMT mode, and the smooth-model inversion results shown in the figures are from the 1D and 2D inversion programs SCSINV and SCS2D, written by Dr. Scott MaclInnes of Zonge Engineering & Research Organization, Inc.

**Basin Reconnaissance Field Example**

A good example of successful reconnaissance-level basin mapping is the Tule Desert project in Lincoln County, Nevada, USA. This survey was intended to aid in understanding the basin characteristics in support of water right applications for a private water company. The data were acquired in three phases, each building on the results of the prior phase. At completion, the survey included 12 lines comprised of 1,567 stations covering 392,000 line feet (about 74 miles) using a 250-foot station spacing (e-field receiver dipoles).

The Tule Desert Groundwater Basin is an elongated basin oriented in a generally northeast-southwest direction, approximately 32 miles long by 12 miles wide. Surface water drainage is by several ephemeral washes, receiving runoff from localized storm events. The surrounding geology, including the regional carbonate-rock aquifer, is the result of complex geologic processes which formed the surface geologic features, and groundwater basin structure.

Prior to conducting any intrusive exploration activities and subsequent geophysical survey, only one small diameter shallow well existed in the alluvial portion of the basin, locally known as the Tule Desert Well. The well supplied water to fill an attendant stock watering tank. Because of the remote location of Tule Desert and extremely limited source water for drilling, the actual method for drilling a small diameter exploration hole over 2,000 feet deep had to be carefully planned. The sites for two initial exploration holes (called MW-1 and MW-2) were selected from available published maps prepared by the Nevada Bureau of Mines. This information was used to estimate the position and extension of fractures exposed in carbonate-rock outcrops peripheral to the basin. The intent of locating wells in this fashion was to access groundwater from fractures within the regional carbonate-rock aquifer.

MW-1 reached a depth of 1,900 feet. Drill cutting samples and downhole geophysical logging indicated that the upper 840 feet of the exploration hole penetrates unconsolidated sediments. Below
840 feet, to 1,900 feet, consolidated rocks occur and are characteristic of the regional carbonate-rock aquifer. Groundwater measurement indicated the depth to water at 700 feet. MW-2 was located approximately four miles distant from MW-1. Logging of MW-2 indicated that the upper 1,200 feet consisted of unconsolidated sediments. Below 1,200 feet, consolidated rock occurs characteristic of the carbonate-rock aquifer. The depth to groundwater at MW-2 was measured at approximately 500 feet.

When comparing the drill cutting samples and downhole geophysical logging information between MW-1 and MW-2, it was difficult to develop cross-sections between the sites based on the apparent lithologic differences. It is interesting to note that one of the adjacent mountains near MW-1 and MW-2 is named Jumbled Mountain alluding to the complex geology of the underlying basin. The cost to drill each small diameter exploration hole was close to $125,000. For this reason, it was decided to perform a limited surface geophysical survey between MW-1 and MW-2 and other select areas of the basin. This would allow further definition of the basin to locate additional exploration holes which could possibly lead to drilling of large diameter water production wells. The cost of one water production well in this area could easily range from $750,000 to $1,000,000.

The CSAMT survey conducted between MW-1 and MW-2 indicated that the most favorable site for drilling of a large diameter water production well (PW-1) was close to MW-1. Subsequent drilling and aquifer testing of PW-1 indicated this well produced groundwater at a constant rate of 1,400 gallons per minute over a seven-day testing period.

A later exploration well, MW-3 was located on information from one of the CSAMT surveys. Drilling of MW-3 was significant because it actually saved the client the cost of drilling a water production well in an area that is now expected to yield low groundwater production. The conductive feature on the CSAMT survey turned out to be a volcanic tuff. The tuff was saturated but would not release enough water for large-scale water resource development. This area of the basin was removed from consideration for developing groundwater.

Prior to the geophysics, one proposed interpretation of the area suggested that the alluvial fill of the entire basin was underlain by volcanics, and that a significant amount of the subsurface water exited the basin through a specific fault zone that created a gap in the bounding mountains. If correct, this interpretation would have significant bearing on the groundwater-use application outcome.

One very important result of Phase I of the AMT survey, however, was the delineation of a previously unrecognized basement high near the center of the basin which effectively divided the basin into two distinct parts. Fig. 1 shows apparent resistivity cross sections for two of the survey lines. The top cross section (Fig. 1A) shows an east-west survey line called Line NBC in the northern part of the basin. The transmitter was located approximately 34,000 feet from the survey line. The results are typical of similar basins: moderate-to-low resistivity basin fill material, bounded on the west and east by high resistivity outcropping bedrock. The unexpected basement high is seen in the cross section in Fig. 1B, which is part of Line 4, a line crossing the basin in the south-central part of the basin, where the basin was expected to be deepest. The transmitter for this line was located approximately 23,000 feet from this segment of the survey line. A broad, very high resistivity feature, nearly 12,000 feet in width, extends from depth to very near the surface in the center of the line.

This unexpected central resistive feature was confirmed and mapped with additional lines in Phases II and III of the survey, and it was found that west of this basement high, volcanics were indeed
present under the alluvial fill. East of the basement high, however, the alluvial fill was underlain by Mesozoic and Paleozoic limestones, which are the principle aquifer targets in this area.
Figure 1: Apparent resistivity cross sections (2D Smooth model inversions) crossing the northern part of the Tule Desert Basin (top, Fig. 1A) and crossing the south-central part of the basin (bottom, Fig. 1B).
A second significant use of the CSAMT results was in better understanding the possible flow paths of groundwater at the boundaries of the Tule Desert Basin. Surface drainage suggested that a gap in the East Mormon Mountains, called Toquop Gap, could be a significant flow path depending on the characteristics of the fault zone that creates the gap. Fig. 2 shows an oblique view of the 2D smooth-model inversion results for a CSAMT line that was acquired through the gap, called the Toquop Line. The transmitter for this line was located approximately 24,000 feet from the line. In this illustration, the inversion results resistivity cross section is hung from the USGS DEM (digital elevation model) data for this area; color shading of the cross section is similar to Fig. 1.

Figure 2- CSAMT 2D smooth-model inversion cross section hung from USGS DEM surface, showing the very resistive nature of the Toquop Gap fault zone. Red dots denote each CSAMT station, at 250-foot intervals. Vertical exaggeration is 3:1; resistivity color scale is similar to Fig. 1. The blue line denotes the primary surface drainage.
High Resolution Fractured Bedrock Example

Since the depth of investigation of the AMT method is not affected by changes in the receiver’s electric-field dipole size, AMT can also be used for mapping narrow targets (by using a small e-field dipole) such as fault and fracture zones. In some environments, fractures in bedrock represent the most attractive targets for developing groundwater resources, and AMT has been used successfully in locating productive fractures for well sites. The Bellemont Project in Arizona, USA, is a good example of this type of target, as well as illustrating the logistical flexibility of the method.

Bellemont is located near the southern extent of the Colorado Plateau physiographic province in northern Arizona approximately 10 miles west of Flagstaff. In this area, several cinder cones are present where thin alluvial sediments and volcanic rocks overlay a thick sequence of predominantly Paleozoic sedimentary rocks. The Bellemont fault is one of the main structural features in the area trending in a northeasterly direction. This fault is evident on the land surface south of the property, but is concealed across the parcel of land available for locating a well. Other wells drilled in the Bellemont fault are reported to yield groundwater at almost 200 gpm.

In this area there are two recognized groundwater aquifers. The shallow aquifer is limited in areal extent and is strongly influenced by periods of surface recharge from precipitation events. The owner of the property has five wells that access groundwater from the shallow aquifer. Water production from these wells ranges from 5 to 20 gpm where groundwater is less than 150 feet below the ground surface. Drought conditions in northern Arizona have impacted other area shallow wells by a decrease in water levels and commensurate loss in water production rates. The shallow aquifer is not considered as a sustainable long-term supply for increased development in the area. In contrast, the regional aquifer is a deep and widespread groundwater system. In the area, groundwater in the regional aquifer is under artesian pressure and measured at depths greater than 1,500 feet below the surface. Well yields can range from less than 10 gpm to over 1,000 gpm. The highest producing wells in the regional aquifer are located on structure controlled systems.

Prior to conducting the CSAMT survey on the property, the owner used the services of local government experts to locate two wells drilled to the regional aquifer. The target for the wells was the Bellemont fault. The methods to locate the well sites consisted of fracture trace analysis and review of regional, general remote sensing studies. These two wells, combined, only produced 34 gpm which was not enough water for the planned development. The cost of drilling these wells was over $650,000.

The Bellemont site is small, and the permitted work area measured approximately 1,000 feet by 1,800 feet. This small size precluded the use of galvanic techniques, which would require large dipoles and large separations to achieve the necessary depth of investigation (greater than 2,000 feet). TEM was also eliminated as a possible tool, since a transmitter loop large enough to provide the necessary depth of investigation would also reduce the lateral resolution. CSAMT was proposed, and a remote transmitter site was located on public lands approximately five miles from the target well site. Since the Bellemont fault zone was presumed to be fairly narrow, the e-field dipole size was only 100 feet. Five short lines of data were acquired, and the possible location of the Bellemont fault was identified in the data. Three additional lines were added to further delineate the fault based on the original data.
The interpretation of this data set was not without ambiguity; the area is in close proximity to a freeway, with nearby powerlines, pipelines, and other cultural noise sources. Static effects are almost certainly influencing some stations, and some expected resistivity contrasts at depth are not clearly evident in the data. However, based on all of the data, including comparisons of 1D and 2D models, using several different static-corrections, a fault was interpreted in the data, and a drill site was selected. Figure 3 shows the 1D smooth-model inversion cross section for one of the lines that intersected the suspected Bellemont fault. Drill hole Bell 2, at station 675, was one of the two deep wells drilled prior to the CSAMT survey. It was drilled to a depth of 2,100 feet, and produces only 23 gpm.

Based on all of the CSAMT lines, and given the need to locate a new well in this very restricted area, a new site (Bell 3) was selected at station 350 on Line 1. During drilling, clear evidence was encountered of faulting in the recovered material. Figure 3 shows the depth at which the top of the Kaibab, Coconino, and Supai formations were encountered in drill holes Bell 2 and Bell 3; the Coconino Sandstone was encountered 435 feet deeper in Bell 3 than in Bell 2. When groundwater was encountered at a depth of approximately 2,500 feet, the hydraulic head was sufficient to raise the water level 900 feet up into the boehole. The well is currently pumping at approximately 75 gpm, and this level is sufficient to meet regulatory needs for the housing development at the site. Recent review of the data by the State regulatory agency resulted in the issuance of a physical availability demonstration for the development in compliance with the Arizona Groundwater Management Act. It is particularly interesting to note that new well Bell 3, chosen on the basis of the geophysical survey, is only 300 feet from Bell 2 which is a significantly lower groundwater producer.
Figure 3: CSAMT 1D smooth-model inversion resistivity cross section from one of the eight lines of data at the Bellemont project site. A deep drillhole at station 350 verified the suspected fault, and now produces 75 gpm, in comparison to the Bell 2 drillhole near station 675, which only produces 23 gpm, even though the two wells are only about 300 feet apart.
Conclusions and Caveats

In recent years, we have found the AMT method to be a cost-effective, logistically-flexible survey technique for groundwater exploration, both as a reconnaissance–level tool as well as a high resolution method for mapping narrow targets. The field crews are small, thus survey costs are low, particularly when compared to the $500,000-per-drillhole costs in the Bellemont project, for example. Line-mile costs are dependent on station spacing, of course, but are often between $3,000 and $5,000 per line mile, and the crews are often able to work in areas not accessible to other survey techniques.

Although this method is often less susceptible to cultural influences than other techniques, interpretation must still take into account near-surface static effects as well as multi-dimensional effects, which cannot be easily modeled. The most challenging aspect of using the technique is to be able to relate the geophysical results of the AMT survey to the hydrogeologic subsurface conditions, since a simple resistivity picture of the subsurface is not necessarily a map or direct indicator of producible water. Considerable experience is required to successfully be able to select high production well sites. Despite this, the AMT method has been extremely useful, and when coordinated with background hydrogeology or other geophysics, it has been very successful in locating groundwater resources.

References