Deep Groundwater Exploration Using Geophysics

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The current and continuing drought in many parts of the world, combined with ever-increasing demands from both traditional and new water users, including municipal, industrial, agricultural and environmental needs, has impacted groundwater resources. Consequently, many groundwater exploration programs are increasingly focusing on deep (1,500 to 2,500 feet below ground surface) production zones. The financial investment in a new 2,500-foot deep groundwater production well can often approach $1 million. Surface geophysical methods can reduce risk and unnecessary costs by assisting in the siting of wells in locations with the most potential to produce acceptable quantities of water.

Surface geophysical methods have been used for decades to successfully and economically explore for groundwater resources. For depths on the order of 200 feet or less, the electrical resistivity profiling and seismic refraction methods are generally useful and economic. For investigations to depths of about 500 feet, the time domain electromagnetic (TDEM) method has been successfully used; however, at greater depths TDEM becomes logistically difficult and less economic. For reconnaissance or regional basin-wide surveys, the gravity and/or magnetic methods have often been applied, but it is risky to select groundwater targets from those methods alone. For exploration depths of 1,500 to 2,500 feet, the seismic reflection and controlled source audio magnetotellurics / magnetotellurics (CSAMT/MT) methods have proven to be successful. However, using high-resolution seismic at those depths is very expensive, and it is often difficult to interpret small faults or fractures zones within bedrock (typical groundwater targets) or to distinguish subtle changes in stratigraphy, such as the amount of clay. Therefore, in recent years, the CSAMT/MT method has become more widely used as it produces economic, structural, and stratigraphic detail to depths approaching 3,000 feet.

CSAMT/MT is a hybrid method that determines subsurface electrical resistivity distribution by measuring time-dependent variations of the earth’s natural electric and magnetic fields (MT), as well as the electric and magnetic fields resulting from high-frequency, non-polarized, artificially transmitted electromagnetic waves (CSAMT). The method measures the resistivity of earth materials in two directions with perpendicular electric dipoles (Ex and Ey) and magnetometers (Hx and Hy) in the field setup shown above. In general, electric and magnetic fields are measured both parallel and perpendicular to geologic strike, thus giving CSAMT/MT a two-dimensional capability that is not achieved by other electrical or electromagnetic methods.

CSAMT/MT field data consist of sounding curves that are logarithmic plots of apparent resistivity versus frequency. Subsurface resistivities can be calculated with forward and inverse computer modeling software by converting the sounding curve data to con-
puter modeled resistivity structure or layering below a given CSAMT/MT sounding. The resulting computer models are used for interpretation of subsurface materials and geologic structures related to groundwater flow, and can be presented as cross sections consisting of several soundings. From these cross sections, data can be presented as individual contour maps from selected depths or combined into a movie showing several depths or other slices. In general, CSAMT/MT data have shown a 10 to 15 percent variation between the actual depths to the anomalies, as verified by test hole drilling, and the depth predicted by the models. The nearby presence of conductors, such as buried metal pipes or drill stem, metal fences or electrical transmission lines, will result in electromagnetic noise that may affect the quality of the data.

The true resistivity of earth material is dependent upon composition, grain size, water content, and other physical characteristics. In general, fine-grained materials have lower resistivities than coarse-grained materials. Unweathered and unfractured hard rocks such as lithified sedimentary rocks, volcanic rocks, plutonic rocks, and some metamorphic rocks generally have high resistivities. The presence of fracturing and weathering lowers the resistivity of these rocks. Additionally, the occurrence of groundwater will greatly reduce the resistivity of all rocks and sedimentary materials through electrolytic conduction. Because of this effect, groundwater is a good target for electrical and electromagnetic geophysical methods that measure resistivity.

The CSAMT/MT method has been used to identify groundwater exploration targets and to site wells in a variety of geologic conditions. A water-filled fracture example is shown in the figure at the top of page 6 from an area with clastics on the surface and weathered-to-unweathered carbonate bedrock at depth. Note that similar results would be obtained from an area with sediments over granitic or metamorphic bedrock. Station spacing for this example is 50 feet, which is considered a detailed survey. Calculated resistivities in ohm-meters are shown in a logarithmic range with colors ranging from red for conductive or low resistivity zones to blue for higher resistivity areas. Clastics in this area generally have lower resistivities and are interpreted with values of less than about 500 ohm-meters (primarily the red to yellow colors on the section). Hard, relatively unweathered and unfractured carbonates are interpreted as much higher resistivities with values from around 1,000 to more than 4,000 ohm-meters (darker blue colors). Resistivity values between about 500 and 1,000 ohm-meters are interpreted as weathered zones, fractures zones, or faults within the hard carbonates. Clastics are interpreted to extend to about 200 to 400 feet depth in the example, weathered bedrock beneath the clastics is interpreted to have thicknesses on the order of 100 to perhaps 200 feet, while carbonate bedrock extends beyond 1600 feet depth. Within the high resistivity bedrock at depths ranging from about 400 to 900 feet, as identified on the figure, are low resistivity water-filled fractures that have been drilled and found to be good groundwater producers.
Water Rights: How Much Do They Cost in the West?

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The average annual prices paid for an acre-foot water right in selected states in the western United States over the period 1990 to 2001 are shown below. The data are taken from research to be published in an upcoming issue of *Southwest Hydrology* that will focus on water as a commodity. The research was performed by Professors David Brookshire, Bonnie Colby, Philip Ganderton and Ph.D. student, and Mary Ewers from the economics departments of The University of New Mexico and The University of Arizona. Even though conditions in water markets vary considerably across the region, and the amount of data contributing to these summary statistics varies from two trades (Wyoming) to 490 trades (Colorado), some general observations can be made. By far the most developed water market of those represented here covers the Colorado Big Thompson (CBT) project area, and with 490 observed transactions, the trend in water rights prices is undeniably upward. Average prices in 1990 for trades in this basin were $1,730, but they had risen to over $11,000 per acre-foot by 2000. Other basins show prices for an acre-foot of water ranging from $500 to $2,500. Prices in New Mexico’s Middle Rio Grande Basin have recently moved from a fairly constant $1,000 to more than $4,000, and many buy offers at that price go unanswered. According to the researchers, the successful development of water markets depends on many economic and institutional factors, which both encourage markets and hinder their expansion. Variations in these factors help to explain the number of trades in each state and the prices at which water rights trade.

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### Mean Water Right Prices ($/acre-foot) by Year for Selected Western States

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Estimating Ages of Hydrocarbon Releases Using Stable Isotopes of Lead

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Estimating the year gasoline was released into the environment has been a difficult task. Most methods, relying upon gasoline additive chronologies or presumed rates of biodegradation, do not provide adequate age resolution and the type of data needed to correlate releases to a specific hydrocarbon source.

In 1982, Ng and Patterson published results of stable lead isotope analyses ($^{206}\text{Pb}/^{207}\text{Pb}$) from leaded gasoline-impacted Southern California marine sediments that indicated $^{206}\text{Pb}/^{207}\text{Pb}$ ratios of lead in gasoline increased from about 1.15 in 1965 to about 1.20 in 1978. This variation was attributed to the increased utilization of Mississippi Valley Type (MVT) lead ores in the production of tetraethyllead; MVT ores are known to have extremely high or radiogenic $^{206}\text{Pb}/^{207}\text{Pb}$ ratios, ranging from about 1.3 to 1.35.

If temporal variations in gasoline lead isotope ratios could be calibrated, an improved method of age-dating gasoline releases might result (Hurst 2000, 2002). Such a method would have advantages over other gasoline age-dating models because: (1) lead does not biodegrade, so it provides a long-term record of a release in soil and groundwater; (2) its isotopes do not fractionate; and (3) lead isotope ratios can be analyzed accurately by thermal ionization mass spectrometry.

**Development of the ALAS Model**

Samples of archived leaded gasoline (with lead concentration ranging from about 30 to 1,000 parts per million) and gasoline-impacted soils were acquired and analyzed; for each sample, the year the gasoline was produced or released into soil was accurately known. More than 100 samples from the United States have been analyzed to produce a well-defined calibration curve termed the ALAS model (Anthropogenic Lead ArchaeoStratigraphy; Figure 1).

As observed by Ng and Patterson (1982), the increases in gasoline $^{206}\text{Pb}/^{207}\text{Pb}$ ratios as a function of time are directly related to the increased use of radiogenic MVT ores in the production of tetraethyllead by gasoline additive manufacturers, such as Ethyl Corporation and DuPont. Increases in gasoline lead isotopic ratios continued through the end of the leaded gasoline era in about 1990, as documented by $^{206}\text{Pb}/^{207}\text{Pb}$ ratios measured in ALAS model calibration samples and as calculated from U.S. Bureau of Mines lead production figures (Figure 1, Hurst, 2002). Since 1992, there have been numerous applications of the ALAS model to site remediation investigations involving leaded gasoline and heavier distillates contaminated by accidental additions of tetraethyllead through common transfer lines during refining. The correlation between ALAS model ages and release ages

See Lead isotopes, page 30
high-arSENIC aquifer zones or to increase yield from untapped low-arSENIC zones; • installation of replacement wells, designed according to system need and hydrogeologic conditions to produce from low-arSENIC aquifer zones; and • identification of alternate water supplies, and modification or addition of infrastructure to use them.

Non-treatment options are generally far less expensive than treatment options, especially when long-term O&M costs are considered. Hydrogeologic investigations can be conducted for a low-to-moderate cost commitment to assess the feasibility of achieving arsenic compliance either without treatment or with a substantially reduced level of treatment. Even in cases where conditions are not conducive to a non-treatment approach, data obtained are valuable for long-term operation of the well field and for proper design of a treatment alternative. In addition, these methods may be used to simultaneously evaluate a wide range of groundwater quality problems, such as nitrate, fluoride, sulfate, total dissolved solids, heavy metals, pesticides, and solvents.

Although the deadline for compliance with the new arsenic standard is 2006, hydrogeologic investigations and feasibility assessments for both non-treatment and treatment alternatives should be conducted early in the planning process so that all options and associated costs are identified prior to selecting a compliance method. State and federal funding is available for these feasibility assessments.

The Arizona ArSENIC Master Plan provides information on treatment and non-treatment methods, as well as funding mechanisms for grants and low-interest rate loans to small water providers, and can be viewed at www.adeq.state.az.us/environ/water/dw/arsenic.html.

For more information, contact Mr. Victor at bmvictor@elmontgomery.com.

Lead isotope ratios and the ALAS model have significantly advanced the capability to estimate the year of a leaded gasoline release into the environment. In the era of unleaded gasoline (gasoline with ppb-range concentrations of lead derived from crude oil), lead isotopes are used to correlate unleaded product releases and/or dissolved phase gasoline constituents, such as MTBE, to their source.

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References