Multi-Method Geophysical Approach for Characterizing a Deep Fractured Bedrock Aquifer, Anniston Army Depot, Anniston, Alabama

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The correct positioning of deep wells to monitor groundwater and entrained contaminants is greatly aided by using remote sensing methods. The geologic setting at the Anniston Army Depot (ANAD) consists of a sequence of fractured dolostones and clastic rocks that have been thrust-faulted, creating a highly complex and heterogeneous aquifer. The drilling of deep bedrock groundwater monitoring wells at this site is expensive due to depth, the nature of the rock, and the required use of casing-advancement drilling techniques; thus, well positioning is critical. A geophysical program consisting of seismic reflection, seismic refraction, electrical imaging (EI), and magnetotellurics (MT) has been used at ANAD to position groundwater monitoring wells at locations selected to intercept fractured bedrock. In addition, borehole geophysical and hydrophysical logging has been completed to assess flow conditions and to calibrate the geophysical survey measurements.

Past operations at ANAD included the disposal of large volumes of spent solvents, resulting in the presence of dense nonaqueous-phase liquids (DNAPL) in the shallow residuum and underlying fractured bedrock. The investigation of the groundwater flow conditions and direction within the deeper portions of the aquifer was necessary to determine the nature and extent of groundwater contamination resulting from the presence of DNAPLs. The initial assessment required a hydrogeologic characterization of the previously mapped Jacksonville thrust fault along the southern depot boundary. Three transects, each approximately 2,000 feet in length, were positioned perpendicular to the trace of the thrust fault to complete seismic reflection, seismic refraction, and EI surveys. The results of the surveys were used to position both shallow and deep groundwater monitoring wells within the bedrock portion of the aquifer.

The seismic reflection survey at ANAD was designed to provide information on the interval beneath the top of bedrock to a depth of approximately 2,000 feet below ground surface (bgs). Although this depth extends well beyond the depth required for installation of groundwater monitoring wells, the information collected aided in the interpretation of the location of faults, subsurface stratigraphy, and deeper structural features. A seismic refraction survey was completed along each transect to model the top of bedrock and residuum thickness. The information provided by this type of survey aided in mapping the top of bedrock surface, allowed correlation of fault traces (from the seismic reflection survey) to top of bedrock depth, and aided in positioning of wells designed to monitor the residuum/top of bedrock interface. The refraction survey results also provided information on the thickness of the upper weathered bedrock versus the deeper fractured bedrock. The EI survey was useful for mapping the geoelectric properties of the bedrock along each transect. This imaging method is useful for locating intervals of lower resistivity rock, typically indicative of fractures or cavities.

A fourth method of remote sensing (MT) was completed along one transect in an attempt to identify a location for a deep groundwater monitoring well. The results of the seismic reflection, refraction, and EI resulted in drilling rock with permeability too low for construction of monitoring wells. An MT survey was completed, and the results were used to identify a well location that intersected a high-permeability fractured bedrock interval, thus allowing completion of a deep monitoring well. MT surveying is now used to locate deep bedrock wells at ANAD, as correlation of survey results to drilling results is quite high, costs for this type of survey are relatively low, and the completion of a survey can be performed in a short field effort.

Borehole logging of each hole, using a suite of downhole geophysical tools, was followed by HydroPhysical™ testing to determine the correct placement of well screen intervals at depths correlative to fracture flow zones. Borehole logs also allowed transect-to-transect correlation of subsurface formations to allow extension of the subsurface geology beyond an individual borehole and transect. This multi-method approach of remote sensing was successful in providing characterization data for the Jacksonville fault zone and the nature of the fractured rock aquifer. The collection of similar data using only drilled wells would have been prohibitively costly and inefficient.

Introduction

The positioning of deep wells to monitor groundwater and entrained contaminants in complex geologic settings may be greatly aided by using remote sensing methods. A surface geophysical program, aided by drilling and borehole testing, allowed the installation of deep groundwater monitoring wells at locations and at depths sufficient to monitor a highly fractured aquifer downgradient of DNAPL source areas at ANAD. Fractured rock aquifers will typically require an integrated study to characterize the hydrogeologic properties and degree of heterogeneity (Cohen 1995, EPA 2001). The drilling of deep bedrock groundwater monitoring wells at this site is expensive due to depth, the nature of the rock, and the required use of casing-advancement drilling techniques; thus, proper well positioning is critical. A geophysical program consisting of seismic reflection, seismic refraction, electrical imaging (EI), and magnetotellurics (MT) has been used at ANAD. In addition, borehole geophysical and hydrophysical logging has been completed to identify open fractures, select the depth for well screen intervals, and to calibrate the surface geophysical survey measurements. The survey program was completed along three separate transects positioned perpendicular to the trend of the Jacksonville thrust fault. The fault was considered a potential flow zone controlling migration of contaminated groundwater from the ANAD Southeast Industrial Area (SIA).

Geologic and Hydrologic Settings

ANAD occupies 15,200 acres and is located in Calhoun County in northeast Alabama and is situated approximately 10 miles west of the city of Anniston (Figure 1). The depot was constructed during 1941 to serve as a munitions storage facility. General activities at the depot have included overhauling, testing, and storage of combat vehicles, primarily within the SIA, and storage of munitions within the adjacent Ammunition Storage Area. The storage, maintenance, and industrial functions of ANAD have historically resulted in the generation of hazardous wastes. From about the 1940s through the late 1970s, wastes generated at ANAD were disposed of on-site in trenches, lagoons, landfills, or other holding structures. Investigations addressing the quality of groundwater at ANAD have revealed that contaminants have migrated to the groundwater (SAIC 1997). As a result of groundwater contamination, the SIA was placed on the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 National Priorities List in 1989.

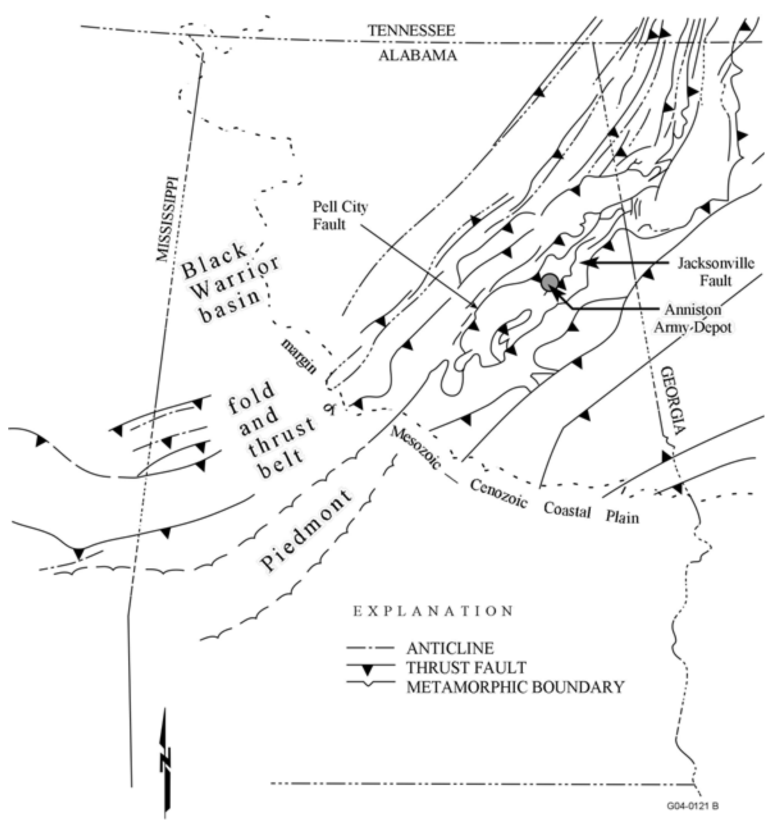


Figure 1 Geologic setting and stratigraphy of the ANAD area

ANAD lies within the fold-and-thrust belt of the Appalachian Valley and Ridge Province (Figure 1). The fold-and-thrust belt is characterized by Paleozoic rock formations that were repeatedly folded and thrust-faulted by northwestward-directed tectonic stresses during the Appalachian orogenesis (AGS 1988, Thomas and Neathery 1982). As a result of this deformation, major geomorphic and geologic structures, including fold axes, fault traces, and lithologic boundaries, are commonly oriented in a northeast–southwest direction. Northwestward transport of the Paleozoic rock sequence along thrust faults has resulted in the overlapped stacking of large slabs of rock referred to as thrust sheets. Within an individual thrust sheet, smaller faults can splay off the larger basal thrust fault, resulting in multiple stacking and repetition of rock units (Osborne and Szabo 1984). Geologic contacts in the region are generally oriented parallel to mapped faults, and repetition of rock units is common in vertical sequences.

The major thrust fault in the Anniston area is the Pell City fault, a regional-scale feature along which Cambrian and Ordovician rocks have been thrust over younger Mississippian-Pennsylvanian rocks. The Pell City fault also defines the western boundary of the Appalachian Valley and Ridge Province in Alabama. The smaller Jacksonville thrust fault, which was the focus of this geophysical investigation, is a northeast-to-southwest-trending, low-angle thrust fault interpreted as a major splay of the Pell City fault (Osborne and Szabo 1984). Rock formations encountered in the vicinity of ANAD include, from youngest to oldest, the Knox Group, the Conasauga Formation, the Rome Formation, the Shady Dolomite Formation, and the Chilhowee Group (a stratigraphic column is provided in Figure 6). In many areas of ANAD, it is typical that the original depositional sequence of the strata is disrupted by the movement of rocks of older age atop rocks of younger age (e.g., older Chilhowee Group rock atop younger Knox Group rock).

ANAD is located at the leading edge of the Jacksonville thrust fault and its associated minor faults (Figure 1). The method of thrust-faulting related to generation of the Jacksonville thrust fault zone is typical within the Appalachian Valley and Ridge foreland and is referred to as bedding plane thrust [i.e., thrust faults along surfaces that parallel rock bedding (Odom and Hatcher 1980)]. Faults within aquifers, such as the Jacksonville fault, can add complexity to flow paths, acting both as groundwater conduits and as barriers to flow. Faults and fractures may actually create secondary porosity and permeability that did not exist in the rock previously, and mapping of these features may allow delineation of preferential pathways for water flow. The role of the Jacksonville fault as a factor in controlling groundwater flow and contaminant migration within the Anniston area of Calhoun County has been previously studied (Scott et al. 1987). Warman and Causey (1961) noted that many of the springs in Calhoun County are located along the trace of thrust faults with discharges larger than would be expected if recharged from the local area. The implication is that thrust faults are conduits along which groundwater from deep or distant sources reaches the surface.

Investigations were conducted to determine the hydrogeologic conditions at the southern perimeter of ANAD, especially the role of the Jacksonville thrust fault in controlling groundwater movement. Prior to this investigation, the proximity of the Jacksonville thrust fault to documented groundwater contaminant plumes within the SIA and the geologic characteristics of the fault zone were critical concerns related to nature and extent assessment of groundwater contamination. The ultimate goal of the hydrogeologic characterization of the fault zone was to begin to determine the potential for the Jacksonville thrust fault to affect offpost migration of contaminants sourced from the SIA; to identify exit pathways for potential future contaminant migration; and, ultimately, to optimize long-term remedial actions and associated remedial effectiveness monitoring.

Geophysical Surveys and Interpretation

The investigation of the Jacksonville fault and deep groundwater flow benefited from the integration of seismic, EI, and MT survey methods to allow the optimal positioning of groundwater monitoring wells. The results of these sensing methods were supplemented by borehole hydrophysical testing and downhole geophysical logging. The integration of these data yielded a comprehensive evaluation of the fractured aquifer in the ANAD area, especially the SIA.

The geophysical profiling and well drilling of the fault zone for the investigation were primarily conducted along three transects, each approximately 2000 feet in length. To the extent possible, considering access restrictions and terrain, each transect was positioned perpendicular to the mapped surface trace of the Jacksonville thrust fault, as mapped by the Geological Survey of Alabama (GSA 1984). As indicated in Figure 2, the transects are designated as X-2 (at the south end of the SIA), X-3 (near the entrance to the

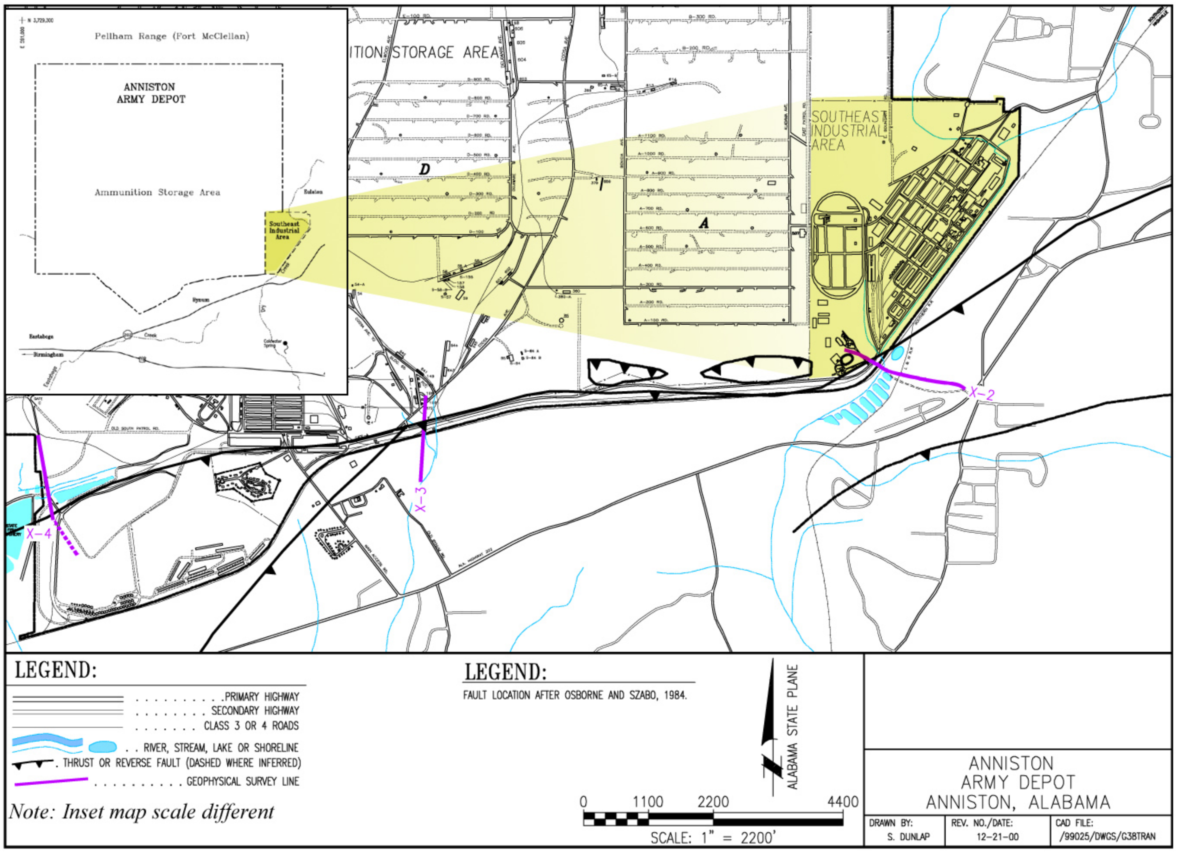


Figure 2 Location of the X-2, X-3, and X-4 geophysical survey transects

Ammunition Storage Area), and X-4 (at the southwest corner of ANAD). Originally, a transect X-1 was planned near the northeastern end of the SIA, but it was relocated as an extension onto the southeastern portion of transect X-2.

The investigation was designed to perform the remote sensing surveys along the three transects, process and evaluate the data, and then use the information to select locations for the drilling of deep bedrock borings to be completed as groundwater monitoring wells. Following the drilling program, vertical velocity profiles were completed in several transect boreholes to allow calibration (via reprocessing) of the seismic reflection data to site conditions. Even though the reprocessed seismic data were not available for borehole location selection, the improved data were used in the final integration of the project data. For the purposes of this paper, the primary focus will be the results of the X-3 and X-4 transects, which are representative of all three transects.

EI Survey

The EI method involves the measurement of the geoelectric response of the earth layers to an input of electricity that can provide information on distinct subsurface electrical boundaries and conditions that can indicate depth to bedrock, water table location, vertical bedrock fractures, and weathered zones below top of bedrock. EI surveying involves the measuring of apparent resistivity and relative resistivity changes to characterize the subsurface materials in the near surface along a series of profiles. Electrodes spaced along a conducting cable are placed in the ground at fixed intervals. The instrumentation includes an automatic multi-electrode switching system, which passes current through the ground (via the electrodes) at various paths and depths. The electrode system then measures the potential differences along these various paths and records the data. The length of a profile, the desired depth of the investigation, and the resolution determine the electrode spacing. The resistivity data are modeled using two-dimensional (2-D) forward and inverse modeling software with resistivity ranges displayed using color variation.

The resistivity of soils and rocks is predominately controlled by the porosity and permeability of the system, the amount of pore water, and the concentration of the dissolved solids (Benson et al. 1982). The dominant lithology of the ANAD area is silicified carbonate bedrock, which when competent, typically will have a high resistivity. Saturated, fractured, less competent and weathered rock typically has a lower resistivity than competent rock. EI surveys were conducted along each of the three primary transects, as well as along five secondary lines for which seismic profiles had previously been conducted (Figure 2).

The lower panel of Figure 3 presents the EI survey results in a cross-sectional profile for the X-3 transect spanning a distance of approximately 1850 feet. Higher resistivity values are indicated with the yellow-to-red colors, with green-to-blue indicating lower resistivity areas. Several EI station locations are indicated at the top of the figure, and an elevation column is presented for the vertical scale. It is evident a highly resistive feature (red) occupies the central portion of the line and is abruptly terminated to the south of the EI station 69. The location and shape of this subsurface feature were also detected with the seismic survey. The rise in surface topography at the southern end of the line correlated with the presence of this subsurface feature, indicating a ramp anticline is present. The northern third of the survey line is impacted by the presence of railroad lines, creating anomalous low resistivity (blue) features.

It was found during this investigation that the EI results were useful in identifying potential areas for boring installations along each transect but, due to the cultural interferences (e.g., railroad tracks, pipelines), it required the integration of the results from the seismic survey to make a final drilling location decision. It was necessary on all three transects to either shift the line position to minimize the cultural influences, such as power lines, railroad tracks, buried utilities, etc., or recognize that the data within certain intervals of the line would be impacted by these features. The EI resistivity information was used cautiously to prevent placing a well at a site at which the response was not due to subsurface (i.e., natural) geoelectric contrasts.

Seismic Reflection and Refraction Surveys

Seismic surveying involves measuring the elapsed time for an acoustic energy signal (e.g., a "shot) generated at the land surface to return to the surface after reflecting or refraction off of geologic layers and features at depth. The returned signal is measured in units of elapsed travel-time, typically microseconds to seconds. A seismic reflection profile models changes in acoustic impedance (velocity and density variations) and is used to construct a profile of the reflected images in the subsurface (Thompson et al. 2000). Seismic energy is also refracted and diffracted at boundaries in the subsurface where a significant velocity contrast exists, such as the interface of the lower-velocity unconsolidated residuum and the more competent (higher-velocity) bedrock. A seismic refraction model is created using the travel-time of the first returning seismic signal. Figure 4 is a cross-sectional diagram showing the ray paths of various types of seismic waves in the earth resulting from input of the vibration energy pulse (e.g., shot point). The direct, refracted, and reflected waves are annotated on this figure. Direct waves travel just below the ground surface whereas the paths of the reflected and refracted waves are dependent upon the velocity contrasts of the geologic layers. A linear array of geophones was laid along each transect and used to measure return energy generated at the surface. An elastic wave generator or hammer and steel plate were the primary energy sources for the ANAD surveys.

Refraction and reflection seismic surveys were used to profile the intervals above and below the top of the unconsolidated/bedrock horizon, respectively, with emphasis on resolution of the Jacksonville thrust fault zone. The contribution from the refraction and reflection profiling was an initial estimation of the depth to bedrock and an imaging of the subsurface structures within the bedrock. These seismic data were used to evaluate the likely position of the Jacksonville thrust fault zone, other ancillary faults, and potential fractured rock areas. For all three transects, the placement of borings was dependent upon the interpretation of the seismic data and EI data.

The seismic survey along the X-3 transect was completed over a distance of 1870 feet. The results of this survey mimicked the response of the EI survey, indicating a significant change in rock character from north to south. The seismic reflection profile section along the X-3 transect, the upper panel of Figure 3, is presented with shot point stations along the top and a vertical axis in elapsed signal travel time (milliseconds). Strong reflector

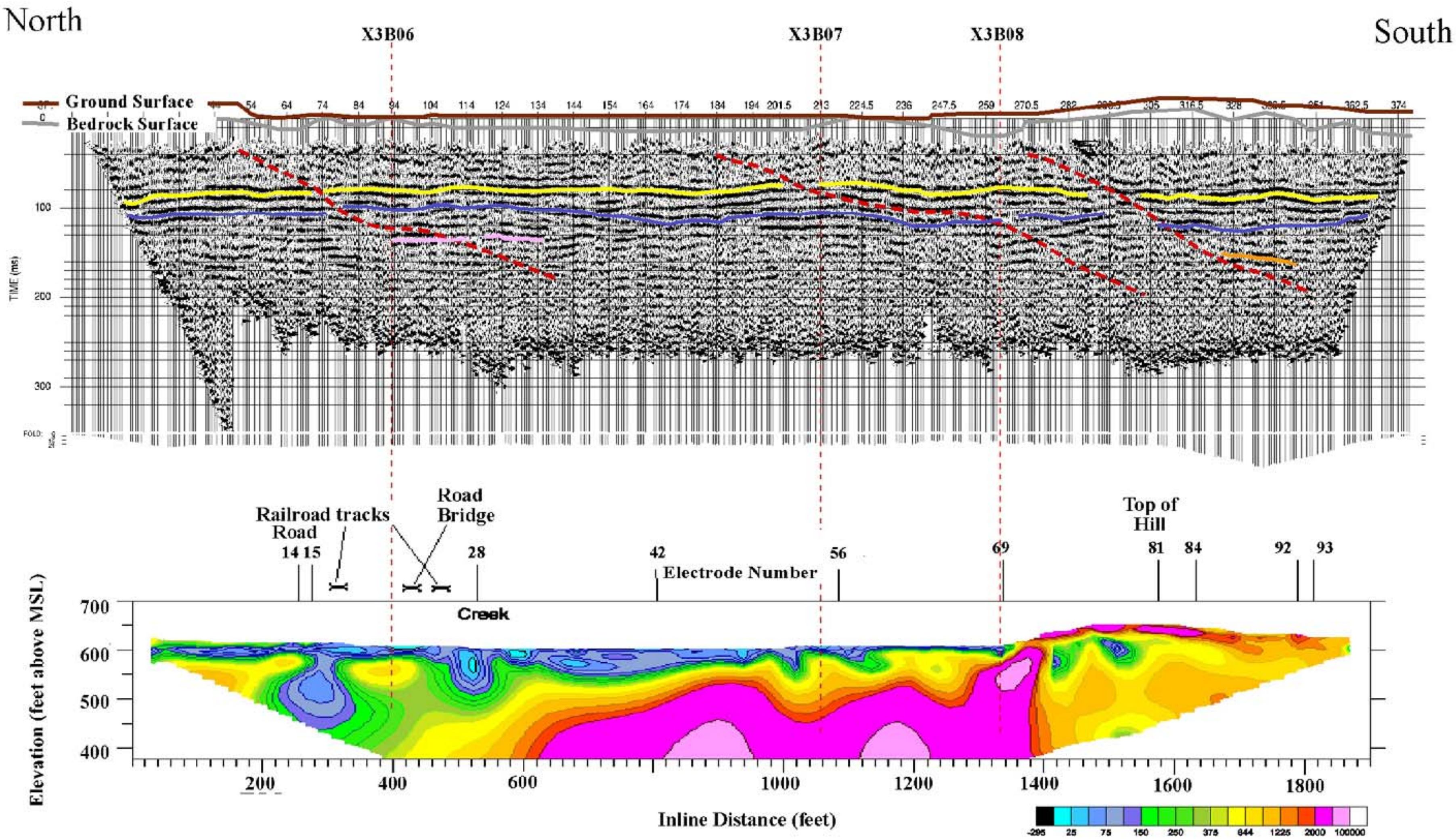


Figure 3 Transect X-3 electrical imaging (lower panel) and seismic reflection profile (upper panel)

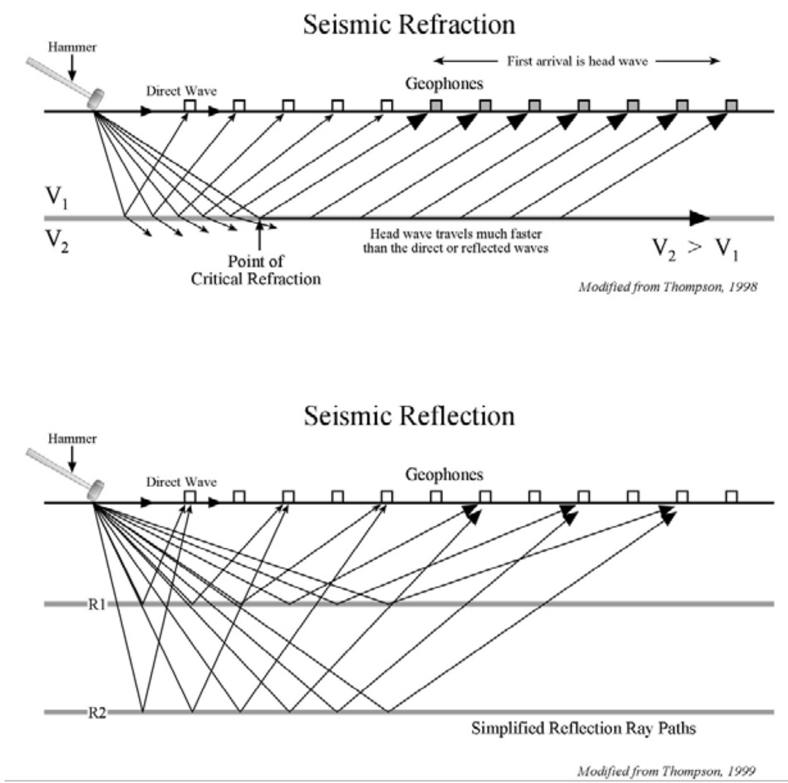


Figure 4 Seismic ray paths following activation of surface energy source

packages have been annotated with color lines to emphasize continuity and terminations. The seismic reflection response indicates relatively flat reflectors with several reflector interruptions that likely indicate faults arising in the direction of thrust movement (i.e., to the north–northwest). The fault indicated by the red-dashed line and break of the yellow reflector between shot point stations 282 and 305 is interpreted as the leading fault in front of a ramp anticline at the south end of the transect. Faulting has placed the older Rome Formation atop the younger Conasauga Formation, as indicated in the seismic section and by the sharp contrast in EI response. This interpretation was supported by expression of the fault at the ground surface, where slickenside was evident in the rock at the X3B08 drill site. Boring X3B08 was placed at this location (at approximately shot point 270.5) to investigate potential flow zones along the fault and the transition from the Conasauga Formation to the Rome Formation.

The refraction profile generated from these data was created using a simple three-layer model to account for surface cover, the residuum interval (unconsolidated), and bedrock (Figure 5). The profile is overlain along a topographic relief profile and depicts a residuum interval (stipple pattern) of variable thickness, even along the higher relief feature at the southern end of the line. As confirmed by the drilling of three boreholes along this transect (X3B06, X3B07, and X3B08 in Figure 5), the prediction of the top of bedrock by this method was relatively accurate with the actual drill depths for rock being slightly deeper than predicted depths. Note the variability of the rock interval velocities, as measured during post-drilling vertical velocity surveys. Refraction profiling was evaluated as the most reliable of the surface geophysical methods and, due to its capability of resolving the unconsolidated/weathered bedrock depth, useful in the mapping of the depth of this contact.

The evaluation of the EI and seismic data results from the transect surveys was used to select three locations for the drilling of boreholes for evaluation of aquifer properties and installation of groundwater monitoring wells. Borings X3B06, X3B07, and X3B08 were drilled to depths of 410, 301, and 276 feet bgs, respectively. The

X-3 Transect

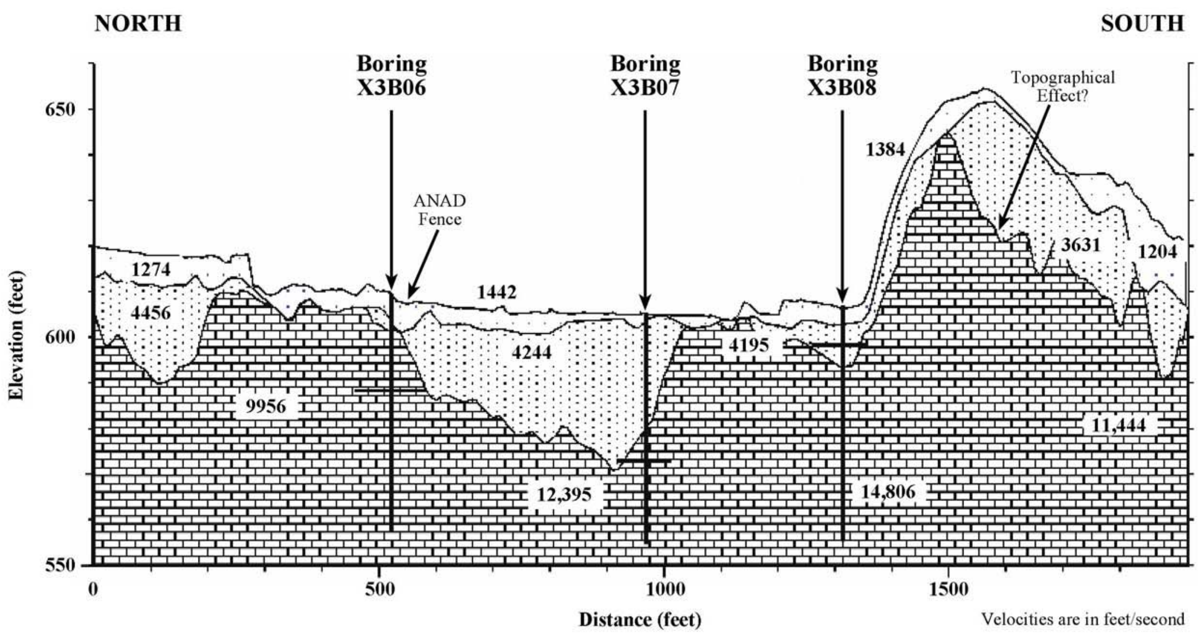


Figure 5 Transect X-3 seismic refraction profile

information provided by drilling the borings, such as lithology and formation contact depths, and the borehole logging, as discussed below, allowed construction of a transect conceptual model. Figure 6 is an interpretation of the subsurface structure in a cross-section profile with projected fault locations and formation contacts. Similar profiles for the X-2 and X-4 transects were incorporated into a site conceptual model for ANAD.

MT Surveys

Despite the information obtained through the completion of an EI and seismic survey, the use of an additional geophysical survey method was necessary in order to locate a fractured rock interval following the drilling of two unsuccessful borings along the X-4 transect. The first two borings for the X-4 transect drilled into indicated anomalies yet penetrated dense rock that yielded no groundwater. At this point, an MT survey was designed and completed along the X-4 transect with the results allowing the drilling of water-productive boring that was completed as a dual-interval groundwater monitoring well. The successful (and fortuitous) use of MT along the X-4 transect has subsequently led to using this survey method for locating all subsequent deep bedrock wells at ANAD. This type of data allows optimal locations to be selected that have a high potential for intersecting fractured rock and possible flow zones.

MT is an electromagnetic geophysical method commonly used in the groundwater and mining industries. MT determines the earth's subsurface electrical resistivity distribution by measuring time-dependent variations in the earth's natural electric (E) and magnetic (H) fields, as well as the electric and magnetic fields resulting from high-frequency-induced electromagnetic fields (Hasbrouck 2003). MT is particularly adapted to deep groundwater investigations as the signal-to-noise ratio actually increases with depth, which allows better resolution of a potential target with depth.

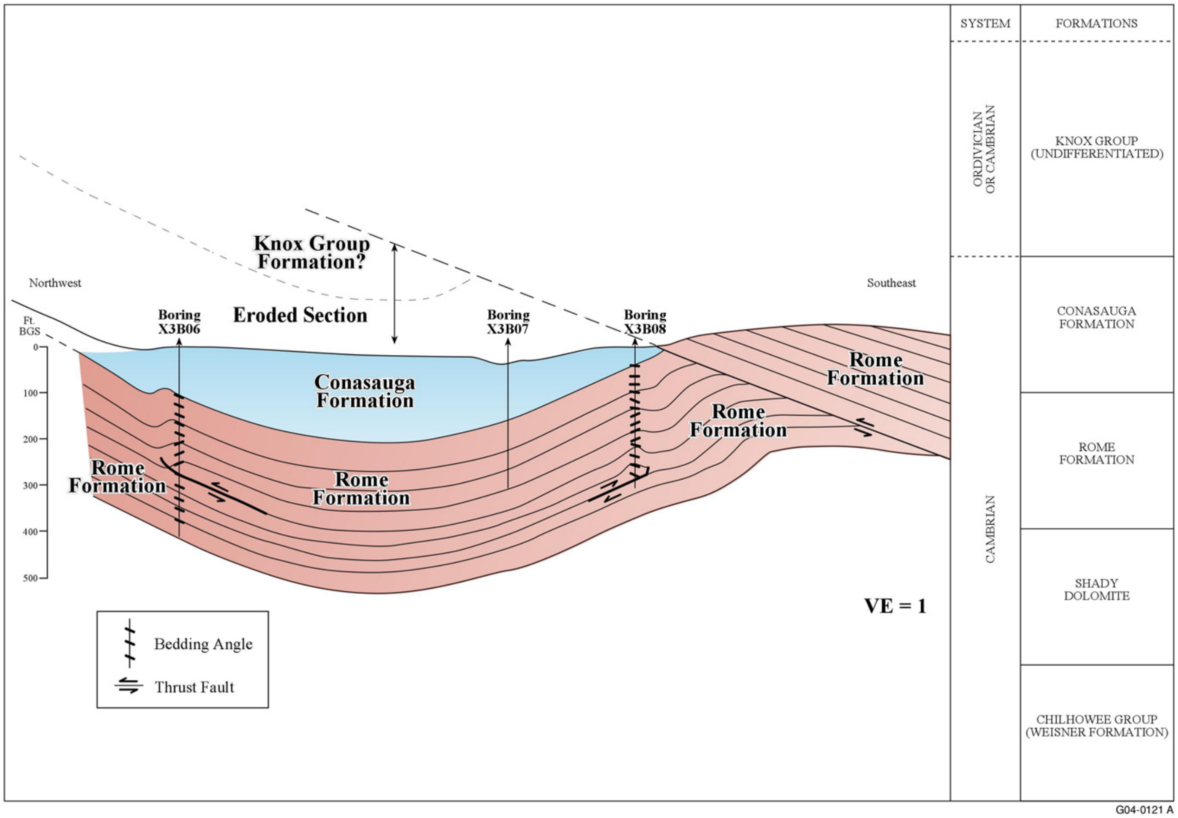


Figure 6 Conceptual model of X-3 transect subsurface structure and ANAD stratigraphic column

The MT survey equipment consists of a transmitter and electrodes that are placed at multiple stations along the survey line. The transmitter consists of a dual-loop antenna, transmitter electronics, and controller. The magnetic fields are detected with two perpendicular magnetic-field sensors. The electric fields are detected by measuring the differential voltage between the two electrodes of the electric dipoles. The response of the field sensors is amplified and filtered, and converted from analog to digital for signal processing. MT measures the resistivity of earth materials in perpendicular directions. This is achieved by measuring the E and H fields in perpendicular directions, thus giving MT a 2-D capability that is not achieved by other electromagnetic methodologies. These modes exhibit significantly different resistivity values over planar geologic features and are, therefore, useful to resolve such features. In general, MT measurements over homogeneous and isotropic materials, such as thick sections of sedimentary material, are similar in perpendicular directions. However, measurements over planar geologic features, such as faults or fracture zones, exhibit different resistivities in perpendicular directions. This allows for the resolution of such features that store and transmit significant amounts of groundwater (SAIC 2000). Once the sounding data are processed and modeled, they are used to construct cross-sections of subsurface resistivity. A modeled cross-section was used for selection of a potential fractured area on the X-4 transect for placement of a third boring.

The cross-section profile of the X-4 transect MT survey shows low-resistivity areas with red-to-yellow colors and higher resistivity areas in shades of blue and grey (Figure 7). In terms of detecting groundwater pathways with this survey method, the low-resistivity areas are of prime interest. The MT results indicate two potential locations to place a boring to intercept low-resistivity features: the feature between line distance –300 and –400 feet and between –900 and 1,000 feet. The red-to-yellow feature within the –300- to –400-foot section extends from surface to depth and implies migration of deep groundwater upwards to near the surface in this area. This interpretation is supported by the presence of two deep-sourced springs in the vicinity that emerge into ponds. Therefore, boring X4B09 was placed at the –350-foot station. Drilling of this boring resulted in encountering several fractured and weathered intervals. As indicated in Figure 7, borings X4B10 and X4B11, which were drilled prior to the MT

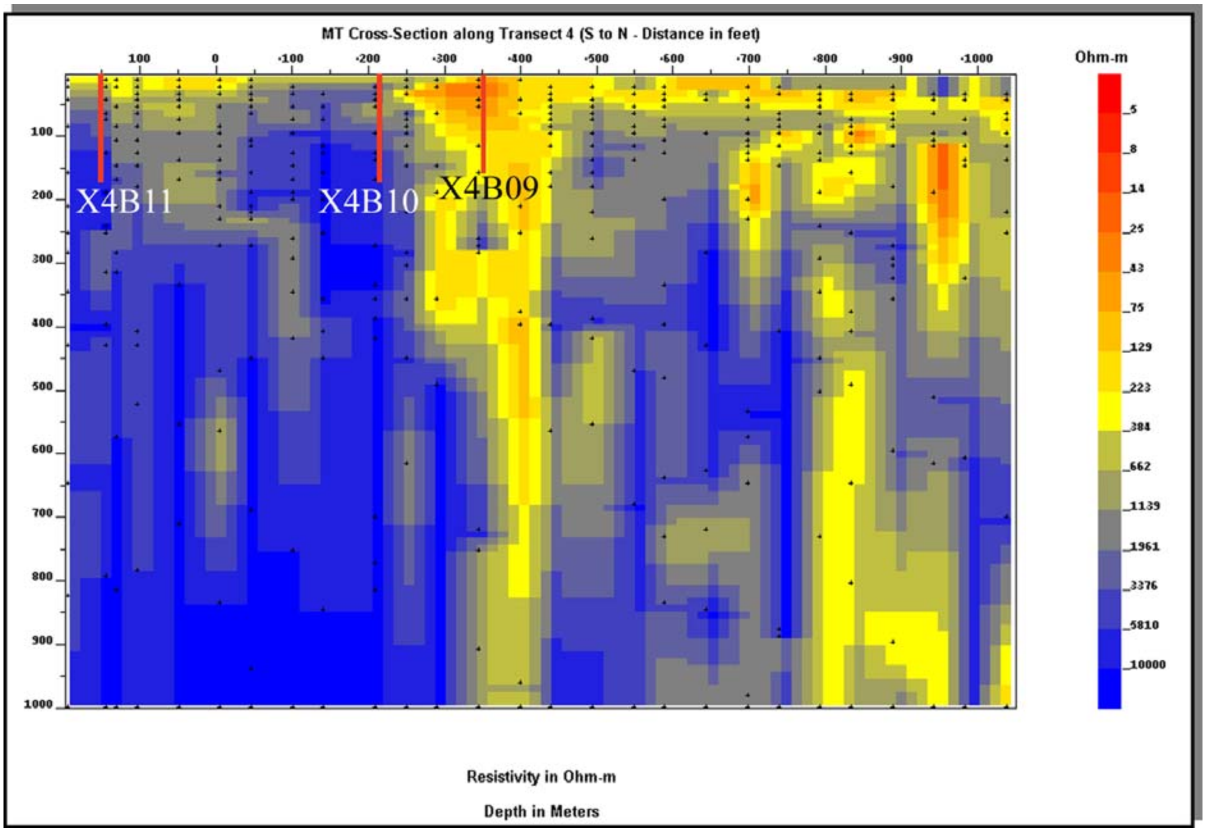


Figure 7 MT survey profile along the X-4 transect

survey, were placed in an interval corresponding to high resistivity. The dense rock encountered in these borings correlated to high resistivities resulting from the pores spaces lacking water to conduct electrical current.

The success of the MT method in locating fractured rock at ANAD has been confirmed with the drilling of recent wells for ongoing groundwater investigations. Subsequent to the drilling program described here, four additional deep wells (>500 feet) have been located following completion of an MT survey. In addition, several other considerations make this remote sensing method appealing. The method is less expensive (per linear foot) to complete in the field relative to EI and seismic surveying, the data processing time following acquisition is short, and the method does not require extensive terrain preparation. Similar to the EI method, nearby sources of metal or electricity must be considered when locating survey stations.

Borehole Evaluation Methods

The evaluation of each borehole was completed by downhole logging using gamma, density, caliper, acoustic velocity, and resistivity tools and by the completion of HydroPhysical™ testing. Gamma and density measurements are critical to assessing lithology changes and formation bulk densities. A caliper tool is useful as an indicator of fractured bedrock intervals and an assessment of borehole conditions prior to logging with other tools. Acoustic velocity can be used for calculations of porosity and for calibration of seismic velocity data. Resistivity measurements were useful in well-to-well correlations and determination of lithology transitions.

Borehole logging was performed following cessation of drilling beginning with the lowering of the caliper tool into the hole. As the rock formations in the ANAD are highly fractured, borehole collapse and bridging was a constant concern. Therefore, an assessment of the borehole condition was critical prior to lowering the less expendable tools downhole, especially the density tool containing a radioactive source. Using a suite of tools also allowed logging both the cased and open (uncased) sections of the borehole, as only the gamma and density tools are capable of recording measurements through the metal casing. The casing-advancement drilling method used by SAIC allowed retrieval of the casing from the borehole during well construction; therefore, measurements of the cased section of the borehole were necessary.

HydroPhysical™ testing is an in situ flow characterization method that allows identification of fracture flow zones and the calculation the zone-specific flow rates and hydraulic conductivity (COLOG 2001). The method involves the replacement of borehole water with deionzed water and the measurement of the subsequent changes in borehole fluid conductivity and temperature over time. Following the placement of the deionzed water, the inflow of native groundwater via bedrock fractures into the borehole creates a contrast in the borehole fluid conductivity (and temperature) as ion replacement occurs. This change in water chemistry is measured using a combination conductivity/temperature sonde that is passed continuously up and down the borehole for an extended period of time. Testing of the borehole can be performed under both ambient and pumping conditions, but is limited to the open hole section of the boring.

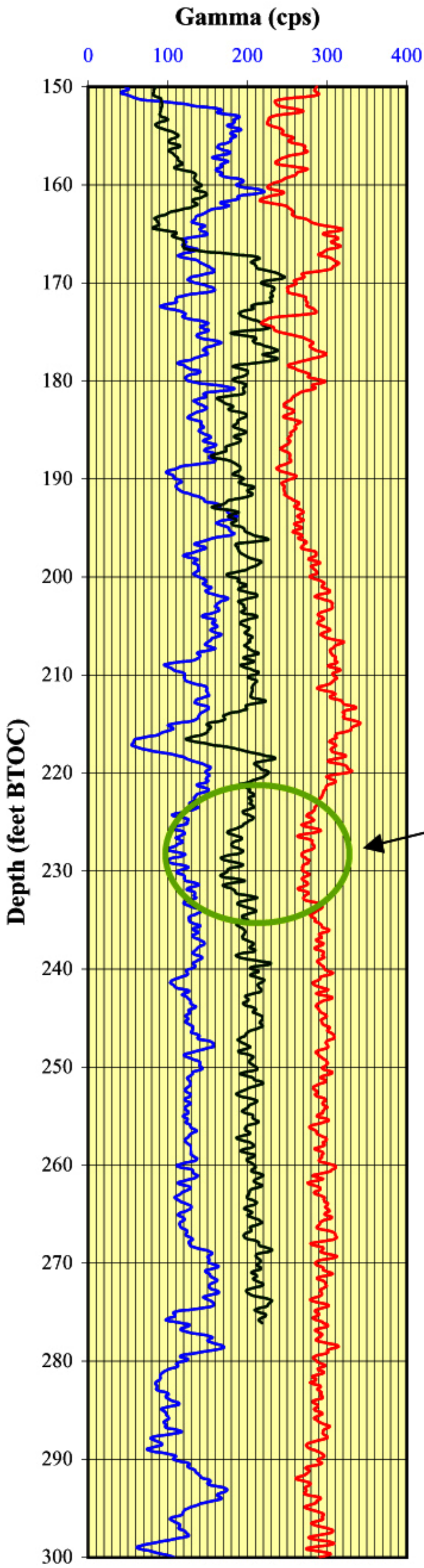
An enhanced video survey was also completed in the borings X3B06 and X3B08, as the waters in these holes were sufficiently clear to record an image of the borehole wall. The tool for this survey consists of a downhole camera, a light source, and a swivel connection for rotation of the camera to allow axial views (vertical section of the wall face) or radial views (a 360º horizontal view). Digitization and processing of the raw optical image are used to produce visual displays that allow measurement of apparent strike and dip of bedding, fracture aperture, and a continuous 2-D projected image.

Borehole Data Interpretation

The interpretation of the borehole data consisted of an initial field evaluation for the selection of screen interval depths for the construction of monitoring wells. Field evaluations were necessary to utilize drill rigs for well construction and prevent additional costly mobilizations. The data provided by the drilling and logging of each borehole was more fully utilized when integrated with adjacent transect boreholes, the transect EI, MT, seismic reflection/refraction results, and other transect data. The use of the drilling and logging data for borehole-to-borehole correlation and for selection of flow zones is presented as an example of the usefulness of these data.

The correlation of the X-3 boring drilling logs with the geophysical logs allowed integration of the data collected at each boring in terms of transect stratigraphy, hydrologic connections (e.g., flow zone to flow zone), and structural setting. The best method for correlation was found to be comparison of gamma curves, drilling responses, and significant lithology changes. Gamma curves are correlatable at several intervals on the X-3 boring logs, indicating penetration of the same rock in each boring, therefore allowing depth alignment for stratigraphic correlation. For example, a similar shift in the curve from 222 to 232 feet in X3B06 is correlatable to 242 to 252 feet of boring X3B07 and the 182 to 195 interval of X3B08 (Figure 8). The ability to correspond to subsurface depths in each borehole was critical to validation of the structural interpretation along each of the three transects. The video survey confirmed high-angle beds and significant lithology changes, which supported the gamma curve correlations. Bedding dip angles derived from this survey aided in interpreting the structural setting.

HydroPhysical™ testing of the boreholes along the X-3 transect provided information on the depth of fracture flow zones, critical information for the placement of monitoring well screen intervals. The method identified eight flow zones in the X3B06 borehole and five zones in both the X3B07 and X3B08 boreholes. Figure 9 is a plot of the change in fluid conductivity over time during the test of the X3B06 borehole depicting the increase in fluid conductivity as groundwater replaces the deionized water. Each curve represents a pass of the conductivity/temperature sonde up the hole. A flow zone in this borehole is indicated by the curve deflections between the depths of 210 to 217 feet. An ambient flow rate of 0.146 gallons per minute (gpm) was calculated for this interval. The zone from 210 to 217 feet provided inflow to the borehole (along with two other deeper intervals) whereas fluid exited the borehole within the 150- to 153-foot interval. Following ambient condition testing, each borehole was pumped to identify other fracture flow zones. Pumping rates of approximately 8 gpm were used for the X-3 transect boreholes whereas rates of approximately 30 gpm were required for the X-2 transect boreholes. The information provided by this testing method was critical in the overall hydrogeologic characterization of the Jacksonville thrust fault zone and the creation of a site conceptual model for contaminant migration.



Alignment of gamma ray curves from X-3 transect boring to show correlation using marker horizons. Curves for X3B07 and X3B08 have been depth shifted to match X3B06. Gamma values for X3B07 and X3B08 have been adjusted for graphic to create separation between the curves.

Figure 8 Correlation of gamma response for X-3 transect borings

Summary and Discussion

The hydrogeologic characterization of the Jacksonville thrust fault at ANAD was possible using an integration of surface and borehole geophysics, and hydrophysical testing along three separate transects. EI, seismic reflection, and seismic refraction surveying were completed along each transect to aid in the positioning of deep bedrock wells to be used to monitor groundwater. An MT survey proved necessary following the drilling of two dry boreholes along the X-4 transect in order to identify a fractured rock interval. Several key lessons were learned during the investigation that may be valuable for other similar investigations in complex aquifer settings.

The high cost of drilling deep boreholes in the fractured rock of the ANAD area requires that the optimal location be selected for groundwater monitoring wells. The combination of using a casing advancement drill method, air rotary drilling, and the containment of potentially contaminated drill cuttings/produced water greatly increases the cost per foot relative to conventional drilling techniques. As such, it was planned that well locations would be positioned using surface geophysical survey results and that well screen intervals be selected using borehole logging information. This approach involved a field effort solely for completion of the geophysical surveys, well in advance of the drilling program, to allow for geophysical data processing and interpreting the data. Selection of well locations was performed by the ANAD Partnering Team (the guiding team for this investigation) following a technical review of the survey results and a recommendation by SAIC. The information gained during borehole logging and testing was presented to the Partnering Team in a teleconference, allowing for nearly real-time decision-making in the field. This process minimized drill rig and field crew standby costs.

The data accumulated during the drilling and logging of each borehole allowed borehole-specific interpretations, borehole-to-borehole correlations along separate transects and between transects, and conceptualization of localized geology and setting. The borehole-specific data accumulated during the drilling and logging were used for identification of flow zones, degree of fracturing, geologic contacts, and other parameters useful in selection of monitoring well screen depths. The flow characteristics of the different rock formations drilled at each transect, such as the Rome and Conasauga Formations along the X-3 transect, were used in assessing these rock types in other areas of the depot that were not included in this investigation.

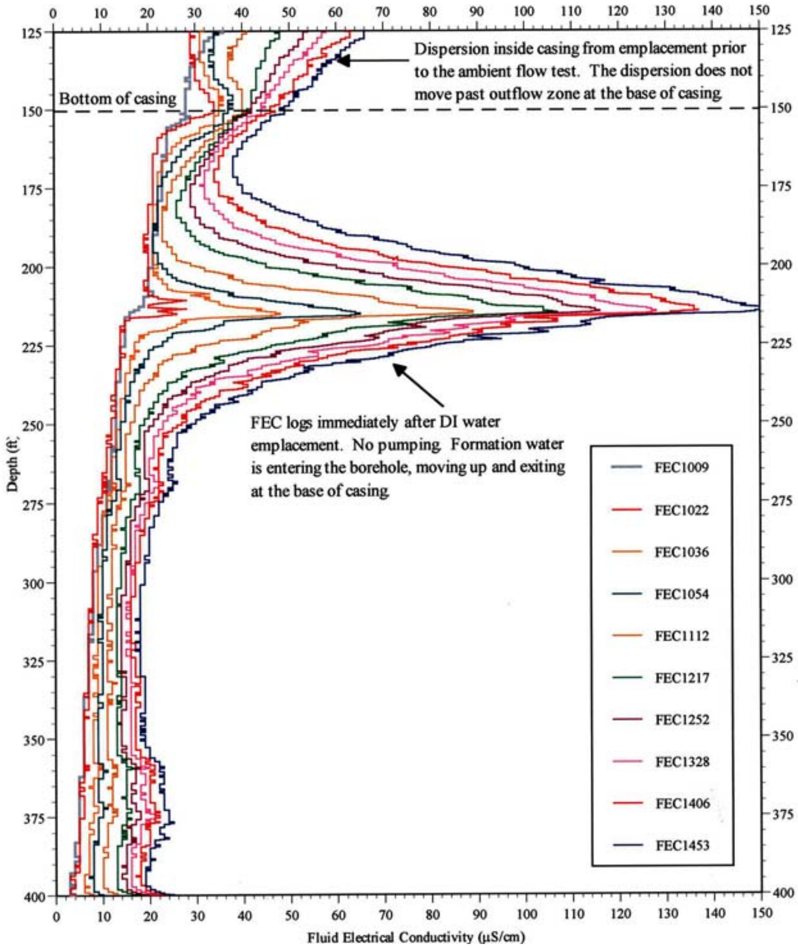


Figure 9 Representative hydrophysical test data for X3B06 borehole

By combining borehole information with transect survey results, a refinement of the initial interpretation of the geologic setting for each of the three transects was possible. For example, the ramp anticline feature on the X-3 transect (Figure 6) was recognized in other areas of the depot as a common indicator of small splay faults along the Jacksonville thrust fault trend. The information gained along each transect has been used to build a complete site conceptual model, incorporating information gained on the site stratigraphy, structural setting, and rock formation flow characteristics. This model has also been used to identify areas for monitoring groundwater and contaminant flow from the SIA.

As mentioned, the seismic data can be calibrated and reprocessed using the downhole acoustic velocity data, the vertical velocity profile data, and drilling data, such as drill depth to top of competent rock. It was found that the modeled seismic refraction sections matched subsurface depths for top of rock when checked against actual top of rock depths from each of the borings. Thus, at ANAD, refraction surveys were a useful tool for predicting subsurface geology and positioning wells in bedrock lows or highs, as needed. The post-drilling reprocessing of the seismic reflection data using the velocity data indicated a greater degree of variability in seismic signal travel-time than originally used in the initial processing. The velocity profile data indicated travel-time velocities are much faster in the ANAD area than the values used to model the pre-drilling seismic refraction and reflection data. The use of faster formation velocities during the reprocessing caused a downward shift in the reflectors (i.e., to deeper depths). This information led to the conclusion that many of the observed structural features along the seismic sections are actually below a reasonable drill depth for ANAD.

The EI survey was useful in identifying potential areas for well installation but required the integration of the results from the refraction seismic survey. It should be noted that the EI survey data could not be recalibrated using downhole measurements; they could only be reinterpreted as the drilling progresses. In addition, as discussed for the X-4 transect, this method can be misleading in identifying potential targets in complex geologic settings and needs confirmation of targets with an additional surveying method.

The use of MT has been successful at ANAD in identifying locations for drilling wells to intersect water-productive fractured interval(s). This method has been used exclusively since the X-4 survey to locate an additional four deep bedrock wells, each of which has intersected productive fractured intervals. Relative to seismic surveying, the method is less expensive, the data can be collected quickly, and the processing time is short. The method is most useful for sites with knowledge of subsurface lithologies and for positioning deep bedrock wells.

The integration of the survey results and the borehole logging information has been extrapolated along the trend of the Jacksonville thrust fault to allow for a reinterpretation of its direction and placement, the discounting of its role as a controlling feature for groundwater flow (i.e., as a preferential contaminant pathway), and a reinterpretation of the overall ANAD area geologic setting. The economics of this type of approach to characterizing a complex aquifer, when compared to obtaining a similar level of data from a drilling program alone, make the approach a sound use of project funds.

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