GEOPHYSICAL IMAGING TO ENHANCE ANALYSIS, DESIGN AND DRILLING OF LARGE-SCALE GEOTHERMAL SYSTEMS

John A. Mundell, Mundell & Associates, Inc., Indianapolis, Indiana
Gabriel Hebert, Mundell & Associates, Inc., Indianapolis, Indiana

Abstract

Improvements in alternative energy sources in the United States have received much attention over these last few years as petroleum-based fuel availability and prices have been tied to concerns about national security and the need to control global warming through reductions in greenhouse gas emissions. Consideration has increased for alternative energy sources, notably wind and solar. Geothermal energy, while considered a 'mature' industry, is again being reviewed as a potential alternative for new, large-scale, multi-structure, high-occupancy energy systems. New efforts are now being made to improve the design and installation techniques so that enhanced system efficiency and reduced 'first costs' are achieved. This has led to the desire to better understand the impact that the subsurface geologic environment within large geothermal wellfields can have on the thermal conductivity distribution that has been assumed to be present using limited boring information. Geophysical surveys using 2-D Electrical Resistivity Imaging (2-D ERI) and downhole logging, supplementing standard site drilling information, have recently been applied to the largest geothermal heat pump project in the United States. The technique has been shown to yield detailed subsurface characteristics that can be used to improve the analysis, design, and drilling of these large-scale geothermal systems.

Introduction

Geothermal heat pump (GHP) systems have been in use for decades and are a recognized alternative energy system for residential and small commercial facilities. Also known as geoexchange, earth-coupled, earth energy or ground-source heat pumps, they act as central heating and/or coolling systems that pump heat to or from the ground using a system of tubing containing heat-exchange fluids. The U.S. Environmental Protection Agency (EPA) has called GHPs the most energy-efficient, environmentally clean, and operationally cost-effective space conditioning systems available (U.S. EPA, 1993). However, because they are characterized by high initial capital costs, their expansion for use in large-scale systems involving multiple structures and larger populations has been limited.

The high initial costs for GHPs include the material costs for geothermal well installation, as well as the actual drilling of borings for the placement of the supply line tubing loops. Currently, geothermal borehole fields are "laid out" based on the thermal conductivity distribution of the ground in the area under consideration. In order to determine the thermal conductivity, the owner of the system must engage the services of a well driller and diagnostics firm to drill a "test" hole and to run a multi-day test to determine the degree to which that ground will conduct heat. The higher the thermal conductivity the better, since GHPs are most efficient when the surrounding ground more readily defuses heat from (in the cooling season) or transfers heat to (in the heating season) the fluid that is running through the pipe.

The problem with today's practice is that the limited pre-design and installation test borehole process (*i.e*., the drilling of only 1 or 2 pre-construction holes) that has commonly been used for small scale systems (less than 50 geothermal wells), is likely not a scalable process for large geothermal systems that require much larger areas and more than a 1000 wells. Subsurface conditions in many geologic areas vary considerably over short distances, and the likelihood that the system will be designed with inappropriate assumptions is very high. As a result, the system's costs may be higher than required to achieve the thermal performance that is necessary, or may operate in an inefficient manner for the selected wellfield area. As such, in order to obtain a better picture of the thermal conductivity, the owner must bear the rather significant costs of additional test boreholes.

The use of geophysics coupled with selected drilling has the capability to dramatically reduce the need for extensive pre-installation test boreholes. In addition, the ability to rapidly map entire green spaces for their thermal conductivity capabilities at various depths, can permit a designer to more precisely lay out the field using the fewest number of production boreholes, resulting in more efficiency for a given area. In addition, knowing the distribution of geologic materials using geophysics will allow improved determination of the spacing and depth of the installation boreholes ahead of time, as well as improved drilling installation bids. It will be important to determine at what depths the various piping systems will be more efficient, due to a higher a thermal conductivity of the surrounding strata. When paired with a clear understanding of the surrounding geologic formations, new knowledge about the "sweetest spots" (and depths) will prove of immense value to system designers.

Project Background

Ball State University, located on a 660-acre campus in Muncie, Indiana, plans to convert its central heating and cooling system consisting of coal-fired boilers and electric chillers, to one employing geothermal fields and energy centers, which will service more than 45 buildings on campus. This conversion process will occur over a 10-year transition period. The proposed system, which would be the largest of its kind in the United States, will require more than 4,100 boreholes in two geothermal well fields located near "energy stations" that contain several heat pump chillers (see **Figure 1**). A closed-loop piping system, with water as the exchange fluid, will draw and replace heat from the boreholes that each extend 400 ft into the earth. A heat pump chiller will cycle the water into a campus wide network of pipes, entering into cold or hot water loops and passing through campus buildings' exchanges to cool or heat the interior. The university expects that heating and cooling via geothermal will realize more than $ 2 million in annual energy savings and cut BSU's on-campus carbon footprint in half, or by approximately 80,000 tons per year. The price of the project is estimated at $65 million to $70 million.

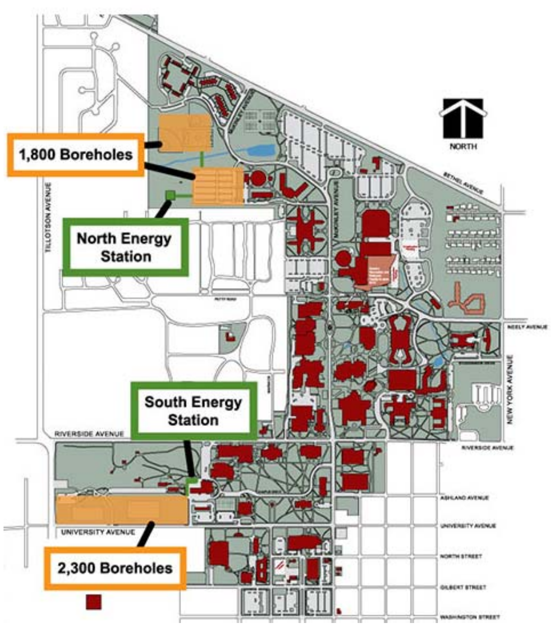

Figure 1: Geothermal Wellfield Map for Ball State University

As a typical initial characterization program for their North Wellfield, the university drilled two test boreholes to determine the subsurface conditions there. Test Boring #1 was located in the extreme northwest corner of the wellfield, and Test Boring #2 was located along the southern border of the wellfield. The interpreted linear-sloping top of bedrock map produced from these two borings is shown in **Figure 2a**. Later drilling of three additional boreholes completed in the northern portion of the wellfield resulted in the 'improved' top of bedrock map shown in **Figure 2b**, which conservatively covered only the western one-half of the proposed wellfield.

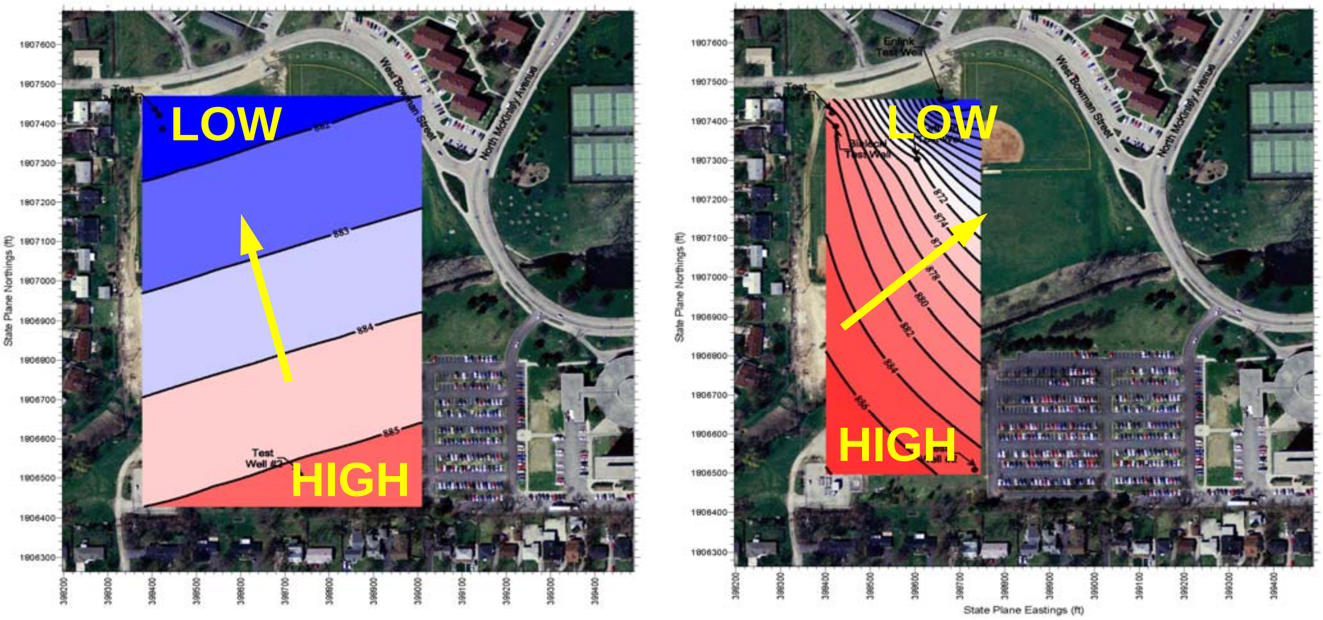

Figure 2: Top of Bedrock Map based on a) a 2-point constant slope model and b) a 5-point interpolated borehole model.

The Ball State campus lies within the Indiana Tipton Till physiographic plain. In this part of the state, the thickness of the unconsolidated material above bedrock (which consists predominantly of fine-grained glacial till with lesser amounts of interbedded coarse-grained sediments) ranges from approximately 20 to 140 feet. The underlying bedrock is composed of Silurian limestone and dolomite, which is prone to weathering and solutioning. Concerns regarding the accuracy of the interpreted subsurface conditions based on the limited boring program led BSU to consider the use of geophysics as a supplemental methodology for characterizing the wellfield. Based on the expected subsurface soil and bedrock conditions at the site, and the type of information desired by the geothermal designers and well drillers, two-dimensional electrical resistivity imaging (2-D ERI) supplemented with downhole logging was selected as the technique that could provide the best results within a limited budget.

Field Techniques

The area of investigation for this project consists of the North Wellfield, which contains two softball diamonds, a soccer field, and a southern parking lot that is separated by Cardinal Creek. An electric substation and radio towers were located in the southwest quadrant. This area is approximately 20 acres in size, and is located south and west of the intersection of West Bowman Street and North McKinley

Avenue in Muncie, Indiana (see **Figures 1** and **3**). At the time of the field work, approximately 1,700 geothermal wells were to be installed at this site, each to a depth of 400 feet. Thus, the goal of this geophysical survey was to provide Ball State with detailed non-intrusive data that provides insight into the geologic conditions beneath the site.

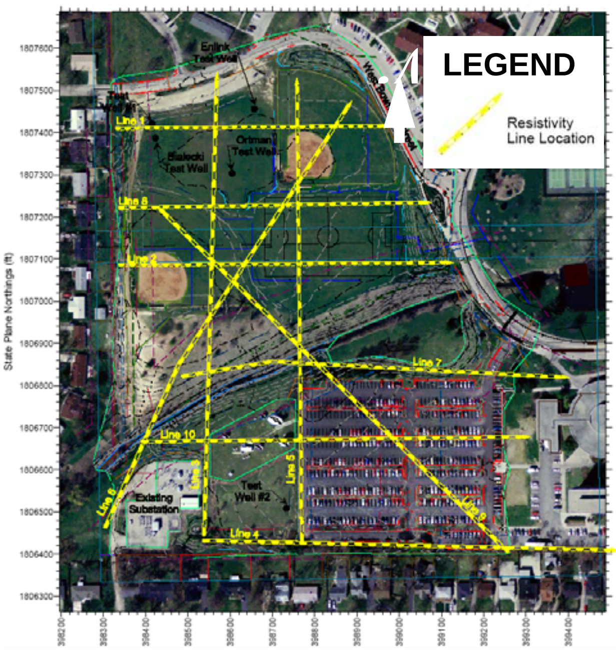

Figure 3: North Wellfield and 2D Resistivity Profile Line Orientations

Ten (10) 2-D ERI lines were collected in north-south, east-west, southwest-northeast, and northwest-southeast orientations (see **Figure 3**). For this project, resistivity data were collected with an *AGI SuperSting R8* earth resistivity meter using a dipole-dipole array of 60 electrodes along profile *Lines 2*, *4*, *6*, and *9*; and a dipole-dipole array of 56 electrodes along profile *Lines 1, 3, 5, 7, 8,* and *10*. The electrode spacing of each of the resistivity lines was dependent on the orientations of the lines and the amount of area available for data collection. Thus, *Line 1* has an electrode spacing of 3.5 meters (approximately 11.5 feet), *Lines 2* and *8* have a spacing of 4 meters (approximately 13 feet), *Lines 4, 7,* and *10* have a spacing of 5 meters (approximately 16.5 feet), and *Lines 3, 5, 6,* and *9* have a spacing of 6 meters (approximately 20 feet). Once the data were collected, they were downloaded to a computer and subsequently inverse-modeled using the software *EarthImager 2D v1.8.1* to obtain an "actual", true resistivity cross-section of the subsurface.

Downhole conductivity and caliper logging were completed in two of the boreholes to a depth of 400 ft in order to directly evaluate the variation in the subsurface soils and bedrock encountered, and to aid in the calibration of the 2-D ERI results.

Results of Analysis

Four (4) selected east-west 2-D ERI are presented in **Figure 4**. Based on the survey results, it is apparent that the subsurface soil and bedrock conditions underlying the site are much more complex than would have been anticipated by the drilling companies (based on the few test borings that were completed for the area), with rapidly changing conditions observed over distances of less than a hundred feet. However, while there is variability over all of the resistivity profiles, there are general patterns that are common among them. High resistivity values, *i.e.*, approximately 750 to 3000 ohm-meters, are generally interpreted to reflect the presence of dense, competent limestone rock (presented as a pink color). Moderately high values (300 to 750 ohm-meters) reflect areas where the bedrock is weathered, fractured or solutioned. Mid-range values (80 to 300 ohm-meters) are interpreted to be coarser-grained soils (sand and gravel) in the shallow subsurface, and possible severely weathered/fractured rock or soil/water-filled voids in the lower subsurface. The lowest range of values, *i.e.*, less than 80 ohm-meters, is interpreted to be fine-grained glacial till soils with a high clay content (purple to green). A resistivity of 0 ohm-meters (dark purple) is indicative of buried metallic utilities and interference from buried electrical lines and the electrical substation in the southwestern corner of the Site.

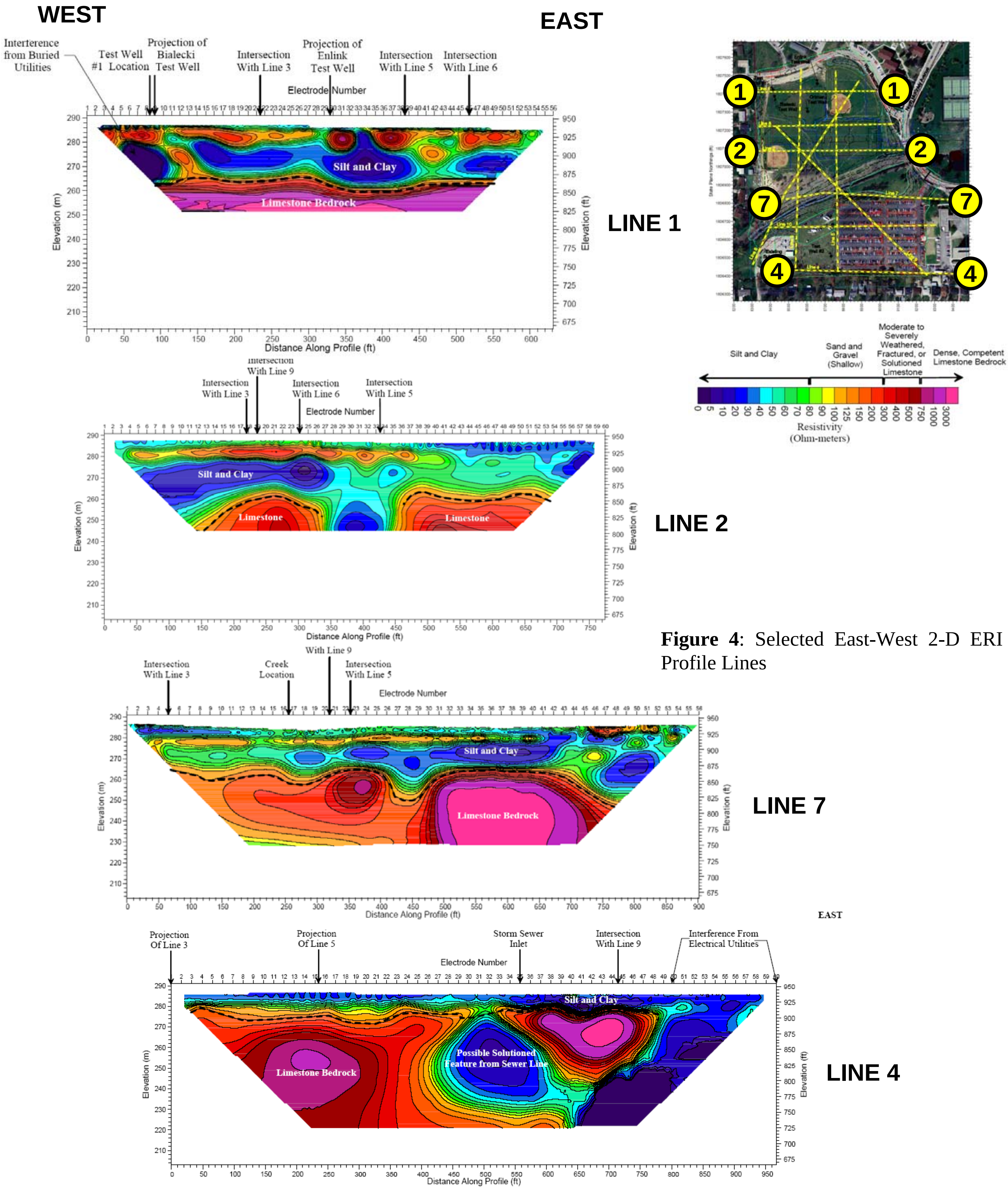

Figure 4: Selected East-West 2-D ERI Profile Lines

In general, the majority of the profiles show a thin (10 to 20 feet) layer of silt and clay overlying a thicker (20 to 30 feet) body of sand and gravel, under which lies a clayey layer of variable thickness (30 to 70 feet). The estimated bedrock surface shown on these profiles is denoted by a black dashed line, and one can see that it is quite variable and undulating, ranging in depth from just over 20 feet on *Line 4* to 140 feet on *Line 3*. Some of this variability is likely due to solutioning of the calcareous

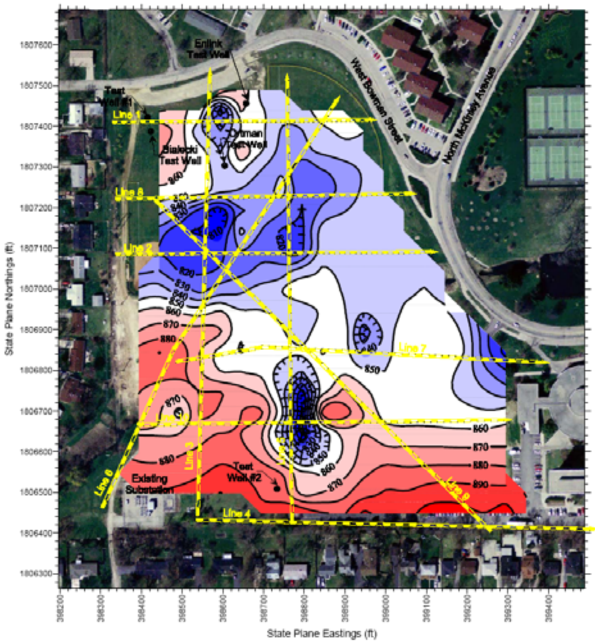

Figure 5: Top of Bedrock Topographic Map.

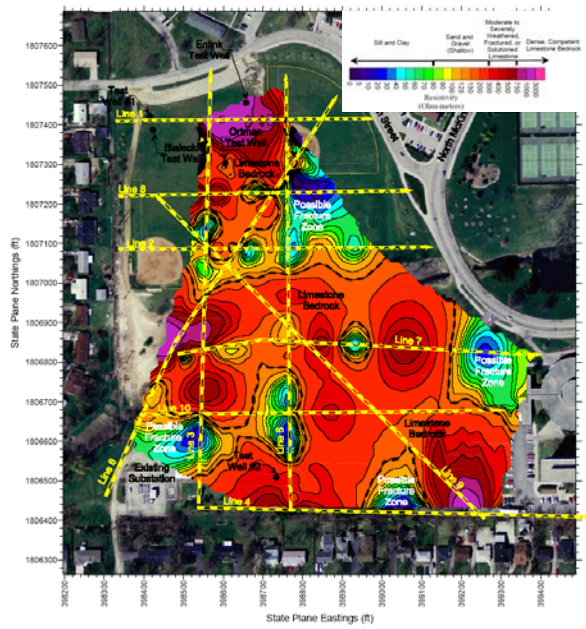

Figure 6: Resistivity Slice Map at Elevation 840.

limestone bedrock, and several solution prone features can be seen on the resistivity profiles, the most notable of which is located on *Line 4*, just west of a storm sewer inlet.

After the individual resistivity cross-sections had been generated, the interpreted bedrock surface from the individual profiles was digitized and uses to generate a top of bedrock topography map, which is presented as **Figure 5**. In addition to this map, several lateral (*i.e.*, constant elevation) resistivity slice maps were generated as well, by combining the individual cross-sections into a three-dimensional data set and taking slices at various constant elevations. The resistivity slice taken at elevation 840 feet is presented in **Figure 6**. While the shallower slice maps show the lateral extent of the shallower fine- and coarse-grained layers, the deeper maps detail where the bedrock is competent and where it is more fractured and solutioned. It should be noted that electrical interference from utility lines, the existing substation, and the foundations of the radio antennas are likely to have caused decreases in measured resistivity values in some areas that may not be indicative of actual subsurface conditions. In these areas, only direct inspection through drilling will determine actual conditions.

Further evidence of bedrock solutioning is found in the conductivity and caliper logs of the two test well locations (see **Figure 7**). These logs show the presence of several fractured/solutioned zones, the most severe of which is located from approximately 360 feet to 400 feet below ground surface. This zone of severely weathered limestone and clay is very soft and was confirmed by the drilling logs.

The results of this mapping were included in the drilling bid packages, and resulted in extremely positive comments from the dozens of well drillers around the country who reviewed them. The drillers were fascinated to "see" what they would encounter at various depth strata. The geophysical mapping occurred at the ground surface, but produced a multi-colored 3D image down to an excess of 250 feet.

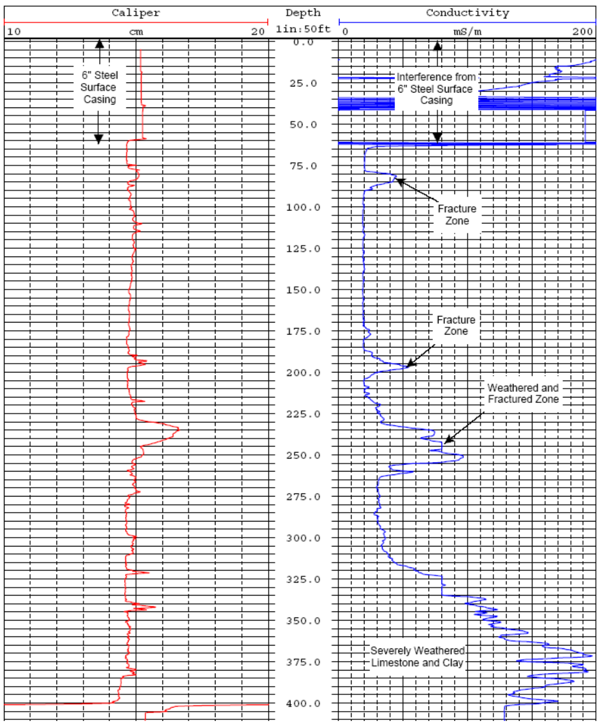

Figure 7: Downhole Log of North Wellfield Boring.

Conclusions

The use of geophysical surveys of the location of proposed geothermal wellfields provides enhanced characterization for final design and development of drilling specifications for the geothermal system. In this case history, the combination of a few selected drill holes with 2-D resistivity imaging and downhole logging over a period of a few days, allowed for detailed subsurface information that would have taken more than one year of continuous drilling to accomplish. This added information has the potential for allowing a more detailed design and drilling analysis of these large-scale systems prior to their installation, which could lead to more efficient systems and reduced 'first costs', making the systems a more competitive alternative to existing energy systems. As the understanding of the performance of large-scale (1000 plus wells) geothermal systems are better understood with their installation and operation, an enhanced understanding of how the system performance is impacted by the underlying geologic strata will be allowed by the greater knowledge gained through geophysical surveys.

References

Environmental Protection Agency (1993). *Space Conditioning: The Next Frontier - Report 430-R-93-004*. EPA.