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MAPPING GEOTHERMAL RESOURCES: A MINIMALLY INVASIVE PROCEDURE

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ABSTRACT

Understanding the location and extent of groundwater resources is very important to the geothermal industry for obvious reasons. It is critical to have a cost-effective method of understanding where concentrations of geothermal water are located as well as the preferential flow paths of the water in the subsurface. Such information can assist companies to optimize the location of production and injection wells among other things.

AquaTrack™ is a patented, geophysical magnetic-based groundwater mapping solution, from Willowstick Technologies®, LLC that has proven successful in the geothermal industry to better characterize groundwater conditions and flow patterns. AquaTrack's technical name is Controlled Source-Frequency Domain Magnetics (CS-FDM) and will be referred to as such hereafter in this paper.

This paper presents a geothermal case history using a relatively new but proven technology that can accurately map groundwater at significant depths (up to 1,000 meters) over large areas (square kilometers) in short periods of time (weeks).A description of how the technology works and a review of a case study will be presented. This paper will focus on how a geothermal company used the AquaTrack technology to gain insightful understanding of groundwater flow.

PROJECT HISTORY AND BACKGROUND

Global environmental standards continue to become ever more stringent, increasing the appeal and demand for green power. Because of this, geothermal energy is experiencing enormous growth. As a part of this growth, Amp Resources (Amp) recently purchased the Salt Wells geothermal site near Fallon, Nevada. This geothermal resource has long been believed to be marginal because of its lower water temperatures in comparison to traditional geothermal resources.

Amp Resources looked to new and emerging technologies to assist them in the exploration of their newly acquired asset. As a result, they turned to Willowstick Technologies, LLC (Willowstick). Willowstick was contracted to assist Amp to better characterize and delineate areas of greatest geothermal groundwater concentrations and highest groundwater temperatures. This geophysical investigation proved to play a key part in Amp Resources' placement of geothermal production wells, injection wells, and a geothermal power plant at Salt Wells.

A significant amount of geothermal exploration work had been conducted at the Salt Wells site including: exploratory well drilling, hydrogeologic reconnaissance, temperature gradient holes, soil-mercury surveys, self-potential and gravity and magnetic surveys. However, none of the surveys clearly identified where high temperature groundwater was located and how best to develop the resource for optimal electrical power production.

Amp Resources also retained the services of Roger L. Bowers, P.G. to review the CS-FDM results from Willowstick Technologies and compare its findings with the other geothermal exploration surveys previously done for the Salt Wells site. Upon Mr. Bowers review of the CS-FDM work, and after comparing its results with previous studies, Mr.

Bowers assisted in the preparation of the final report submitted to Amp Resources.

PROJECT OBJECTIVE

The project objective of the CS-FDM geophysical investigation was to characterize and delineate areas of greatest geothermal groundwater concentrations within the study area. A secondary objective of the investigation was to map probable blind faults suspected of containing and conducting high temperature groundwater beneath the site. These project objectives were necessary in order to locate and optimize hot water production from the geothermal resource for the purpose of generating electrical power. The depth of the targeted geothermal groundwater below ground surface ranges from approximately 100 to 170 meters.

The characterization or delineation of the groundwater within this area was used to:

- Aid in siting production wells to further evaluate and fully develop the geothermal resource.
- Provide insight to locate an injection well that would not adversely impact the hot water production.

HYDROLOGICAL/GEOLOGICAL SITE CONDITIONS

The Salt Wells geothermal resource lies 30 kilometers to the southeast of Fallon, Nevada on the eastern flank of the Bunejug Mountains and the west side of Eightmile Flat. The Bunejug Mountains are basalt flows of the Bunejug Formation of Late Tertiary age. The basalt is approximately 700 meters thick based on the results of a test well drilled to a depth of 2,600 meters. The basalt is underlain by granite of unknown age. The mountains are partly covered by young Quaternary Lake Lahontan sediments. The low topographic relief of the mountains and the thick basin fill of young Lahontan sediments have inhibited the formation of alluvial fans on the flanks of the mountains.

The Bunejug Mountains are cut by numerous near vertical faults, but displacements are believed to be small. It is possible that some of the faults follow original columnar jointing of the basalts. The basalt flows generally dip to the east and southeast, but it is unknown if the dips represent original flow from a vent area or resulted from subsequent faulting or folding of the mountain range. (Willden and Speed, 1974)

Most of the project area is covered by sand and clayey silt and sand deposits. Numerous sinter and silica-cemented sand deposits, believed to be the result of geothermal activity, were mapped on the surface in the northwest part of the project area. (Faulds and Coolbaugh)

Groundwater flow is believed to be generally eastward off the flanks of the mountain range into Eightmile Flat and then northward toward the Carson Sink. Temperatures and temperature/depth profiles from temperature gradient holes show an upwelling of geothermal fluids in the Simpson Pass area, most likely up a fault zone, with outflow to the northeast in the upper part of the basalt and at the basalt/alluvium contact.

INTRODUCTION TO CONTROLLED SOURCE–FREQUENCY DOMAIN MAGNETICS

To assist the reader, the following section provides a brief overview of the CS-FDM approach. This technology is patented, with exclusive rights held by Willowstick Technologies, LLC, and given the trade name of AquaTrack. It is important to remember that each CS-FDM investigation is site specific and therefore, each job varies in the application of electrodes, antenna configurations and interpretive parameters.

CS-FDM uses a low voltage, low amperage audio frequency electrical current to energize the groundwater of interest. Electrodes are placed in strategic locations to facilitate contact with the groundwater. An alternating current with a specific signature frequency is applied to the electrodes. The resulting alternating current, flowing between the electrodes, follows the groundwater along preferential flow paths. Because groundwater is generally the best conductor in a given area, the electrical current concentrates in the groundwater between the strategically placed electrodes. As the electrical current flows through the groundwater in the area of investigation, it creates a magnetic field characteristic of the injected electrical current. This unique magnetic field is identified and surveyed from the surface of the ground where magnetic field measurements are recorded. The locations of the field measurement stations are identified using a Global Positioning System (GPS). The measured magnetic field data are then processed and correlated to other hydrogeologic data to bring together an enhanced groundwater model.

Measurements of the magnetic field are made using three orthogonal magnetic sensors oriented with two sensors in the horizontal and one in the vertical. The sensor output is amplified and quantitatively filtered and then passed on to a Campbell Scientific CR1000 data logger where the sensor data signal is pre-processed. GPS is used to establish and geographically map the locations of the field measurements. A Windows-based, Allegro CE handheld computer is connected with these instruments to store and correlate the GPS data with the magnetic field data.

CS-FDM is a non-intrusive geophysical groundwater mapping system capable of delineating subsurface water concentrations and structure that influence groundwater concentrations and flow patterns. Because saturated strata act as the best subsurface electrical conductors, the CS-FDM energy follows the water-saturated zones from one electrode to the other. CS-FDM maps the groundwater flow paths because of this relationship. It is important to remember that each CS-FDM investigation is site specific and therefore, each survey varies in the application of electrodes, antenna configurations and interpretive parameters. The antenna array of wire and electrodes are dependant upon site conditions. Electrode placement is based to optimize contact with the groundwater in question as well as the total area to be surveyed.

SALT WELLS SURVEY

December 1st, 2004 marked the beginning of the Salt Wells geothermal mapping. From previous geologic and geophysical studies conducted at Salt Wells, a target area of roughly 700 by 1000 meters feet was selected as the study area. This area was believed to have subsurface faults suspected of conducting the greatest amount of geothermal groundwater in the area

To provide optimum coverage of the designated area, two horizontal dipole antenna/electrode configurations were initially employed that energized two suspected water bearing fault zones. These antenna/electrode configurations consisted of connecting surface antenna wire to existing steel cased temperature gradient holes that were drilled into the geothermal water by previous owners of the resource. These gradient holes were abandoned some years ago once the temperature information was obtained. These wells were located adjacent to, and on opposite sides of, the survey area.

Approximately 460 magnetic field measurements were recorded over the study area. These measurements were taken along 11 lines, each line spaced 200 meters apart and each measurement station placed at 30 meter intervals along each line. Each of the 11 lines ranged in length from 500 to 700 meters. The measurement station spacing used in this survey is a relatively sparse grid in comparison to most CS-FDM surveys.

During the first week of gathering data related to the induced signature frequencies, it was discovered that unusual elevated magnetic interferences were polluting the information. Tests conducted on site concluded that the interference was probably the result of operational activities from a nearby Naval Air Base. Once the problem had been identified, the CS-FDM equipment was reprogrammed to recognize the unusual magnetic interference.

SURVEY RESULTS

The analysis of the CS-FDM geophysical investigation entailed reduction of field data to useable matrices. The data were then subject to a number of comparisons and corrections for atmospheric (sunspots, diurnal magnetic variations, etc.) and ground noises (60 hertz power supplies, cathodic pipe protection, etc.) as well as effects induced by the electrodes and antenna. The removal of the effects of the antenna and electrodes is done by mathematical algorithms and is accomplished through a series of iterations until the effects of the antenna are sufficiently reconciled.

The resultant data were then contoured to form a "footprint", or map of the conductive highs and lows. These conductive highs and lows can be interpreted as areas of high or low groundwater saturation.

Geologic and hydrologic features in the area of study alter the alignment of the magnetic field generated by the CS-FDM energy introduced into the ground and where the energy propagates. When this energy crosses a geologic boundary it results in a change of the subsurface electrical properties. Additionally, the fluctuation in the flow of energy in the ground results in orientation changes in the magnetic field. Evaluating the magnetic field components of the CS-FDM data provides an indication of areas where groundwater changes occur and where groundwater structures can be delineated. Most notable are the subsurface features that inhibit current flow and concentrate the flow in east-west channels that are probably faults that transect the subsurface basalt flows. The jointing patterns in the basalt probably control the local subsurface movements of the geothermal water. The geothermal waters are likely ascending along the highly fractured zone of the intersecting faults, controlled primarily by the fault that creates Simpson Pass. The geothermal zone is then enlarged by geothermal water flowing into the fractured basalt.

QUALITY CONTROL

The quality of the data collected during the CS-FDM investigation was excellent in most areas of the survey. Various maps, such as the Signal to Noise and Signal Repeatability maps gave a degree of confidence that the magnetic field measurements were identified and recorded. Also, the correlation of

CS-FDM to other geologic, hydrogeologic and geophysical investigations is also performed. For example, Anadarko Petroleum Company conducted several geothermal exploration surveys of the site in the late 1970's and early 1980's to delineate the geothermal resource. These surveys included numerous temperature-gradient holes, gravity and ground magnetic surveys, a soil-mercury survey, and a self-potential resistivity survey. All were common surveys used by the geothermal industry at the time. The CS-FDM results correlated extremely well with the temperature data, gravity, self-potential, and soil-mercury surveys. All surveys showed an anomalous zone with two major directional components: a major fault that cuts the Bunejug Mountains through Simpson Pass, and a range-front fault typical of Basin and Range structures.

CONCLUSIONS AND RECOMMENDATIONS

The major findings of the CS-FDM geophysical investigation were as follows:

1. The evidence indicates increased groundwater saturation at and near what is interpreted as the intersection of specific faults. This is consistent with the fracture sets identified in the geologic and hydrogeologic reconnaissance studies previously performed for the site.

2. The dark shading on the magnetic contour map (See Figure 1 – Salt Wells Map) represents areas of higher conductance and lightly shaded or almost white areas represent lower areas of conductance which is interpreted as areas of higher and lower saturation.

3. Subsurface features inhibited current flow and concentrated the flow in what appears to be channels or possible blind faults that intersect one another within the study area. The dashed lines, shown on the map (See Figure 1 – Salt Wells Map), are major changes in electrical properties and are interpreted as areas of significant change or probable blind faults.

4. The magnetic contour maps, generated from the CS-FDM geophysical survey method, showed a very strong contrast between areas of high electrical conductance (current concentration or flow) and areas of low electrical conductance. The areas of high electrical conductance are interpreted as areas of greatest geothermal groundwater saturation. The survey showed strong indications of elevated groundwater content (electrical conductance) in areas that are consistent with the conceptual model of probable groundwater locations and fracture patterns.

All of the data available to Willowstick suggested the optimal location for placement of production wells. Five well locations were depicted on the magnetic contour maps as the locations most probable to intercept high temperature and high volumes of geothermal water. The data also suggested the optimal locations for a network of injection wells.

RESULTS OF WELL PLACEMENTS

Following the completion of exploratory work, Amp began drilling operations. Amp prioritized the well locations based on previous geophysical exploration activities and depended heavily upon the CS-FDM technology. The resultant wells turned out to exceed expectations with flows exceeding 2500gpm (170 liters per second) with no draw down and temperatures above 285 degrees Fahrenheit (140 degrees Celsius).

SUMMARY

The CS-FDM technology generated accurate and timely groundwater maps from which Amp Resources made informative decisions about exploratory and production well drilling operations. The data provided invaluable feedback during the planning of placement of production wells.

The CS-FDM survey investigation provided significant information regarding the geothermal resources of the Salt Wells area. These data, when compared to the data previously collected by geochemical sampling and geophysical methods, provided a valuable tool for Amp Resources to formulate the next phase for geothermal resource development. The survey data identified high potential targets for intercepting geothermal water. It also recognized areas where spent geothermal water injection wells may be positioned.

The information supplied by Willowstick portrayed a very specific "subsurface groundwater image" that aided Amp Resources in optimizing drilling operations to capture high temperature and high production geothermal water within the study area.

The CS-FDM technology proved to be a significant help to Amp Resources. With Willowstick's assistance, Amp was able to take a property, previously believed to be devoid of significant geothermal potential, and turn it into a large producer of clean, geothermal power.

REFERENCES

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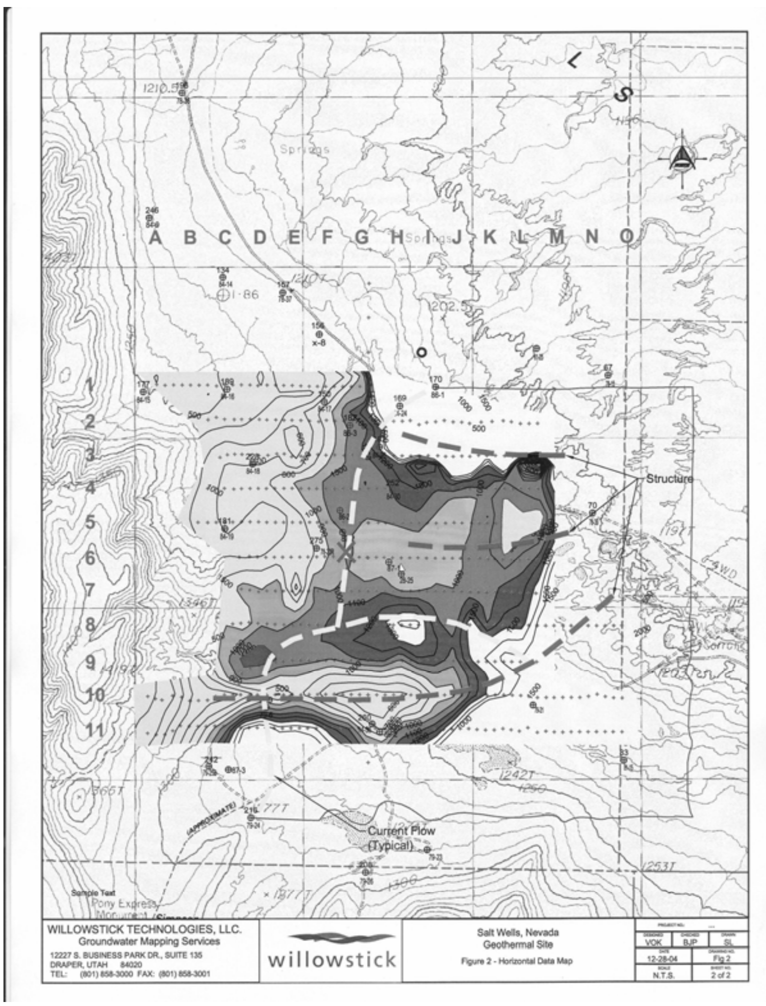

Figure 1 - Salt Wells AquaTrack Map