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Optimizing Geothermal Well Placement: Advantages of a Phased Approach Including Fracture Trace Analysis and Geophysical Techniques

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ABSTRACT

Bedrock drilling represents a substantial part of costs associated with the development of geothermal resources. Drilling costs can be reduced utilizing a series of phases that build upon each other to assess favorable drilling targets. Phase I should consist of review of all relevant geological and well data, fracture trace analysis and site reconnaissance. Site reconnaissance should document key geological features including rock lithologies, and fracture characteristics (orientation, spacing, aperture widths).

Phase II should consist of surface geophysical surveys to locate transmissive fractures, including very low frequency, seismic, and resistivity. Re-processing available seismic data should be considered using alternative algorithms and/or alternative geophysical survey techniques to gain confidence that potential productive zones are not overlooked. The results of geophysical surveys should indicate the existence of favorable zones for test-well drilling.

Phase III should consist of test well drilling and borehole geophysical logging. During drilling, the drill rig behavior, and changes in drill cuttings, water loss or gain, and drill bit advance rate should be documented as well as the depth of potential fracture zones. After cased open-hole test well(s) are completed and cleaned-out, borehole geophysics should be performed to determine breakouts, the depth of transmissive fractures, fracture orientation and fracture spacing. Discrete interval sampling of transmissive fractures, in conjunction with fracture orientation, and knowledge of regional fracture orientations may provide further insights into fluid characteristics and potential production rates.

In this paper, I will summarize the advantages of a phased approach utilizing fracture trace analysis, surface geophysics (seismic, resistivity, very low frequency [VLF]), and borehole geophysics (temperature, caliper, heat pulse flow meter, televiewer). Utilizing a phased approach and selected non-intrusive and in situ techniques can result in meeting investigation objectives in a single investigation thereby minimizing drilling costs. The phased approach utilizing applicable techniques, as described in this paper, can minimize drilling costs associated with commercial ground-source heat pump (GSHP) systems, exploration of hydrothermal resources, and stimulation of enhanced geothermal reservoirs.

1.0 Introduction

Drilling represents a substantial part of costs associated with the development of geothermal resources. It is widely recognized there are a number of geologic factors that influence the location and depth of geothermal wells. The presence of a fracture system hydraulically connected to a geothermal source is desirable to reduce drilling costs. Test wells and production wells completed in fracture systems may possess higher production rates.

The purpose of this paper is to summarize a technical approach consisting of three phases as part of a geological investigation of a site in Massachusetts (Site). The approach enabled optimizing a network of bedrock monitoring wells. A similar approach may reduce drilling costs associated with developing geothermal resources.

1.1 Geologic Setting

The Site study area is approximately 8 acres and consists of an undeveloped parcel in Massachusetts. The Site is located within the Boston Basin which has a well-defined north 80 degree east (N80°E) regional strike. The nearest mapped fault is located within 500 feet west of the Site; it is a north-south (N-S) striking fault, with considerable offset (Zen et. al., 1983). Other N-S striking faults are mapped north and south of the Site (Barosh et. al., 1978).
1.2 Objectives

The objective of the study described in this paper was to identify the horizontal and vertical locations of transmissive fractures and extent of ground-water contamination at the Site.

2.0 Phase I – Fracture Trace Analysis

Phase I consisted of compilation of existing geological maps, reports, well data, fracture-trace analysis, and ground truthing. Fracture-trace analysis is a well documented technique to identify potential lineaments (Fetter, 2001). Aerial photos were viewed under a stereoscope to identify photolinears.

The results indicated one N-S striking photolinear through the eastern portion of the Site (Figure 1). Fracture strike and dip measurements at bedrock outcrops in the vicinity of the Site indicated that the dominant fracture strike is N30°E, dipping toward the southeast at moderate to high (56° to 71°) angles. Secondary fracture strikes are from N50°W to N70°W, dipping toward the southwest at moderate to high (58° and 80°) angles.

3.0 Phase II – Surface Geophysical Surveys

The following surface geophysical techniques were performed at the Site.

3.1 VLF Survey

The objective of the VLF survey was to detect the horizontal location of water-bearing fracture zones. The survey consisted of twelve lines oriented southwest-northeast (SW-NE) and labeled 100S through 1100S and nine lines oriented northwest-southeast (NW-SE) and labeled 100E through 900E (Figure 1). The VLF data were acquired with a station spacing of 20 feet (ft). VLF data are interpreted using pattern recognition of anomalies, with departures of the real component judged to be significant, which may indicate regions along a particular VLF survey line as having increased electrical conductivity. The detection of fracture zones in bedrock in New England is best based on the real component in terms of increased conductivity, which is inferred to be due to conductive bedrock fracture zones.

The VLF survey detected 29 possible conductive zones on the basis of the positive anomalies of the real component, and they are interpreted as possible bedrock fracture zones. However, the VLF anomalies associated with individual fracture zones are not all equal in amplitude. Some are much stronger than others along individual survey lines and some are more consistently strong along the trace of the interpreted fracture zone. Those characteristics were used to assign relative strengths to each of the zones. Although the fracture trace analysis identified many photolinears, only two intersect the Site survey area. Their approximate locations do not coincide with any of the conductive zones determined in the VLF survey. However, their approximate azimuths, 1° and 353°, are reasonably near clusters of the azimuths of conductive zones. Although neither of the two shallow bedrock troughs detected in the seismic refraction surveys coincides with a conductive zone interpreted on the basis of the VLF survey, the azimuths of the troughs, 15° to 36° are reasonably close to the interpreted conductive zones.

3.2 Resistivity Profiling

The objective of the resistivity profiling used in this study was to better estimate the depth of selected water-bearing fracture zones identified in the VLF survey in the bedrock. The data were to be used for locating bedrock test wells to intercept potential transmissive fractures that may act as ground-water contaminant migration pathways.
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The surface resistivity survey was designed to augment the data obtained by VLF. Three resistivity survey lines were oriented perpendicular to the peak azimuth of the VLF anomalies and one survey line was oriented perpendicular to a secondary azimuth of the VLF anomalies. Results of the surface resistivity survey identified five subsurface regions possessing relatively high conductivities. These linear features are interpreted as possible water-bearing bedrock fractures; their locations are shown on Figure 2.

Of significance is the observation that two individual resistivity fracture zones coincide with interpreted VLF fracture zones. Fracture zone 1 is near vertical, strikes N-S, and coincides with a high strength VLF fracture zone. Fracture zone 3, strikes N-S, dips steeply east and coincides with a very-high strength VLF fracture zone. Fracture zone 4, strikes NE, dips moderately NW, and is aligned with a high strength VLF fracture zone that appears to extend the VLF fracture zone towards the southwest. Because Fractures zones 1, 3 and 4 were initially interpreted using VLF and confirmed using resistivity, they were interpreted to more likely to represent water-bearing fracture zones.

4.0 Phase III – Test Well Drilling and Geophysical Logging

Phase III consisted of test well drilling and borehole geophysics. A total of eight borings were advanced approximately 100-feet into bedrock. The annulus of 6-inch inside diameter steel casing was grouted several feet into the top of bedrock at each boring. During drilling, the drill rig behavior, and changes in drill cuttings, water loss or gain, and drill bit advance rate were observed to document the depth of zones of weakness that commonly represent fracture zones, and to perform drill-stem testing to determine if there is water gain or loss.

4.1 Test Well Drilling

Down-hole air hammer rotary drilling ranged from 10 to 45 seconds per foot, generally decreasing with depth. Well yield ranged from 2 to 3 gallons per minute. Bedrock cuttings are consistent with the Dedham Granite formation - a “light grayish-pink to greenish-gray, equigranular to slightly porphyritic, variably altered, granite” (Zen et. al., 1983). Bedrock is overlain by approximately 10 to 30 ft of unconsolidated materials.

4.2 Borehole Geophysics

The following borehole geophysical logging tools were performed in the eight test wells: Caliper logging to identify changes in the borehole diameter associated with fractures; heat pulse flowmeter (HPFM) to measure groundwater flow directions and flow rates within the borehole under both ambient and pumping conditions; and acoustical televiewer (ATV) to develop an oriented image of the borehole walls and measure fracture orientation. The strike and dip of fractures was determined after correction for borehole inclination. Natural gamma logs were included for identification of intrusions (possible fracture zones). The borehole geophysical results are summarized on one figure for each borehole (e.g., Figure 2).

The strike and dip of interpreted features from the ATV logging of eight boreholes are presented on a rose diagram (Figure 3). Most of the borehole fractures strike NE and NW, with fracture sets in some wells showing a variable distribution between NE and NW. This is consistent with the strikes obtained using surface geophysics. Fractures dip mostly from 47° to 79° (moderate–high angle). The fracture strikes determined by geophysical logging are consistent with the fracture-trace analysis that identified two photolinears in the eastern portion of the study area that strike north; bedrock outcrop measurements that identified a primary fracture strike of N30°E with moderate to high SE dips, and a secondary fracture strike of N50°W to N70°W with moderate to high SW dips. These fracture orientations were consistent with the VLF results that indicated fractures that strike north (1° and 353°), and the resistivity results that indicated two fracture zones that strike north and dip vertical to east, and one fracture zone that strikes NE and dips NW.

Figure 2. Borehole Geophysical Logs for MW-405 within the Study Area.

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Based upon borehole geophysics results, zones were selected for discrete-interval groundwater samples using straddle packers. These samples were analyzed for volatile organic compounds (VOCs), on a 24-hour turnaround basis, using EPA method 8260B. The VOC results were used to identify transmissive zones transporting the contaminants. These zones were considered when designing monitoring wells. In boreholes where no transmissive fractures were identified, continuous discrete-interval groundwater VOC results were considered when identifying contaminant zones for monitoring. Two nested monitoring wells were installed in each of the boreholes. The results of this three-phase investigation approach was successful at delineating the extent of contamination in a single investigation, which saved the client tens of thousands of dollars in drilling and associated costs.

5.0 Conclusions

The objective of this paper is to summarize a phased approach that optimized the well network in a single investigation event that saved the client tens of thousands of dollars. This approach consisted of fracture-trace analysis, followed by surface geophysics, test-well drilling and borehole geophysics.

When planning drilling programs, surface geophysical techniques described in this paper are limited to depths of only a few hundred feet below ground surface. Seismic reflection is commonly used to image structures to greater depths. In contrast, borehole logging is not limited by depth; however, the borehole should be 4 to 6-inches in diameter, and must be free of sediment, and be compatible with expected chemical and physical characteristics in the test well.

When planning large-scale open-loop, ground source heat pump (GSHP) systems, the phased approach summarized in this paper should be considered. In an open-loop GSHP system, 1-2 gallons per minute per ton of groundwater with low hardness, low iron/manganese, and low sediment is desirable (Kavanaugh, 2008). Spacing of withdrawal wells and discharge wells is also a consideration, and in-situ drawdown testing should be considered by a qualified hydrogeologist. If a closed-loop GSHP system is chosen, then drilling costs will be significantly higher because well depths are 400 feet deep or less because more wells are typically required in such systems.

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References