Use of the In Situ, Inc. MP Troll 9000 to Locate Fractures Contributing to Ground Water Flow in Bedrock Wells

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Abstract

The In Situ, Inc. MP Troll 9000 is a multimeter capable of the simultaneous measurement of depth below water, temperature, pH, ORP, conductivity and dissolved oxygen. The instrument was used in two bedrock wells to evaluate its ability to identify fractures that contribute to ground water flow. The wells are bored through approximately 280 feet of crystalline metamorphic bedrock to a total depth of approximately 310 feet. Prior to deploying the MP Troll 9000, the wells were logged using both conventional and advanced borehole-geophysical methods. These methods included caliper logging, gamma logging, fluid-resistivity logging, fluid-temperature logging, and both optical- and acoustic-televiewer logging. The wells were also logged under ambient and pumping conditions (<1 gpm) using a heat-pulse flow meter to locate fractures that contribute to flow and estimate associated discharge rates and the direction of vertical flow in the open borehole. The logs were used to corroborate the results of the vertical water quality profiles obtained using the MP Troll 9000. Water quality profiles within the wells were recorded under both ambient conditions and at pumping rates of 0.25-0.8 gpm. These rates are comparable to those used during heat-pulse flow meter logging. Preliminary results reveal that the wells exhibited obvious water quality anomalies that can be associated with the fractures contributing to flow as identified by the other borehole logging techniques. As such, the MP Troll 9000 may be a cost effective means to help locate these fractures. Because the MP Troll 9000 measures water quality parameters, it has the additional advantage of being able to potentially detect which fractures are contributing contamination to a well. Further research is currently being conducted to evaluate how water quality parameters change under higher pumping rates, and with slight augmentation, the tool's use as an effective flow meter.

Introduction

This paper presents the results of field tests conducted to evaluate the ability of a downhole multimeter to identify the fractures controlling the flow of ground water within bedrock wells. To accomplish this goal, the scope of work included the installation and development of two bedrock wells, an assessment of the use of a MP Troll 9000 multimeter on loan from In Situ Inc., and the characterization of the boreholes utilizing select down hole geophysical methods for confirmation of any fractures identified.

The test site is located at Beach Hall at the University of Connecticut, Storrs campus. Surrounding Beach Hall there exists a well field for the purposes of hydrogeologic research. The well field, which includes 6 overburden wells, and 2 multilevel nests comprised of 3 piezometers each, has been recently augmented by two bedrock wells which are the focus of this test. A Site Map is provided as **Figure 1**.

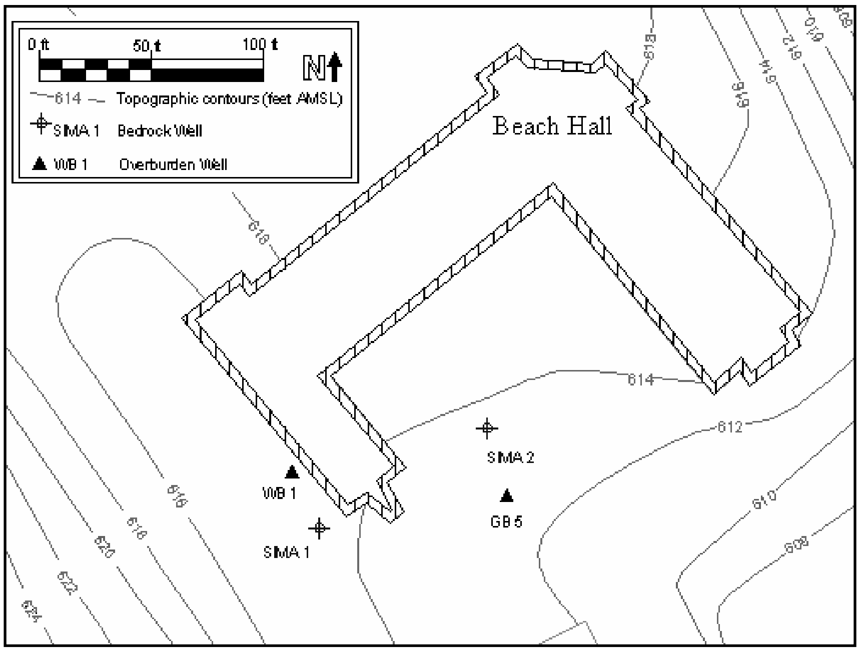

Figure 1. Site Plan depicting the locations of two bedrock and two overburden wells used in the test.

The two bedrock wells were installed March 31, 2003 (SIMA 1) and April 1, 2003 (SIMA 2). Each of the wells was drilled using compressed-air percussion to an approximate depth of 310 feet and completed with 30 feet of 6-inch steel casing grouted in competent bedrock. All measurements are relative to the tops of casings, which extend approximately 1.75 feet above grade.

Geology

According to published data, overburden at the site consists of undifferentiated till averaging 15 feet in depth. Contrary to published data, direct observation during the installation of the wells surrounding Beach Hall indicates a varied but often graded overburden, with poorly graded deposists continuing to bedrock in some areas and fill over stratified sequences of sand in others. As the site is located on the western side of a large valley, native overburden is most likely derived from contact with glacial melt water rather than glacial ice. The two overburden wells most proximal to the bedrock wells are WB-1 and GB-5, which are located approximately 20 feet northwest of SIMA 1 and 25 feet south of SIMA 2, respectively. Similar to the overburden wells, bedrock well casing intercepts 5 feet of fill, underlain by 10 feet of till, underlain by 5 feet of gravel in SIMA 1 and 6 feet of fill, underlain by 11 feet of till, underlain by 4 feet of wet sandy till in SIMA 2.

The bedrock beneath these surficial deposits consists of metamorphic and igneous rocks of Paleozoic and Proterozoic age, which originated as oceanic sediments and crust (Iapetos Terrane). Specifically, the site is underlain by the Hebron Gneiss. The Hebron Gneiss is defined (Rodgers, 1985) as an interlayered dark-gray schist and greenish-gray, fine- to medium-grained calc-silicate gneiss. Pegmatitic intrusions are common. The bedrock is further defined (Pease, 1988) as the Southbridge Formation of the Paxton Group, which is a medium-grained, granular, evenly thinly layered quartz-plagioclase-biotite schist and gneiss exhibiting ambphibolite facies regional metamorphism. Though rare in outcrops, bedrock descriptions note intervals of light-gray, medium- to coarse-grained, massive to weakly layered felsic gneiss as much as 2-meters thick. Regional foliation and layering tend to mimic the trends of two ductile faults (the Black Pond Fault to the northwest and the Lee Brook Fault to the southeast) that define the extent of the formation. Brittle deformation superposed on ductile features is often present, indicating movement at lower metamorphic grades.

Methodology

The In Situ, Inc. MP Troll 9000 is a multimeter capable of the simultaneous measurement of up to 9 water quality parameters while deployed down hole. Measuring only 1 ¾-inches in diameter, the instrument is equipped with an integrated datalogger to retain measurements allowing unattended, long-term monitoring of water quality with respect to time. In addition, users can achieve real-time data via connection to a laptop computer or PDA, as was the case in this experiment. This technology allows updates on chemical parameters approximately every 2 seconds providing that the sampled medium is stable. Changes in water quality with respect to depth were inferred to indicate sources of groundwater derived from different transmissive zones. While using the MP Troll 9000 to create a vertical profile of water chemistry, anomalous changes in the chemical parameters measured should indicate the depth of transmissive fractures. Likewise, both the number of stations where readings are obtained and the interval between them dictate resolution. Using a twenty-foot depth interval, the multimeter was lowered from just below the water surface to the bottom of the borehole (rate = <4-ft/s). A handheld PDA was used to keep track of depth and ensure that chemical parameters stabilized prior to advancing the instrument to subsequent stations. Stabilization typically took no more than a couple of minutes, with dissolved oxygen being the slowest. Plotting the parameters with respect to depth (pressure as measured in feet of water less barometric pressure plus depth to water from top of casing) revealed discrete zones where further resolution was desired. Initial tests conducted at twenty-foot intervals were followed by tests at ten-foot and two-foot intervals. Upon completion of the test, data was exported as a spreadsheet file. The data was reduced by taking the last set of stabilized readings at each station. These data sets are easily recognized as subsequent readings change drastically as the probe is lowered. The data is graphed with respect to depth to provide a chemical profile of the well. Six sensors were used in this experiment including pressure, temperature, pH, oxidation-reduction potential (ORP), conductivity and dissolved oxygen (DO). The sensors deployed are described briefly as follows:

Pressure

The pressure transducer used on the MP Troll 9000 in this study measured absolute pressure. The strain gauge offers a range of 0-692 ft with an accuracy better than +/- 0.1% FS and a resolution of 1 mm.

A downhole pressure transducer measures the force exerted on the strain gauge by a column of fluid above (air and water) in pounds per square inch. Options are available for unit conversions. Recording pressure in feet of water enables the user to define the depth of the probe. The pressure above water (barometric pressure) is recorded as a reference. Depth to water is recorded from top of casing. Options are available to allow user-defined references. In this manner the depth to water less barometric pressure is added to subsequent pressure readings to determine the depth of the probe below the top of casing. Using a barometric pressure sensor with vented cable allows for a more precise, corrected measurement of probe depth. However, it should be noted that slight changes of barometric pressure during this experiment would have little effect on the depth of fractures. Pressure readings are dependent on the density and temperature of the water column. Though these changes are typically orders of magnitude smaller than what was recorded, this may be of concern in deep undeveloped wells, saline wells or heavily contaminated wells.

Temperature

The temperature sensor is a platinum resistance thermometer. It can be used to indicate thermal pollution and/or to compensate conductivity measurements for temperature changes. The sensor offers a range of -5°C to 50°C, an accuracy of +/-0.1°C and a resolution of 0.01°C.

pH

The pH electrode uses a potentiometric method to measure the hydrogen ion activity in the solution. The values are temperature-compensated automatically. The sensor is equipped with a glass sensing bulb with Ag/AgCl reference half cell, double junction, reference electrolyte gel providing a range of 0-12 pH units, a pressure range from 0-807 ft, an accuracy of +/- 0.09, and a resolution of 0.01.

ORP

This sensor uses a potentiometric method and is equipped with a platinum wire and Ag/AgCl reference half cell, double junction, reference electrolyte gel providing a range of +/- 1400mV; a pressure rating of 807 ft, an accuracy equal to +/- 4mV and a resolution of 1 mV.

Conductivity

Conductivity was measured in μS/cm without temperature compensation. Though conductivity is dependent on temperature, the minor changes anticipated in temperature values does not appear to significantly affect the large offsets in conductivity indicative of fractures. (A 1° C change in temperature can cause a 2% change in conductivity or roughly up to 35 μS/cm across the entire range of temperatures encountered). Similar to depths dependent on barometric pressure, conductivity can easily be compensated for temperature values on a spreadsheet. The sensor uses a 4-cell conductivity ac drive with a range of 3-50,000 μS/cm and a pressure range to 807 ft. The accuracy of the sensor is the greater of 0.5% or 2 μS/cm when calibrated in range of interest.

Dissolved Oxygen

The D.O. meter is a Clark-type polargraphic sensor that consists of two electrodes in an electrolyte separated from the measured water by a 0.05mm polymeric membrane. Dissolved gases diffuse through the membrane into the electrolyte that provides a potential causing a chemical reaction. Oxygen is reduced at the cathode and silver is oxidized at the anode. The resultant current is proportional to the oxygen crossing the membrane giving the partial pressure of dissolved oxygen. The sensor can be calibrated in water-saturated air or in air-saturated water using a small aquarium pump ensuring that the temperature probe is submerged and that no air bubbles contact the membrane. The latter is preferred for this experiment. The D.O. sensor values are automatically compensated for temperature and pressures changes. Since these experiments were conducted, In Situ, Inc. has introduced an option for an "RDO" sensor that should be considered for these experiments. Time required for stabilization is dependent on membrane thickness (1-mil requires 1-2 minutes and 2-mil requires 1.5 to 3 minutes). The sensor has a range of 0 to 20 mg/L, a pressure range to 807 ft, an accuracy of +/- 0.2 mg/L and a resolution of 0.01 mg/L.

Calibration of the pH, DO, ORP and conductivity sensors was achieved using In Situ Inc.'s Quick Cal Solution. The Quick Cal solution offers an expedient one-point field calibration for all four parameters. Although only a one-point calibration method was used, it is important to note that for this specific experiment absolute values are not a concern. However, to validate the utility of the solution, pH, DO and conductivity were calibrated in the laboratory with traditional two and three point methods with similar results. In addition, the MP Troll 9000 sensors were compared to different meters that also provided similar results.

Borehole Logging

Geophysical methods were used to both validate the location of fractures dominating flow as determined by the MP Troll 9000 and to further characterize the wells for further research. The choice of geophysical methods employed was based largely on the recent investigation of the UConn landfill conducted by the U.S. Geological Survey (Johnson, 2002). Conventional logging was used to determine rock properties and infer the locations of fractures demarcated by variations in the rock or fluid properties. A brief description of the conventional logging used in this investigation follows:

> Caliper logging utilizes a three-arm, spring-loaded caliper to measure the diameter of the borehole with respect to depth. Fractures are inferred where an increased borehole diameter is located.
>
> Gamma logging detects variations in natural radioactivity originating from changes in concentrations of the trace elements uranium, thorium and the major rock-forming element, potassium[40]. Since the concentrations of these naturally occurring elements vary between different types of rock, natural gamma-ray logging provides an important tool for lithologic mapping, stratigraphic correlation and the detection of alteration zones.
>
> Fluid-temperature logging is used to identify the locations where water enters or exits the borehole. In the absence of fluid flow and sources or sinks of heat, the temperature of the fluid within the borehole tends to change gradually based on the geothermal gradient. Any deviations from this anticipated gradient indicate potential zones of transmissivity.
>
> Fluid-resistivity logging measures the apparent or general resistivity of the fluid within the borehole and is the inverse of the specific conductance typically measured in overburden investigations and measured by the MP Troll 9000. Fluid resistivity is an indirect measurement of the total dissolved solids present in the fluid within the borehole. Differences in resistivity with respect to depth indicate sources of groundwater derived from different transmissive zones.

Advanced geophysical methods were used to define the lithology at depth, to determine both the location and orientation of fabric and fractures associated with the bedrock, and finally to determine borehole flow between fractures and/or transmissive zones. A brief description of the advanced logging used in this investigation follows:

> Optical-televiewer logging (OTV) uses a 360-degree lens to record an oriented, optical image of the borehole wall permitting direct observation of bedrock features. As such, it is most useful when such features exhibit a high optical contrast and borehole fluid exhibits low turbidity.
>
> Acoustic-televiewer logging (ATV) records reflected waves generated by a rotating, high frequency acoustic beam to produce an oriented image of the borehole wall. Lithologic features are inferred from variations of the acoustical properties of the bedrock.
>
> Heat-pulse flow meter (HPFM) logging records time required for a heat-pulse tracer to move a predetermined distance via advection providing both rates and directions of vertical flow within the borehole. Unlike the ATV and OTV logs, measurements are obtained at discrete locations between fractures or fracture sets. The ATV, OTV and caliper logs may be viewed simultaneously to judiciously choose fixed-depth stations. Measurements are recorded under both ambient and stressed conditions. Subsequently, well bore transmissivity can be apportioned to individual fractures or fracture zones using the subtraction of inflows method described by F.L. Paillet and P.A. Stamile (U.S. Geological Survey, written commun., 1999) and flow profiles measured during ambient and steady-state pumping.

The borehole logging was conducted June 23-24, 2003 and the HPFM tests were conducted September 9-11, 2003. SIMA 1 was stressed using a submersible pump set 33-feet below top of casing and the flow tests were conducted at rates of 0.25, 0.5 and 0.8-gallons per minute. The pump was also set 30-feet below top of casing in SIMA 2 and flow tests were conducted at rates of 0.25, 0.5 and 0.7-gallons per minute.

On October 3-5, 2003, water quality profiles were obtained using the MP Troll 9000 while stressing the well at approximate pumping rates of 0.25, 0.5 and 0.75-gallons per minute. For these tests a submersible pump was set 33-ft below the top of casing in both SIMA 1 and 2.

Results

Anomalies revealed by plotting five chemical parameters as a function of depth provide evidence of the depths of fractures and/or fracture zones that control groundwater flow within the well bore. There are strong anomalies at depths of 36-, 50-, 130- and 300-feet below top of casing in SIMA 1 and less pronounced anomalies at depths ranging between 210- to 230-feet below top of casing. There are strong anomalies at depths of 38- and 250-feet below top of casing in SIMA 2 and less pronounced anomalies at depths of 82-, 150-, and 298-feet below top of casing. Profiles created with data collected during the June 9 - 11, 2003 tests of SIMA 1 and SIMA 2 are provided as **Figures 2** and **3**, respectively.

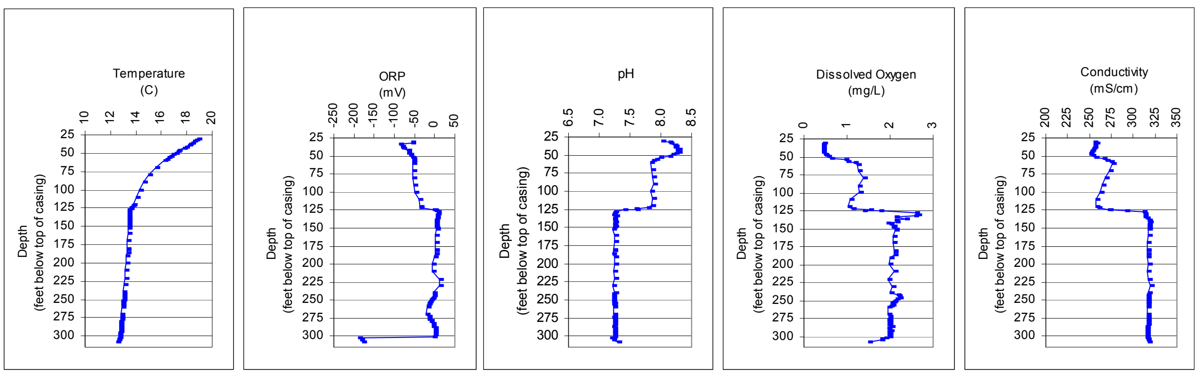

Figure 2. Water quality profiles for MP Troll 9000 tests conducted in SIMA 1.

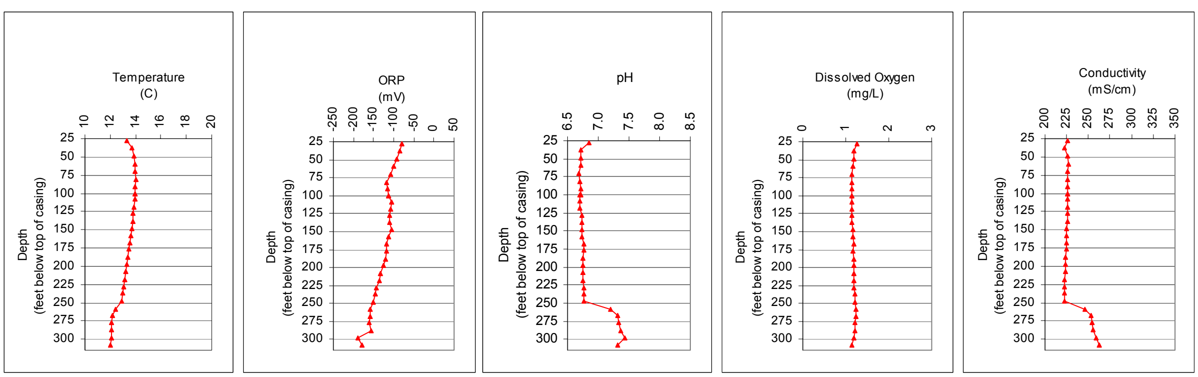

Figure 3. Water quality profiles for MP Troll 9000 tests conducted in SIMA 2.

There is evidence of sensor contamination when the tests were conducted while pumping, resulting in inaccurate readings. Though this methodology does not rely on the accuracy of absolute measurements rather only a relative change from one station to the next, inaccurate readings for the majority of the sensors did not return to range while profiling. As such, any potential anomalies that may have been presented at higher elevations would be masked by the inaccurate results. Following these suspect profiling experiments, the MP Troll 9000 was again tested in the laboratory. Though calibration was achieved while in the laboratory, inaccurate spikes during deployment did not always return to within normal range, thus negating even relative data.

The depths of fractures located with the MP Troll 9000 were corroborated by the advanced geophysical methods employed. Within SIMA 1, the depths determined with the MP Troll 9000 (36-, 50-, 130-, and 300-ft. below the top of casing) were evident as fractures and/or fracture sets 36-, 52-, a large subvertical fracture centered about 129.5-, and 304-feet below top of casing. Within SIMA 2, the depths determined with the MP Troll 9000 (38- and 250- ft. below the top of casing) were evident as fractures and/or fracture sets at (35-, 39-, 41-) and 248-feet below top of casing.

Evidence of the slight chemical changes exhibited between 210- and 230-feet below the top of casing in SIMA 1 was not exhibited in the geophysical logs. However, water quality changes at depths of 82-, 150- and 298-feet below the top of casing in SIMA 2 appear to be the result of fractures located at depths of (83- and 91-); (146- and 150-); and what appears to be a higher frequency of minor fractures, the largest of which occur at 292- and 294-feet below the top of casing. The latter may be an alteration zone presenting a relatively high gamma count with relatively little pegmatite. Those fractures associated with abrupt changes in water quality are clearly evident in the OTV, ATV, and caliper logs. Select images of the SIMA 1 and SIMA 2 are provided as **Figures 4** and **5**, respectively.

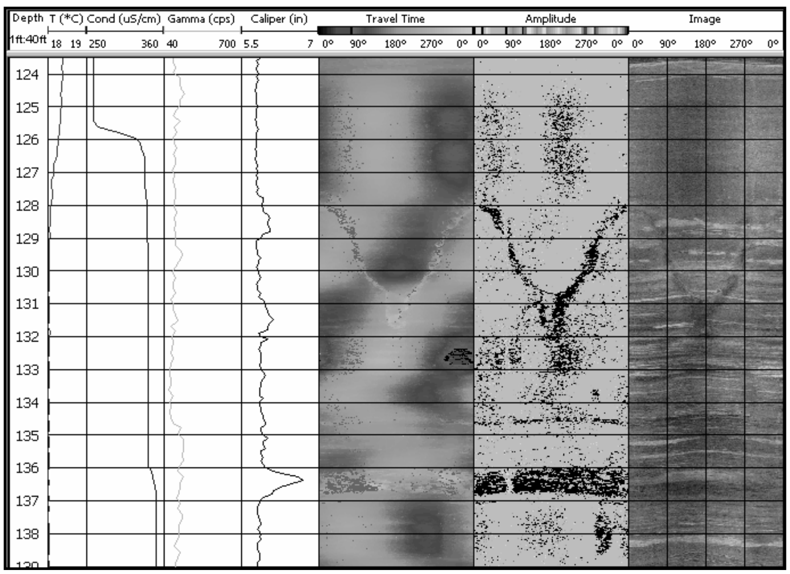

Figure 4. Geophysical logs of fracture located 130-feet below the top of casing in SIMA 1.

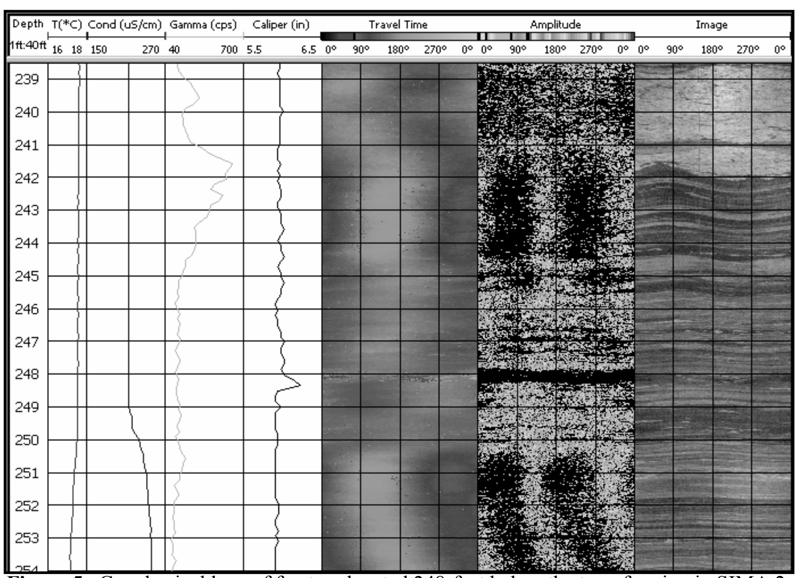

Figure 5. Geophysical logs of fracture located 248-feet below the top of casing in SIMA 2.

In addition to validating the evidence of transmissive fractures revealed in chemical profiles, the image logs provide a means to calculate the strike and dip of both fractures and foliation. The strikes and dips of fractures exhibiting evidence of transmissivity including aperture, staining, a strong acoustic signal, and/or caliper fluctuation were calculated. In this manner, fourteen fractures from SIMA 1 and eleven fractures from SIMA 2 were selected as potential transmissive zones. The majority of fractures as well as the foliation of the bedrock exhibit a shallow to moderate dip to the north-northwest. The orientation of fractures and foliation within SIMA 1 and SIMA 2 is provided as **Figure 6**.

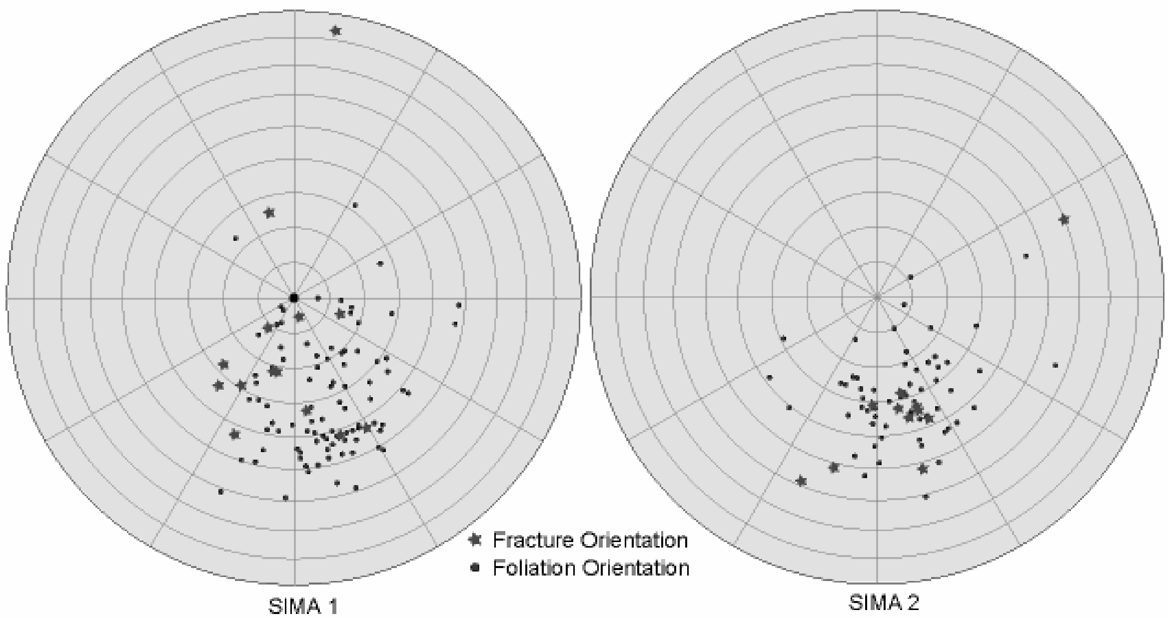

Figure 6. Polar, equal area, southern hemisphere stereographic projections of poles to fracture and foliation planes exhibited in the optical televiewer images of SIMA 1 and SIMA 2.

With the exception of the large subvertical fracture that intersects SIMA 1 at a depth of 130-feet below top of casing, fracture orientation mimics that of foliation. The subvertical fracture presents itself as a south-dipping brittle fault and is clearly evident in the water quality profiles. Though orientation does not vary much, foliation appears to dip less with depth. Though not particularly obvious, close inspection of fractures and lithology apparent in OTV images indicates a possible correlation of features between boreholes. A sequence of light-gray, massive, medium-grained felsic gneiss 56- to 57-feet below the top of casing in SIMA 1 may be the same feature present in SIMA 2 at a depth of 61- to 62-feet below the top of casing. A set of fractures 51- to 53-feet below the top of casing in SIMA 1 may continue to SIMA 2 at depths of 54- and 56-feet below the top of casing. SIMA 2 exhibits substantially more felsic rock with more frequent intrusions of pegmatite.

Five transmissive zones were identified in each of the bedrock wells following the HPFM logging. Transmissivity was apportioned to individual zones by interpretation of flowmeter data using the subtraction of inflow method (Paillet, 2000). Though flow was recorded in the immediate vicinity of the subvertical fracture within SIMA 1 under ambient conditions, neither the magnitude nor the direction of flow could be duplicated. Therefore these measurements were considered scatter and no flow was recorded under ambient conditions. The most transmissive fractures while pumping SIMA 1 at 0.8 gpm are located at depths of 85-, a fracture set 130 to 135-, and 281.6-feet below the top of casing. The transmissive fracture located at a depth of 85-ft in SIMA 1 may have similar water quality as the fracture zone below it and as such is masked during profiling. A sum of recorded flows accounts for 80% of the discharge rate. Under ambient conditions, SIMA 2 exhibited slight inflow (0.08 gpm) 34-feet below the top of casing and outflow 40-feet below the top of casing. The most transmissive fractures while pumping SIMA 2 at 0.7 gpm are located at depths of 34- and 248-feet below the top of casing. A sum of recorded flows accounts for 76% of the discharge rate.

Summary

Flow through fractured media can be complex, especially so in Connecticut, where the protolith strata of both metamorphic and sedimentary rocks exhibit many fractures but relatively few that significantly contribute to and/or control the flow within a well. Adequate solutions to determining flow in bedrock wells require options dictated by the scopes of individual projects. The costs, training, and impressive resolution associated with this method suggest great promise for its use prior to, in addition to, or possibly in lieu of the USGS "toolbox" approach.

- The MP Troll 9000 was capable of quickly and easily determining the location of the most transmissive fractures under ambient conditions. The acquisition and analysis of data is real-time, with

- Because the MP Troll 9000 measures water quality parameters, it has the additional advantage of being able to potentially detect which fractures are contributing contamination to a well and/or to track the advective transport of remedial measures.

- Individual sensors may be adversely affected when placed in the immediate vicinity of producing fractures while stressing a well. Further research is currently being conducted to determine parameter sensitivity to pumping rates.

- Further research is currently being conducted to evaluate the tool's use as an effective flow meter by augmenting the probe with an innocuous tracer.

References

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Biographical Sketches

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