Report for 2001CT741B: A Tracer Dilution Method for Deriving Fracture Properties in Crystalline Bedrock Wells

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Report Follows:

Title: A Tracer Dilution Method for Deriving Fracture Properties in Crystalline Bedrock Wells.

Statement of Critical Regional or State Water Problem:

Most rural domestic wells in New England derive their water from fractured crystalline rocks. Unfortunately, our knowledge of the hydraulic characteristics of subsurface, water-bearing fractures is sparse. Such information is critical in evaluating ground water supplies, in conducting wellhead protection, and in preventing and remediating ground water contamination in crystalline rock. In recent years, the U.S. Geological Survey (USGS) has developed cutting edge techniques to perform downhole fracture testing. These techniques, however, may be cost prohibitive to be applied on a large scale. This research is aimed at developing more cost-effective methods for conducting downhole fracture characterization. As such, it should aid the rural community and state and local environmental regulators in assessing the availability of ground water and the source and transport of contamination in fractured crystalline rock.

Statement of Results or Benefits:

The goal of this research is to develop a cost effective, technically sound method for conducting downhole fracture characterization using tracers. The research is focused on developing a unifying method that can identify water bearing fractures that intersect a well, that can provide information on the interconnectiveness of fractures in relation to a well (recharging and discharging fractures), that can be used to determine the transmissivity of fractures, used to determine the hydraulic head in fractures, and that can quantify fracture water quality (including contamination). Uniquely, we have an opportunity to compare our tracer results with those of the U.S. Geological Survey, derived using their integrated downhole geophysical and hydraulic packer test methods. If brought to fruition, the tracer test method may make downhole testing more practical. As such, it can help in assessing the availability of ground water in fractured crystalline rock and in protecting the ground water resource.

Nature, Scope and Objectives of the Research:

Most rural domestic wells in New England derive their water from fractured crystalline rocks. Unfortunately, our knowledge of the hydraulic characteristics of subsurface, water-bearing fractures is sparse. As such, drilling productive domestic wells in crystalline rock is a hit or miss proposition that could result in consumers laying out thousands of dollars for a “dry hole”. This lack of information also prohibits performing, in any quantitative fashion, ground water resource estimates that can be used in guiding developers or land use planners. A lack of information also inhibits applying the concepts of wellhead protection to municipal wells founded in rock. Importantly, when bedrock wells are impacted by contamination, the absence of fracture information complicates evaluating contaminant sources, and means to remediate these problems.

Over the last several years, the USGS has conducted geophysical and hydrologic research aimed at developing techniques to characterize fracture hydrology as part of their *Toxic Substances Hydrology Program*. This research has shown that that superficial investigations of ground water conditions in bedrock wells (that basically entail water level measurements and well sampling) can be highly misleading owing the nature of fracture flow. Their research has shown that fracture rock assessments requires detailed characterization. In that light, they have developed “tool boxes” of techniques that can be applied in characterizing fracture hydraulics and water quality. A detailed borehole investigation might entail the use of the following tools: a downhole television camera that provides a 360 degree digital image of the borehole wall for defining rock characteristics and location of fractures, an acoustic televiewer that provides magnetically oriented borehole wall images for determining fracture dip and strike, and a high resolution flowmeter for discerning water bearing fractures and identifying inflowing and outflowing fractures under both pumping and static conditions. These logging techniques would then be followed by packer testing to determine the hydraulic head in individual fracture zones, to conduct hydraulic testing for fracture transmissivity, and to collect water quality samples. Although the information derived by applying the USGS methods is comprehensive and definitive, it is also costly. The costs and the timeframe associated with the approach can inhibit its practicality.

The objective of this proposal is to develop a tracer technique to derive fracture information downhole, as a cost-effective compliment to the USGS "tool box" methods.

Methods, Procedures and Facilities:

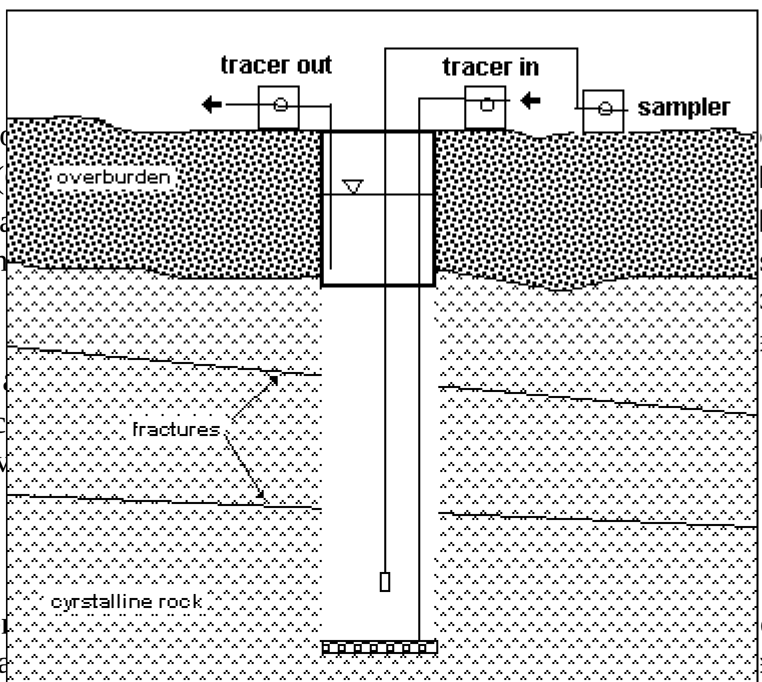
The research will be divided into three tasks:

Task 1 Literature Review

A literature review will be conducted to summarize past research on the use of chemical tracers downhole in crystalline fractured rock. The review will derive an annotated bibliography of methods, procedures and results. Also, it will aid in developing our test technique in task 2.

Task 2. Field Tracer Test

The USGS Branch of Geophysical Applications and Support is located on the University of Connecticut's, Mansfield Depot Campus. The Mansfield Campus is underlain by crystalline metamorphic bedrock. The USGS drilled three 6'' diameter bedrock wells, ranging in depth between 223 and 443 ft., on the Campus. These wells will be used to test the tracer method. A conceptual model of the tracer method is shown on Figure 1.



The method c... xic tracer will be pumped at a constant rate (... ll be pumped out the top of the well but at a r... low into the well from fractures. The tracer con... stant. Then the tracer concentration ... dure will then be repeated at different flow ... and recharge rate (Q_I) of fractures. As ... The concentration of tracer below the frac... was contributing flow to the well, just abov...

Equation 1 pe... e well would permit determining the fracture tr... .g., in Hvorslev (1951). To be more rigorous we propose to determine the recharge rate and the hydraulic head in the well at three different pumping rates. By continuing to sampling up the well, one can determine the recharge rates of each inflowing fracture using equation 2.

(2) $$C_i = C_{in} * Q_{in} / (Q_{in} + Q_1 + Q_2 \ldots Qi)$$

Again, given the recharge rates and the head in the well, the transmissivity of fractures can be calculated.

To be successful in identifying outflowing fractures that intersect a well, the head in the well must be lowered below that of the lowest head of any outflowing fracture. Under static conditions, the head in the well represents a weighted average head with respect to inflowing and outflowing fractures and their transmissivities, as shown in equation 3

$$(3) \qquad h_w = \Sigma(h_i * T_i) \Sigma/(T_i)$$

where h_w = hydraulic head in the well, h_i = hydraulic head in fracture i, and T_i is the transmissivity of fracture i. By monitoring the tracer concentration profile at different flow rates, one can determine when a fracture is converted from outflowing to inflowing. This approach also permits determining the hydraulic head in fractures. By pumping tracer in at the top of the well and out at the bottom at a rate that causes the head in the well to rise, one can determine the head in the inflowing fractures through tracer profiling.

A number of details are still to be worked out. For example, what should the optimum flow rates be for pumping and sampling, how should the tracer be delivered at the bottom of the well, how should the tracer be sampled so as not to disturb the vertical tracer profile, and what water treatments are needed following experiments.

Presently, we are considering the use of a dual tracer approach using bromide for field measurement and rhodamine for laboratory measurement. The bromide would be measured in the field using ion specific electrodes. The analytical sensitivity for rhodamine is several orders of magnitude, which would permit identifying fractures having several orders of magnitude difference in transmissivity. We have available to us in our Department or on campus all the field and analytical equipment to perform this research including water level sounders, peristaltic pumps, ion specific electrodes and meters and a florescence spectrometer. Additionally, we have access through cooperative efforts with QED Environmental Incorporated, to downhole sampling pumps if needed.

Task 3 Comparison to USGS Methods

The tracer tests will be performed without knowledge of any fracture information about the wells. Our results will then be compared to downhole tests performed by the USGS using the methods cited above. This will provide a unique opportunity to evaluate the tracer test results with those derived by the USGS methods.

If successful, this research would put us in a position to seek NSF, EPA or private sector funding to conduct a joint study with the USGS on the use of the tracer method at contamination sites. Here, we could conduct comparative testing as well as evaluate the use of the method for discerning which fracture may be contaminated.

Related Research

The use of tracers has long been used to characterize hydraulic properties in fractured rock. Methods that have been used include conventional well-pumping tests, tracer travel time between wells, and tracer dilution (Lewis et al., 1966). Various tracer dilution tests have been conducted by Raymond and Bierschenk (1957), Moser et al. (1957), Nuemaier (1960), Ochiachi and Rodriguez (1962) Michalski and Klepp (1990), Tsang (1990) and the United States Geologic Survey, to name a few. Although there are similarities in some of these methods with the method we are proposing, there are substantial differences. Most of the previous methods involve injecting a slug of tracer into the borehole, mixing the borehole fluids to achieve a homogeneous state, and then measuring tracer dispersion throughout the well depth. Certain methods also included the use of packers to isolate a specific fracture. The proposed research will involve active pumping of a specific concentration of tracer into and out of the borehole. This greatly simplifies interpreting the tracer data. A brief summary of previous tracer research follows.

Raymond and Beirschenk used hydraulic conductivity logging in 1957, as a means to determine the velocity of ground water passing through a well. Salt solutions were added to the well and then allowed to mix. Conductivity measurements were taken, using two probes, every five minutes, for a certain time period at a specific depth (Lewis et al, 1966).

Moser et al., as well as several others, (Lewis et al., 1966) has implemented the use of radioactive isotopes. The isotopes were introduced to the well. The radioactive activity was monitored for a period from a few hours to a day. The hydraulic conductivity was then computed from the data. The hydraulic conductivity computed was very close to that derived from pumping tests (Lewis et al., 1966).

Ochiachi and Rodriguez refined the radioactive isotope method in 1962 (Lewis et al, 1966). They designed the flow meter such that their model not only determined ground water velocity but also direction of flow.

In 1990, Michalski and Klepp reported on the use of a single well tracer study to compute the transmissivity of fractures intersected by the well (Mickalski and Klepp, 1990). A slug of deionized sodium chloride water was introduced to the well. The solution was introduced to what is considered "upstream", dependent on vertical flow direction. The volume of slug injected was kept to below one well diameter to reduce any hydraulic head or flow change. An electric conductivity probe was lowered into the well and used to measure electric conductivity throughout the depth of the well. From the tracer profiles, not only could intrawell flow and transmissivity of fractures be characterized, but also incoming water quality could be determined.

Tsang, Hufschmied and Hale (1990) also used an electric conductivity method to estimate the transmissivities of intersected fractures within a single well. The water in the well was first replaced with deionized water. Then the well was pumped at a low flow rate. An electric conductivity probe was then lower through the well depth. This was performed a number of times and several conductivity logs were created. Using these logs the inflow characteristics of the fractures could be determined (Tsang et al, 1990).

Recently (1997) the United States Geological Survey as part of their *Toxic Substances Hydrology Program* (USGS, 2000), has also used tracer dispersion methods to determine water predicting and water receiving zones in the Newark basin area in Pennsylvania. (Sloto, 1997) This was a dual method test, using both a brine-tracing method and a heat-pulse flowmeter. 93 boreholes were logged, 83 using the brine-method and 10 using the flowmeter. A slug of high conductivity fluid was injected into the 83 boreholes and vertical movement was tracked using a fluid resistivity tool under nonpumping conditions. By correlating caliper logs with the fluid resistance and fluid temperature logs, it was possible to determine water receiving and water producing fractures (Sloto, 1997).

Similar methods were also used by the USGS in 1997, for the Lockatong and Brunswick Formations in Montgomery County, Pennsylvania. By correlating caliper, natural gamma, fluid-resistivity and fluid-temperature, fluid-movement (brine-tracing or heat-pulse flowmeter), and borehole video logs it was possible to determine water producing fractures (Senior and Conger, 1997).

In 1997 and 1998 the USGS used similar methods at a Superfund site in Chester County, Pennsylvania to determine horizontal and vertical distribution of contaminated water moving from the source area. Fluid temperature and resistivity logs were used to determine water producing and water receiving fractures. Slug tests were then used to determine the transmissivity of those fractures (Conger et al., 1999).

All of this research is similar to the proposed research in that tracer dilution methods were used to measure certain hydraulic properties (i.e. receiving vs. producing fractures, flow direction within those fractures and the fracture transmissivity.) The number of hydraulic properties was limited to about two parameters in each case. Our proposed research characterizes at least four hydraulic properties during one testing period. In addition, the proposed research will be compared to results computed by the United States Geological Survey using downhole tools and packer tests to characterize fractures. This will permit a rigorous evaluation of the accuracy of the tracer method.

Principal Findings and Significance

The results of this study are described in the masters thesis, "A Stepwise Discharge Tracer Dilution Method for Deriving Fracture Properties in Crystalline Bedrock Wells," Richard J. Brainerd, Dept. Geology and Geophysics, University of Connecticut, 2002. The major conclusions of this study include:

* The ability to characterize the flow properties of transmissive fractures in bedrock aquifers is of the utmost importance, not only for water supply but also contamination transport. Throughout the years, many methods have been used to try to gain knowledge of these flow properties. These methods include various geophysical, borehole logging, conventional hydraulic test and tracer test techniques.

* This research evaluated a tracer method to characterize the flow properties of water-conducting fractures intersecting a borehole in fractured crystalline bedrock. This method allows the determination of the fracture hydraulic head directly. Thus, the calculated transmissivity, which is directly related to the effective drawdown of the fracture, is not subject to ambiguities associated with the assumption of a uniform aquifer head.

* Fracture hydraulic head and ambient flow are determined graphically, thus avoiding the use of any of the multiple equations for flow which all require, in some way or another, assumptions to be made. As is known, these assumptions were developed for unconsolidated material and are often invalid when describing fracture flow.

* The tracer dilution test method was able to characterize two fractured bedrock wells. One fracture was identified and characterized in BGAS-3, while four fractures were identified in BGAS-1. Only tow of the fractures in BGAS-1 could be completely characterized.

* The three wells are hydraulically, very connected by a highly transmissive fracture. This is seen in the imeediate response in the observation wells to a change in the water level in the pumping well.

* Several recommendations to improve the developed method are given. These include: lowering the injection rate and concentration, using more accurate flowmeters, and using a different criteria for identifying the presence of a fracture.

* Tracer tests are a valuable tool in helping to characterize flow conditions in fractured bedrock aquifers. They can be used as a preliminary screening tool or as a stand-alone method.

* In recent years great strides have been made in our ability to decipher the subsurface but we have far to go to. It is only with the integration of many such techniques that the pieces of the puzzle of teh subsurface fracture networks will become clear.

* The unknown aspects of fracture interconnectivity will continue to test the ability to put those pieces of the puzzle together. It is for that reason that the ability to describe the interconnectivity of fractures and how that interconnectivity effects flow properties could be one of the most important areas that further research needs to concentrate on.

Citations:

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