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Enhanced detection of hydraulically active fractures by temperature profiling in lined heated bedrock boreholes

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SUMMARY

The effectiveness of borehole profiling using a temperature probe for identifying hydraulically active fractures in rock has improved due to the combination of two advances: improved temperature sensors, with resolution on the order of 0.001 °C, and temperature profiling within water inflated flexible impermeable liners used to temporarily seal boreholes from hydraulic cross-connection. The open-hole cross-connection effects dissipate after inflation, so that both the groundwater flow regime and the temperature distribution return to the ambient (background) condition. This paper introduces a third advancement: the use of an electrical heating cable that quickly increases the temperature of the entire static water column within the lined hole and thus places the entire borehole and its immediate vicinity into thermal disequilibrium with the broader rock mass. After heating for 4–6 h, profiling is conducted several times over a 24 h period as the temperature returns to background conditions. This procedure, referred to as the Active Line Source (ALS) method, offers two key improvements over prior methods. First, there is no depth limit for detection of fractures with flow. Second, both identification and qualitative comparison of evidence for ambient groundwater flow in fractures is improved throughout the entire test interval. The benefits of the ALS method are demonstrated by comparing results from two boreholes tested to depths of 90 and 120 m in a dolostone aquifer used for municipal water supply and in which most groundwater flow occurs in fractures. Temperature logging in the lined holes shows many fractures in the heterothermic zone both with and without heating, but only the ALS method shows many hydraulically active fractures in the deeper homothermic portion of the hole. The identification of discrete groundwater flow at many depths is supported by additional evidence concerning fracture occurrence, including continuous core visual inspection, acoustic televiewer logs, and tests for hydraulic conductivity using straddle packers as well as rock core VOC data, where available, that show deep penetration and many migration pathways. Confidence in the use of temperature profiles and the conceptual model is provided by numerical simulation and the demonstrated reproducibility of the evolution of the temperature signal measured in the lined holes with and without heating. This approach for using temperature profiling in lined holes with heating is a practical advance in fractured rock hydrogeology because the liners are readily available, the equipment needed for heating is low cost and rugged, and the time needed to obtain the profiles is not excessive for most projects.

1. Introduction

Most or essentially all groundwater flow in rock formations occurs in fractures. To gain insight into how contaminants behave in these environments, and to enable more accurate predictions of their arrival times at receptors, better characterization of groundwater flow in fracture networks is needed (e.g., Berkowitz, 2002; NRC, 1996; Sara, 2003). Many numerical models have been developed for simulating flow and contaminant transport in discrete fracture networks in rock (FRAC3DVS, Therrien and Sudicky, 1996; FEFLOW, DHI-WASY, 2009; HEATFLOW, Molson and Frind, 2012); however, advances in the acquisition of field data for fracture parameterization for such models has lagged far behind advances in numerical codes. Data acquisition from boreholes is the primary approach to contaminated bedrock site characterization

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and many methods are used to identify fractures, including inspection of continuous core, borehole imaging (e.g., acoustic and optical televiewing), caliper logging, and hydraulic tests such as borehole fluid conductivity alteration (Tsang et al., 1990), flow meters (Paillet, 2000), straddle packers (e.g., Quinn et al., 2011) and flexible liner profiling (Keller et al., submitted for publication). However, these methods cannot distinguish fractures with and without active groundwater flow under ambient conditions. In this paper and in the context of active groundwater flow, the term 'fracture' refers to any secondary permeability feature in the rock mass that acts as a preferential flow path relative to the low-permeability rock matrix, and thus includes bedding parallel fractures, joints, styolites, isolation channels, and any other geologic features with enhanced flow. There is an abundance of literature concerning the identification of zones with flow in open boreholes with cross-connected flow, or under forced gradient conditions that are created when the hole being investigated is pumped and monitored or when one hole is pumped and responding holes are monitored. However, this paper concerns the identification of fractures that have active, ambient groundwater flow or, in other words, flow in the rock uninfluenced by the borehole and not imposed by pumping or injection for the purposes of fracture identification.

Temperature profiles measured in open boreholes in rock offer insights about fractures with flow (e.g., Bidaux and Drogue, 1993; Robinson et al., 1993; Trainer, 1968). However, temperature has generally seen only minimal use in fractured rock investigations at contaminated sites. Two recent advances provide the impetus for temperature profiling to become much more important. The first is the greatly improved sensor resolution for temperature measurement (on the order of 0.001 °C). The second concerns measurement of temperature profiles in holes sealed using impermeable flexible liners produced by FLUTe (http://www.flut.com) to prevent cross flow between fractures (i.e., hydraulic cross-connection). Using these two advances, Pehme et al. (2010) identified numerous fractures that were under ambient hydraulic flow conditions in boreholes in dolostone and sandstone. The number of fractures identified by this method was much larger than the few identified when the holes were unsealed (i.e., open-hole conditions). Identification of all fractures in which active groundwater flow occurs is important for contaminated site investigations because the nature of contaminant plumes is very different between dense and sparse networks (Parker, 2007).

Keller et al. (submitted for publication) describe the impermeable, flexible FLUTe liners and their installation in rock boreholes. Sealing boreholes using these liners is becoming common in contaminated site investigations to prevent cross-contamination caused by flow into and out of the hole from fractures at different depths (Sterling et al., 2005). Although vertical cross-connection in fractured rock holes has been recognized for decades and capitalized upon for investigations in fractured rock, Pehme et al. (2010) show that the open-hole conditions have been misleading with respect to identification of all hydraulically active fractures in the system; improved sensitivity for identifying more active fractures was achieved when boreholes were sealed and a sensitive temperature logging probe used. The impervious flexible liners are urethane coated nylon formed into cylindrical tubes that are temporarily installed in the hole, with inflation by water, prior to installation of a monitoring well or other hydraulic testing. As described by Pehme et al. (2010), the temperature distribution in the static water column inside the liner typically becomes stable several days after installation, at which time the hole is suitable for ambient temperature profiling to identify flow.

Although the use of high precision temperature probes in the static water columns of lined holes enables the identification of numerous hydraulically active fractures (Pehme et al., 2010), this approach has a depth limitation. Fractures are preferentially identified close to ground surface where groundwater flow transports heat perturbations from the surface imparted by the atmosphere (i.e., surface temperature variations due to weather) and urban infrastructure. These surface-imparted temperature disequilibria are attenuated at depth due to thermal conduction in the rock mass. The maximum depth to which this thermal disequilibrium can be used to identify fractures varies considerably depending on both geology (i.e., thickness and nature of overburden, degree of bedrock fracturing) and hydrogeologic conditions (i.e., degree of vertical and lateral flow, recharge versus discharge, etc.). However, there is commonly a need to identify active groundwater flow or contaminant migration at greater depths than the limits of thermal disequilibrium.

This paper describes a method aimed at eliminating the depth limitation for use of temperature profiling in lined holes to identify ambient flow through fractures. In this method, the static water column in the lined hole is heated continuously along the entire length of the hole to rapidly create strong thermal disequilibrium around the borehole. Temperature profiles are then measured as the heat in the water column dissipates. This method is referred to as the Active Line Source (ALS) method applied in lined boreholes. Greenhouse and Pehme (2002) introduced the ALS method to open (unlined) holes for fracture identification and Pehme et al. (2007) applied the ALS method to a lined hole to estimate thermal conductivity and drew attention to the possibility of identifying hydraulically active fractures using this technique. Freifeld et al. (2008) adopted a similar heating process with fiber optic sensing to estimate rock thermal conductivity and thereby paleocooling and Leaf et al. (2012) alter borehole temperature in an open hole by way of fluid exchange. This paper provides the first detailed field examples of ALS for fracture identification where many other methods were also used to acquire evidence of fractures, with the results compared against conventional lined-hole temperature logs to demonstrate the added insights from the ALS method concerning the occurrence of ambient flow in fractures.

The ALS method has been applied in more than 42 lined holes at eight different sites in North America, primarily in dolostone and sandstone. The field results presented in this paper are from two holes: MW-25 located in Guelph, Ontario and UW-1 located in Cambridge, Ontario. These two holes (both situated in a Silurian dolostone aquifer used for municipal water supplies) were selected as examples because the hydrogeologic characteristics of the regional aquifer have been described in detail by others. Perrin et al. (2011) describe the general nature of the secondary permeability, which includes fracture networks with solution channeling. Quinn et al. (2011) present results of hydraulic tests using straddle packers to measure hydraulic conductivity and estimate fracture apertures using the cubic law. Keller et al. (submitted for publication) describe a flexible liner method for measuring hydraulic conductivity profiles in a dolostone aquifer. Pehme et al. (2010) used UW-1 and MW-24, (which is located 490 m west of MW-25), in a study of fractures identified by temperature profiling in lined versus unlined holes without the added heat. MW-25 is the focus of this present study because the most comprehensive data sets using the ALS method in lined holes have been obtained from this hole. At 104 m deep, this hole penetrates through the full thickness of the dolostone aquifer into the underlying shale. The thermal and hydraulic conditions in this hole have less complexity than holes under the influence of municipal pumping wells. MW-25 has a distinct decrease in temperature from top to bottom without any of the temperature reversals observed in other holes in the region; this therefore avoids any complications due to the potential of thermal convection, where temperature increases with depth. UW-25 has no contaminants above drinking water limits; therefore, contaminant cross-connection is not a concern when this hole