Streaming Potential Responses during Constant Head Injection Tests in a Fractured Bedrock Aquifer

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Introduction

Fractured bedrock aquifers are the dominant water resource in rural Atlantic Canada and for a large percentage of Canadians and people worldwide. Understanding how fractures are distributed, and how they influence groundwater flow rates and directions are important for the production and sustainable development of bedrock aquifers and for the siting of wells relative to sources of groundwater contamination such as agricultural chemicals. Flow paths within fractured systems can however, be notoriously difficult to characterize using only the relatively crude information provider by driller's logs and pump tests, and there is recognition within the regional hydrogeological community that there would be great value in bringing more sophisticated and predictive tools into common use.

Recent experiments (e.g. Wishart et al., 2006) have suggested that azimuthal variations in electrical streaming potentials, measured at surface, can be used to infer the directions of ambient groundwater flow in the subsurface. In this paper, we present measurements of streaming potentials taken during hydraulic testing of a fractured rock aquifer. The injection of water into a borehole is shown to generate streaming potential anomalies that are oriented parallel to the strikes of two major sub-vertical populations of fractures identified by televiewer logging. Although the results of this study are preliminary, this study shows potential application of the streaming potential method to be used to identify groundwater flow orientations in other fractured bedrock systems.

Site Description and Methods

This study focused on the fractured bedrock aquifer beneath the Black Brook Watershed, near Saint-Andre (Grand Falls), New Brunswick. Geological conditions consist of roughly 3 meters of glacial till overlying fine-grained siliciclastic bedrock sediments of the Grog Brook Group. Field investigations involved measuring self potential responses on surface in the vicinity of a well during constant head injections of water into borehole intervals isolated with a pair of inflatable packers set 2.2 m apart. Data were collected using an array of 32 non-polarizing $Pb\text{-}PbCl^2$ electrodes arranged in a regular grid (6 meter spacing) and referenced to a remote electrode placed over 250 m away. Two additional electrodes were deployed ~ 20 m south and west of the reference electrode in order provide two "remote dipole" self potential measurements for monitoring of telluric fields. Electrodes were inserted in shallow holes augured to a depth of ~20 cm and seated in bentonite mud in order to promote uniform surface contact, lower contact resistance, and minimize temperature variations during the period of the investigation. Data were logged at 3 second intervals over the duration of the experiment using a Campbell Scientific AM32B multiplexer and CR1000 datalogger system with an input impedance of 20 GΩ. Digital non-linear and smoothing (15 second moving average) filters were applied to the data before analysis to remove intermittent high-amplitude spikes and high-frequency noise. Streaming potential distributions measured on the surface across the electrode array were analyzed and contoured for various time intervals (preceeding, during and following injection) and compared to fracture strike orientations obtained from borehole televiewer logs.

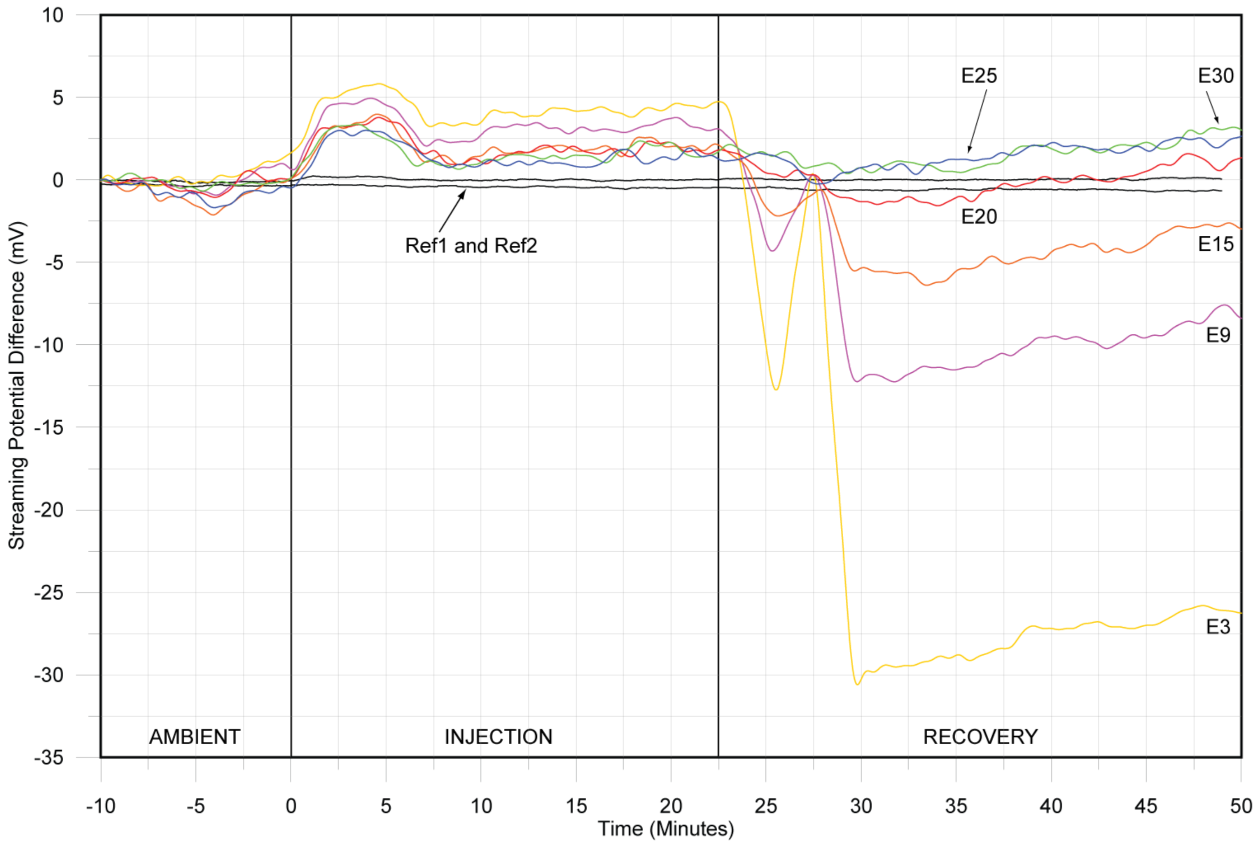

Figure 1: Changes in self potential observed by 6 different surface electrodes prior to, during, and following a constant head injection test at ~44.3 m depth. The selected electrodes show variations in response with respect to distance away from the injection well (colour-coded as in Figure 2). Note the lack of variation in the remote reference (telluric-monitoring) dipoles Ref 1 and Ref2.

Results

Figure 1 shows streaming potentials observed by six electrodes at distances of 5 to 41 m from the borehole collar during the injection of water into the borehole interval between 43.2 and 45.4 m depth. The borehole interval comprises 5 fracture planes with apparent apertures ranging between 3 – 7 mm, determined from borehole televiewer images (DesRoches and Butler, 2009a; 2009b). Constant head test results indicate a hydraulic conductivity of 7.1 x 10^{-6} m/s for the interval. Self potential responses during the ambient phase were monitored to obtain a base level response, an injection response and termination and recovery response. Fluid injection into the packer zone resulted in an increase in hydraulic pressure of 80 kPa which generated fluid flow through the fracture system near the well. The stimulated fluid flow resulted in a measureable change in streaming potential measured on the surface. Data from Figure 1 illustrates a change in streaming potential (~5 mV) associated with fluid injection and the electrode closest to the well shows a sharp drop in magnitude (-35 mV) following the termination of the injection phase and deflation of the packers. The magnitude difference associated with other electrodes placed further away from the well is greatly reduced. During the recovery phase the electrical response began to return towards pre-injection conditions, but recovery remained incomplete after 27 minutes, when the next injection was initiated. Changes in self potentials between the ambient and injection phases are greatest near the well, and along azimuths trending roughly 010^{o} and 065^{o} degrees away from the well. These plots show evidence of streaming potential anomalies that follow fracture orientations previously identified using borehole televiewer imaging tools (DesRoches and Butler, 2009a; 2009b), and suggest that the change in differential streaming potential measurements spatially relate to the increase in applied hydraulic pressure and fluid flow along the fracture system.

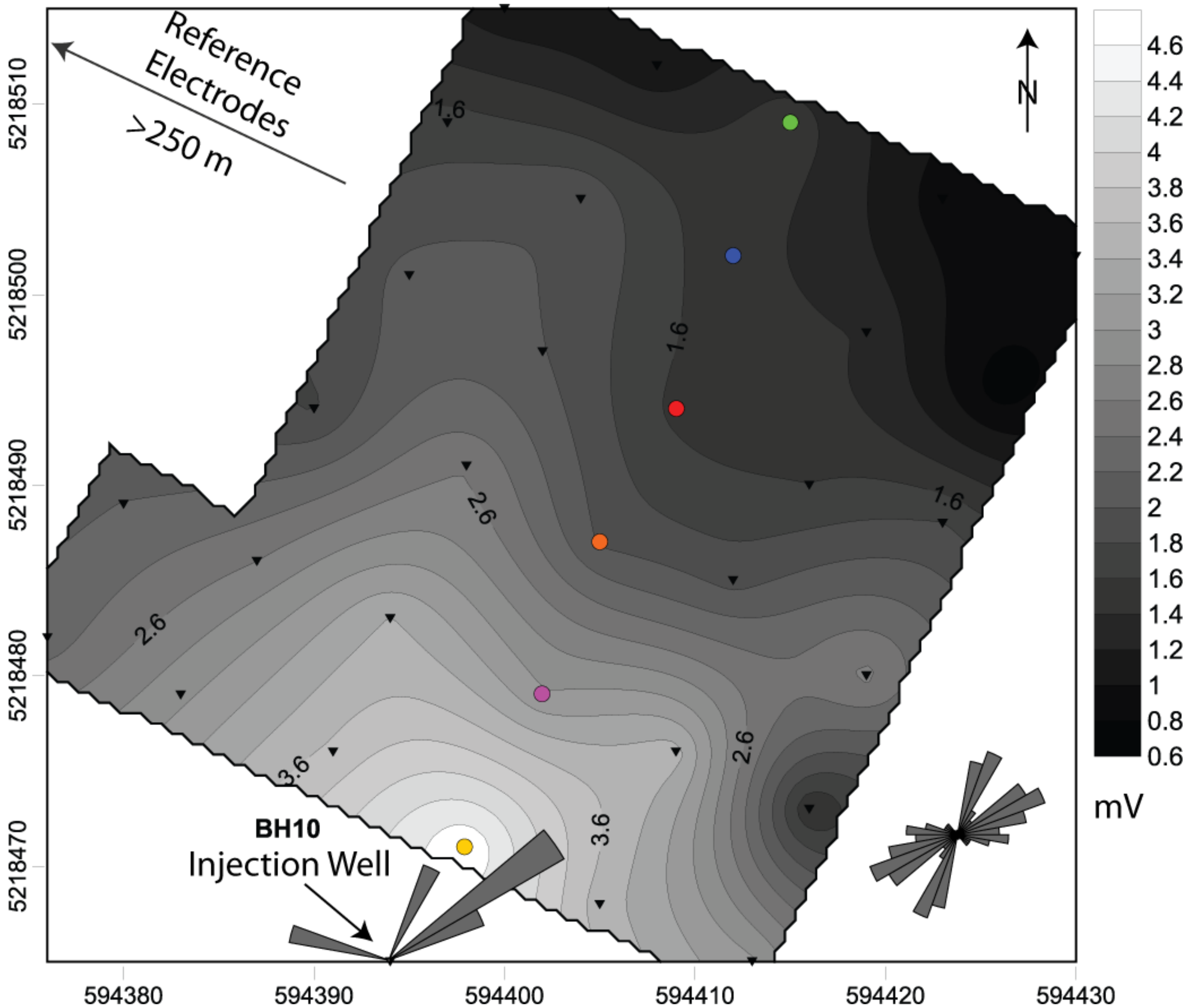

Figure 2: Contour map of the differences between the self potential responses measured during the end of the injection phase and those measured immediately prior to injection. Data were monitored using an array of 32 non-polarizing Pb-PbCl^2 electrodes (6 meter spacing) arranged in a regular grid covering an area of roughly 50 x 50 m on the north side of the well, and 2 pairs of reference electrode dipoles located greater than 250 m away to monitor telluric fields. The rose diagram located on the injection well shows the strike orientation of the 5 fracture planes that intersect the isolated injection interval. The rose diagram on the lower right corresponds to 132 fracture planes that intersect the entire length of the borehole. The coloured electrodes correspond to the locations of the electrode responses illustrated in Figure 1.

Conclusions

The field experiment has identified temporal changes in self potential responses recorded on the ground surface between ambient conditions (immediately before injection), and conditions related to water injection, and aquifer recovery. Time-lapse difference maps illustrate the spatial variability of the changes in streaming potential measurements over the study area, and were consistent with fracture orientations mapped from borehole televiewer logs within the borehole. Although the results of this study are preliminary, this study shows potential application of the streaming potential method to be used to identify groundwater flow orientations in other fractured bedrock systems.

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