INVESTIGATING WELL CONNECTIVITY USING IONIC TRACERS

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ABSTRACT

Fluid circulation in geothermal reservoirs is often impacted by an uneven sweep of water between injection and pumping wells. Poor sweep efficiency may lead to poor fluid circulation or, at the opposite extreme, flow short-circuiting and premature thermal breakthrough at an extraction well. Multiple ionic tracer tests have been proposed as one method by which reservoir conformance issues may be identified. Herein are reported the results of inter-well tracer tests conducted at the Altona Flatrock Fractured Bedrock experimental site during the Summer of 2011. Lithium was used as a reactive tracer and bromide the non-reactive tracer (verified with deuterium oxide). Separation between cation and anion tracers in the breakthrough was minimal except in cases where tracer was circulated between wells with poor hydraulic connection. Numerical modeling of the breakthrough curves indicates that the swept surface area to volume ratio was about 4 times greater between wells with poor hydraulic connection than between those with strong hydraulic connection. Ground penetrating radar images of saline fluid circulated between the same wells confirms that a weaker hydraulic connection results in a more extensive flow sweep of the fracture. This relationship is likely enhanced in fracture networks, suggesting that strong hydraulic connection among geothermal circulation may not result in strong heat extraction as a result of poor sweep efficiency.

INTRODUCTION

The efficiency of multiwell geothermal systems is dependent upon the swept surface area of the hot rock mass. In fractured bedrock system, this equates to the fracture surface area that is encountered by fluid circulated among wells. Estimating this surface area has been a goal of tracer testing for many years. Over 100 tests have been conducted in geothermal reservoirs [Shook and Forsmann, 2005]. The vast majority of these tests have utilized conservative (non-reactive) tracers to measure residence time among well pairs. Recent efforts have been toward “smart” tracers which can provide more detailed characterization of fractures, including surface area [Tester and others, 2006].

One method for interrogating surface are in geothermal reservoirs is to compare the breakthrough of anionic and cationic species in a forced gradient tracer experiment [Dean et al., 2012]. The concept is that cationic tracers will undergo exchange with cations on fracture surfaces, while anionic tracers will be non-reactive in the same system. The separation in breakthrough curves can, therefore, be attributed to the availability of exchangeable cations on the rock surface and the surface area available for exchange.

It is difficult to estimate the cation exchange capacity (CEC) of the rock surface independently from the tracer experiment. Obtaining representative cores of fracture surfaces is challenging because mineral surfaces are chemically altered in the presence of
flowing geothermal fluids, and flow fields are not homogeneous. Even so, ionic tracers tests can be useful in a relative sense. For example, assuming that the CEC of the rock surface does not change before and after stimulation, ionic tracers can provide an estimate of the relative increase in surface area due to stimulation. Furthermore, assuming that the CEC does not vary appreciably throughout a fractured geothermal reservoir, ionic tracers can provide an estimate of the relative surface area swept by fluid flowing between different well pairs. It is this latter application that is investigated in the experiments described here.

Cation exchange reactions may be expressed as

\[
A + BX \rightarrow AX + B \quad (1a) \\
2A + CX_2 \rightarrow 2AX + C \quad (1b) \\
2B + CX_2 \rightarrow 2BX + C \quad (1c)
\]

where A and B are monovalent cations and C is a divalent cation [Dean et al., 2012]. X is a negatively charged surface site. Equation 1 shows that a monovalent cation can exchange either with monovalent or divalent cations on mineral surfaces.

Ionic tracer experiments have been utilized in studies of diffusive exchange between fractures and matrix [Becker and Shapiro, 2003; Callahan et al., 2000; Reimus and Callahan, 2007] and as analogs for radionuclide transport [Reimus et al., 2003]. Ionic tracers in non-porous rock have also shown strong separation with relative capacity for ion exchange [Andersson et al., 2002]. Column tests with rock samples from Fenton Hill indicated that lithium and Cesium were particularly promising ions for use in geothermal tracer studies [Dean et al., 2012].

FIELD SITE

The field site is located in the Altona Flat Rocks, in northern New York, USA about 4 miles northwest of West Chazy, New York. The Altona Flat Rocks region is highly unique in the Northeastern United States, because a glacial flood stripped soil overburden off of bedrock, exposing an expanse of sandstone with shallow groundwater in bedrock fractures [Rayburn et al., 2005]. The relevant formation, the Cambrian-aged Potsdam Sandstone is well cemented with silica and as a consequence has effective porosities of less than 1 percent. Ubiquitous fracturing, however, makes the formation highly permeable and it is used as an aquifer for drinking water supply.

The experiments were conducted in the William Miner Experimental Forest, which is managed by the William H. Miner Agricultural Institute (http://www.whminer.com/). The experimental site was selected due to its lack of soil cover, the shallow water levels, and the presence of strong sub-horizontal bedding plane fracturing. Reconnaissance ground penetrating radar located a reflection at 7.6 m deep that was interpreted to be an open bedding plane fracture. Subsequent drilling of a well field confirmed the location of a permeable fracture that was suitable for conducting tracer and hydraulic testing. Since the drilling of the wells in 2004, multiple experiments have been carried out at the site to investigate flow, solute transport, and heat exchange in fractured bedrock [Becker and Tsoflias, 2010; Castagna et al., 2011; Gultinman and Becker, 2010; Hawkins and Becker, 2012; Talley et al., 2005; Tsoflias and Becker, 2008].

The well field is located near an abandoned dam (Skeleton Dam) that creates a strong hydraulic gradient across the well field as water flow from the created reservoir (Chasm Lake) to a small ledge which produces a seepage face (Figure 1). A five-spot 15 cm diameter well pattern penetrates a conductive sub-horizontal fracture 7.6 m meters below the surface. Transmissivity of the fracture is estimated to be about 5 m²/day which suggests a mean hydraulic aperture of about 0.5 mm based upon the local cubic law [Talley et al., 2005]. For all experiments, the target bedding plane fracture was isolated with inflatable packers such that we could work in essentially an single sub-horizontal flow field.

Figure 1: Map of the field area and well field (inset).
The groundwater at Altona Flat Rocks is very low in dissolved solids. Typical background electrical conductivity can be less than 100 mS/m. ICP-MS cation analyses of background water pumped from the fracture yielded high levels of iron (1440 ppb), and confirmed that calcium (Ca2+), sodium (Na+), magnesium (Mg2+), and potassium (K+) are the dominant cations present in solution. Both lithium (Li+) and bromide (Br-) have very low to nonexistent background concentrations, often less than 1 ppm. The Potsdam bedrock fractures present a quartz rich mineral surface in clean breaks but show iron staining in the presence of flowing water. Ion exchange in the field site, therefore, is likely dominated by secondary mineral coatings on the fracture surface that have yet to be fully characterized. Based upon diffusion cell tests conducted over the period of months, matrix diffusion is negligible at the hour time scales over which these experiments were conducted.

**TRACER EXPERIMENTS**

Lithium and bromide were used at the ionic tracers of choice in the experiments discussed here. Tracer injection solutions were created by dissolving LiBr into extracted groundwater. Tracers were detected in the field using ion specific electrode and samples returned to the laboratory were analyzed using ion chromatography (IC). IC analyses are reported here.

Tracer experiments were conducted under forced gradient in a “full-dipole” configuration between well pairs. For the full dipole test, water is pumped from the extraction well at the same rate it is introduced at the injection well. Before water is returned to the formation it passes through a mixing tank at which tracer can be introduced the recirculating system and breakthrough can be measured at the pumping well (Figure 2). Because tracer is recirculated through the system, breakthrough demonstrates multiple concentration peaks due to the recirculation of the initial injection of tracer. However, since the volume in the full mixed tank is known, breakthrough curves may be modeled using transport equations that account for the convolution of transfer functions representing storage in the mixing tank, boreholes, and formation [Becker and Tsoflias, 2010].

Flow was induced using a variable speed positive displacement pump (Rediflo-2, Grundfos). Flow rates were minimized to maximize residence time of tracer in the formation. However, because there is strong natural flow in the fracture a minimum pumping rate (Q_R) needed to be maintained to get good tracer recovery. Pumping rates ranged between 1.0 and 4.1 L/min.

![Figure 2: Schematic of the tracer test experimental set up. Tracer is circulated through a single bedding plane fracture via a well pair. The same fracture can be imaged using ground penetrating radar (GPR).](image)

Tracer tests were initialized by creating a steady dipole flow field through pumping and re-injection (Figure 2). The test was initiated by adding a known mass of LiBr solution to the surface tank. The tracer mixed nearly instantly in the surface tank and then was gravity drained into the injection well. A packer in the injection well minimized the volume in the injection borehole to about 3 L which was also assumed to be fully mixed. This experimental design was chosen such that the flow field would be steady even while the tracer experiment was transient. Deconvolving the influence of transient flow fields and solute transport on breakthrough curves is, in our experience, nearly impossible.

Results of the tracer experiments are gathered in Figure 3. All breakthrough curves are plotted as Q_R/C/Mo, where Q_R is the recirculation flow rate, Mo is the injected tracer mass and C is the measured concentration in the mixing tank. Because water was recirculated, the tracer was also recirculated and multiple peaks are visible in the breakthrough. The top two plots display the breakthrough between the corner wells 204-304 and 104-504, where 204 and 104 were the injection wells and 304 and 504 were the pumping wells. The remaining four plots display breakthrough in tracer experiments in which the center well, 404, was pumped and tracer was injected at the corner wells, 104, 204, 504, and 304.
Figure 3: Breakthrough curves for lithium and bromide tracers. Well pairs are labeled as injection-pumping.
Mass recovery for the experiments varied widely. Because the traced water was recirculated, calculation of mass recovery by integration under the breakthrough curves (Figure 3) can result in greater than 100% mass recovery. Actual mass recovery was generally much less than 100%, however.

Figure 4: Percentage of injected tracer mass recovered during the tests (integration under the breakthrough curves of Fig. 3). Mass recovery can exceed 100% due to recirculation of traced water.

TRACER SIMULATION

The semi-analytical model RELAP (Reimus et al., 2003) and numerical model MULTRAN (Sullivan et al., 2003) were used in combination to interpret the separation in breakthrough between the anionic and cationic tracers, with a goal of estimating relative surface area to volume ratios in the active fractures in the 104-504 and 204-304 tests. The approach to interpreting the tracer breakthrough curves was to first use RELAP to fit the conservative bromide tracer responses, taking advantage of the extremely rapid computation times of the semi-analytical model to perform numerous trials to estimate transport parameters. A dual-porosity system was assumed, with a matrix porosity of 0.02 and a bromide matrix diffusion coefficient of $1 \times 10^{-6}$ cm$^2$/sec.

The parameters estimated from RELAP were input to MULTRAN to simultaneously simulate/fit both the bromide and lithium breakthrough curves, adjusting only the average fracture aperture, or twice the fracture volume to surface area ratio (assuming parallel-plate fractures), to obtain a reasonable match to both data sets for each test. Because lithium and bromide were co-injected, the RELAP-estimated bromide transport parameters were also assumed to apply to lithium. Some iteration between MULTRAN and RELAP was allowed because fracture aperture estimates are better constrained by the simultaneous matching of the bromide and lithium breakthrough curves. Lithium cation exchange parameters are not well constrained for the Altona system, so published equilibrium constants for cation exchange reactions were used (Appelo, 1996), and a modest cation exchange capacity of 0.2 eq/kg was assumed for the matrix in both tests. Model trials indicate that the simultaneous first arrivals of the bromide and lithium are due to lithium-cation exchange in the matrix or in a weathered skin on fracture surfaces. As a consequence, all cation exchange reactions in the model were assumed to occur only in the matrix.

Figure 5 shows the MULTRAN fits to the test 204-304 breakthrough curves, with the estimated model parameters listed in Table 1. A fracture aperture estimate of 1 mm is approximately the smallest aperture that still provided a reasonable match to both tracer data sets given the assumed matrix diffusion and cation exchange parameters. Smaller apertures resulted in greater separation of the lithium and bromide curves than was experimentally observed.

Figure 5: MULTRAN fits to the tracer breakthrough curves of test 204-304.

Matching the breakthrough curves from test 104-504 was more challenging. When a single fracture flow pathway was employed (as in the case of the 204-304 test), it was not possible to match both the early lithium peak and the significant separation between the tails of the lithium and bromide breakthrough curves. These features could be matched only by assuming that two separate flow pathways contributed to the tracer breakthrough curves; a faster pathway with larger fracture apertures that resulted in
the early lithium peak, and a slower pathway with smaller apertures that explains the separation in the tails of the breakthrough curves.

Figure 6 shows both the single-pathway and the dual-pathway MULTRAN fits to the test 104-504 breakthrough curves. The wavy shapes of the dual-pathway model curves are an artifact of the empirical manner in which tracer recirculation was accounted for; recirculated tracer would normally be distributed between the two pathways in accordance with the flow distribution between pathways, but because RELAP and MULTRAN only simulate one pathway at a time, the distribution of recirculated tracer mass between the pathways could only be approximated. Despite the shortcomings of this approximation, the dual-pathway fit to the lithium breakthrough curve offers a substantial improvement over the single-pathway fit (with the bromide fit being compromised somewhat). The model parameters for the dual-pathway fit are listed in Table 1. It should be emphasized that the fits to the tracer curves were only semi-quantitative; no attempt was made to do a rigorous optimization of the fits because of the uncertainties in the underlying matrix diffusion and cation exchange parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>204-304</th>
<th>104-504 Pathway 1</th>
<th>104-504 Pathway 2</th>
</tr>
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<tbody>
<tr>
<td>Tracer Mass Fraction</td>
<td>0.55</td>
<td>0.06</td>
<td>0.1</td>
</tr>
<tr>
<td>Mean Residence Time, hrs</td>
<td>0.27</td>
<td>0.65</td>
<td>1.1</td>
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<tr>
<td>Peclet Number</td>
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<td>35</td>
<td>16</td>
</tr>
<tr>
<td>Fracture Aperture, mm</td>
<td>1.0</td>
<td>1.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The change in electrical conductivity of water in the fracture results in a change in both amplitude and phase of the reflected GPR signal which may be used to estimate the relative mass of dissolved salt at the reflection horizon. The reader is referred to previous works regarding the theoretical and practical considerations of GPR imaging of saline fluid [Tsoflias and Becker, 2008]. It suffices here to note that the reflection amplitude is a function of both fracture aperture and saline concentration, and neither relationship is linear. However, if amplitude increase between pre-injection post-injection is mapped, the resulting variation in amplitude should be a function of saline concentration only.

Maps of reflected 100 MHz GPR amplitude difference (post-injection minus pre-injection) are displayed in Figure 6. The color scale represents reflected amplitude where more negative amplitudes represent the presence of saline tracer. The open

**GROUND PENETRATING RADAR**

Surface-based reflection GPR has been used at the field site to image saline tracer in multiple experiments [Becker and Tsoflias, 2010; Tsoflias and Becker, 2008]. In these experiments, saline water was introduced passively or injected under forced gradient while GPR was used to image its distribution and transport. In the imaging mode of interest here, saline water is circulated between well pairs while radar antennae are moved about the surface (Figure 5). Because reflection amplitudes were found to be affected by GPR signal polarization, antennae were oriented in parallel and orthogonally to the acquisition line and the amplitudes from both polarizations were summed [Tsoflias et al., 2011]. The grid of these measurements, with spacing of 0.25m by 0.5m intervals, was contoured to produce “maps” of saline tracer migrating through the target fracture (Figure 6).

**Figure 5:** Photograph of GPR images being collected using the custom constructed multi-polarization antenna frame.
A circle represents the injection well and the filled circle the pumping well in each experiment. Asterisks denote wells used for monitoring. Due to difference between the pre- and post-tracer amplitudes, there is a significant amount of noise in the mapped reflections. However, it is apparent that the saline tracer is more widely dispersed in the test conducted between 104 and 504 than 204 and 304.

DISCUSSION AND CONCLUSIONS

Trends in the tracer breakthrough curves (Figure 3) and mass recovery (Figure 4) are evident. First, mass recovery was highly dependent on the orientation of the test to the prevailing natural flow field. Based upon GPR imaging of passive tracer flow through the well field, the flow field appears to trend locally from west to east. This natural flow is generally in line with the head gradient (Figure 1) but is likely influenced by hydraulic anisotropy of the fractured formation. The experiment in which tracer was injected in 204 and recovered from 304 (in an eastward direction) saw 230% and 209% recovery of conservative bromide and reactive lithium tracers, respectively. The test in the perpendicular direction, 104-504, only saw 24% and 14% recovery of bromide and lithium, respectively.

However, tracer recovery is also affected by the hydraulic connection between well pairs. Well 104 is known to be less hydraulically connected to the target fracture than the other wells [Becker and Guiltinan, 2009]. Examining the tracer tests which were conducted from the corner wells to the central well; well 204 had the greatest conservation of tracer and 104 the poorest. Wells 304 and 504 also showed poor recovery, but this is likely because they are oriented perpendicular to the natural flow field.

The separation of cationic/anionic tracer breakthrough is negligible in all corner-well to center-well experiments (104-404, 204-404, 304-404, 504-404). Apparently, the inter-well distance of 7 m, and consequently the reactive surface area, is too small to result in differential sorption between ionic tracers. The separation of cationic/anionic tracer breakthrough is significant in corner-well to center-well experiments (104-504, 204-304). The greater inter-well distance of 14 m provided enough reactive surface area for the Li and Br tracers to behave differently during transport and to allow estimation of fracture surface areas interrogated by the tracers.

The fracture surface area to volume ratio estimate for the 204-304 test is simply the reciprocal of the estimated fracture half-aperture, which is 20 cm²/cm³, or 2000 m²/m³. For the 104-504 test, it is the volume-weighted average of the reciprocal half-apertures in the two-flow pathways. The volume in each flow pathway can be approximated by the product of the tracer mass fraction in the pathway, the tracer mean residence time, and the volumetric flow rate of pumping. Using values from Table 1, we estimate volumes of 9.36 L for the faster pathway and 26.4 L for the slower pathway.

The volume-weighted average of the reciprocal half-apertures is then 79.1 cm²/cm³, or 7910 m²/m³. We emphasize that the absolute estimates of fracture apertures are dependent on the assumed values of the matrix porosity, tracer matrix diffusion coefficients, and lithium cation exchange parameters, which are not well known at Altona. Even so, the model estimated apertures of 0.25 to 1.0 mm compare well

Figure 6: Saline tracer imaged by GPR. Blue color represents the presence of saline fluid circulated between wells 204 and 304 (top) or well 304 and 104 (bottom) (after Tsoflias et al., 2012).
with the 0.5 mm hydraulic aperture estimated from hydraulic tests. Although uncertainty in the absolute values of the mean transport aperture is large, by assuming that the same parameters (other than apertures) apply to both tests, it is possible to obtain good estimates of relative apertures in the two tests. Thus, the surface area to volume ratio in the 104-504 test is estimated to be about 4 times greater than in the 204-304 test.

The overall fracture surface areas in each test can be estimated from the product of the surface area to volume ratio and the tracer-based volume in each test. For the 204-304 test, the tracer volume is estimated to be 36.9 L, and for the 104-504 test it is 9.36 + 26.4 = 35.8 L (i.e., nearly the same total volume in each test, with the lower tracer recoveries in the 104-504 test being offset by the longer tracer residence times in this test). Using the surface area to volume ratios provided above, it is estimated that the overall surface area in the 104-504 test is about 3.8 times greater than in the 204-304 test.

Given that the overall fracture surface area should approximately translate to a 2-D (plan-view) area in the Altona single-fracture system, the relative surface area estimates for the two well pairs are qualitatively consistent with the imaging of saline tracer among the well pairs (Figure 6). Quantitatively, the surface relative surface areas of saline fluid estimated by the GPR imaging appears to be only about 1.5 times as large in the 104-504 test than the 204-304 test. This estimate, however, is based on simple image interpretation of the threshold concentrations displayed in Figure 6. Saline concentration was not accounted for. Processing of the GPR data continues and will produce a more quantitative measure of the ratio of surface volume to area.

In general, the tracer results confirm the conceptual model of flow in the fracture. Saline tracer is conducted in a relatively direct path between 204 and 304 because the flow path aligns with the natural flow direction and because these wells are strongly hydraulically connected. Previous imaging and hydraulic tests suggest that the hydraulic conductivity field is strongly anisotropic, favoring flow in this east-west direction [Becker and Tsoflias, 2010; Tsoflias et al., 2011]. The saline tracer and, presumably, the ionic tracers, follow an induced flow channel that connects the wells.

In the well pair, 104-504, the flow field is much more disperse. Such a disperse flow field is expected when flow is induced orthogonal to a strong anisotropic hydraulic conductivity field. Thus, the poor hydraulic connection actually leads to a better sweep of the formation than the good hydraulic connection. As fracture networks tend to promote flow channeling, one might conjecture that it will be increasing difficult to maintain a good sweep of the formation at larger scales. The reader should be cautioned, however, that his simple relationship is complicated in these experiments by the presence of a strong natural flow field parallel to the principal direction of the hydraulic conductivity tensor. We are in the process of performing two-dimensional flow modeling that accounts for the natural gradient to achieve a more robust interpretation of these tracer experiments.

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