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COMPARISON OF THREE TRACER TESTS AT THE RAFT RIVER GEOTHERMAL SITE

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ABSTRACT

Three conservative tracer tests have been conducted through the Bridge Fault fracture zone at the Raft River Geothermal (RRG) site. All three tests were conducted between injection well RRG-5 and production wells RRG-1 (790 m distance) and RRG-4 (740 m distance). The injection well is used during the summer months to provide pressure support to the production wells. The first test was conducted in 2008 using 136 kg of fluorescein tracer. Two additional tracers were injected in 2010. The first 2010 tracer injected was 100 kg fluorescein disodium hydrate salt on June, 21. The second tracer (100 kg 2,6-naphthalene disulfonic acid sodium salt) was injected one month later on July 21. Sampling of the two productions wells was conducted over 179 days to obtain the tails of both 2010 tracer tests. Tracer concentrations were measured using HPLC with a fluorescence detector.

For the 2008 test, 80% of the tracer was recovered at the two production wells. 85% of the recovered tracer mass was from well RRG-4 indicating a greater flow pathway connection between the injection well and RRG-4 than RRG-1. Despite the differences between the injection rates for the two tests (~950 gpm to 440 gpm) between the 2008 and 2010, fluorescein tracer results appear to be similar between the 2008 and 2010 tests for well RRG-4 with peak concentrations arriving approximately 20 days after injection. The tracer breakthrough results for all three tests suggest that the reservoir is highly fractured and no flow path deviation can be noted during the 30 days of cold water (55 ^{o}C) injection into the 140 ^{o}C geothermal reservoir.

BACKGROUND

Chemical tracer tests in geothermal systems are used to examine the flow pathways in a reservoir. Typically these tests are conducted to determine connectivity between parts of the reservoir, swept volume, fluid velocities, and reservoir geometry often in an attempt to determine the potential of thermal breakthrough of injected water. For this paper, we will discuss two sequential conservative tracer tests that were conducted in 2010 as part of a larger project to evaluate thermally degrading tracers. The purpose of these conservative tracer tests was to help define an appropriate conceptual model of the flow and to be used to interpret the thermally degrading tracer in an attempt to quantify the location of the cooling front before it reaches a production well.

The Raft River geothermal reservoir is located in Cassia County Idaho approximately 6 miles north of the Utah/Idaho border near the town of Malta (Figure 1). This site was heavily studied by the U.S.

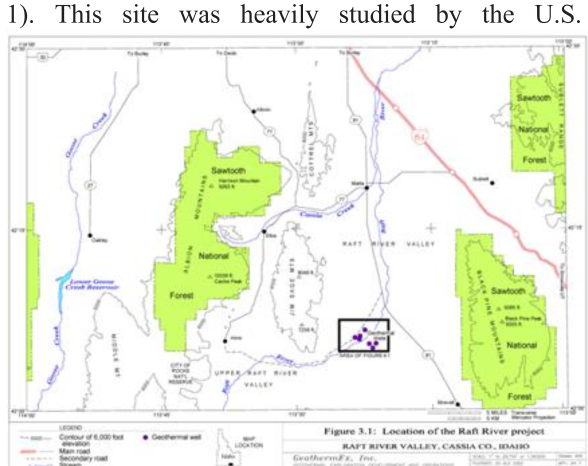


Figure 1: Location of the Raft River geothermal site (from U.S. Geothermal Inc.)

Department of Energy from 1975 to 1982 and was the testing site of the first commercial scale binary (isobutene) cycle geothermal power plant in the world. Presently this site is owned and operated by U.S. Geothermal and is producing power from a 13-MW (nominal) binary isopentane power system.

Geology

The geologic structure in the Raft River geothermal area has been extensively studied using geophysical methods, surface mapping, aerial photography and core lithologic descriptions of subsurface core materials. The Raft River geothermal site is located near the southern end of the Raft River north-south trending valley (Figure 2). This valley is characterized by high-angle normal faulting, low-angle faulting emplacing younger over older rocks, moderate plutonism, and the presence of discontinuous metamorphic terrains (Allman et al., 1982). Beneath the surface alluvium, the Salt Lake Formation is a thick (~1200 meter) poorly consolidated deposit consisting of siltstone and sandstone. Underlying this formation is a 150 meter metamorphized unit, called the metasediments, consisting of sub-units of Schist and Quartzite. The base rock is a Precambrian adamellite. The western side of the valley has been downdropped along listric faults in the Bridge and Horse Well Fault zones

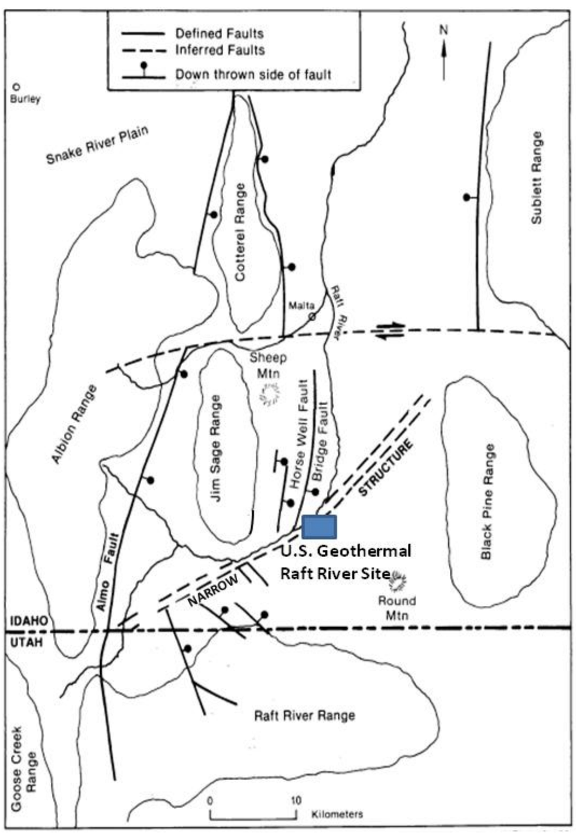


Figure 2: Raft River Valley and major structural features (modified from Dolenc et al., 1981)

through the Salt Lake Formation. These faults dip 60 to 80 degrees to the east at the surface and become nearly horizontal of the Tertiary Sediments and may have produced many near vertical open fractures at the base of the sediments. A geophysical anomaly possibly representing a shear zone, called the Narrows, exists in the basement Precambrian rock.

Hydrology

The Horse Well and the Bridge Faults are thought to play a significant role in the development of the Raft River geothermal reservoir. Movement along of these faults is believed to have created vertical fractures in the base of the Salt Lake Formation and in the underlying Precambrian metasediments that are responsible for the high well yields. There is some uncertainty in the literature about the role of the Narrow zone plays in recharging the geothermal reservoir. The conceptual model presented by Dolenc et al. (1981) describes recharge through basement fractures, possibly along the southwest extension of the Narrow zone (Figure 3). Allman et al. (1982) describes recharge as lateral transport of water from the Jim Sage Mountains through the faulted metamorphic rocks overlying the adamellite basement. More recently, Holt (2008) successfully modeled the reservoir by applying high permeability zones to the fault and metasediments near the fault intersections. His model included both a lateral recharge component (up to 200 gpm depending on the pressure gradient of cold water) and a constant flux of a 175 gpm (380 deg F) at the bottom of his model as the best fit through history matching. Tritium analysis of the geothermal reservoir fluids suggests the fluid is at least 60 to 70 years old. Prior to the geothermal development, static water levels were approximately 100 meters above land surface resulting in presumed leakage of the underlying geothermal water along the faults in the Salt Lake Formation creating some level of heating of the upper aquifers.

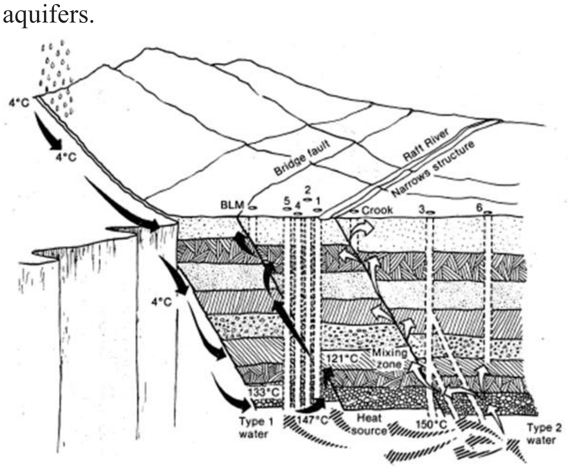


Figure 3: Conceptual model of the hydrology of the Raft River geothermal system (from Dolenc et al., 1981)

TRACER INJECTION

Well RRG-5 has been periodically used as an injection well since 2008. Geothermal water from production wells RRG-1, RRG-2, RRG-4 and RRG-7 are mixed in the binary power plant and reinjected into the aquifer near Well RRG-7. During the summer months, a portion of this water is also injected into RRG-5 to provide pressure support to RRG-1 and RRG-4. Conservative tracers were added to RRG-5 water stream after the initiation of water injection.

After tracer injection, water flowing from the production wells was periodically sampled and analyzed for the injected tracers. RRG-4 lies approximately 740 m from the injection well RRG-5. The distance from RRG-1 to RGG-5 is slightly longer at approximately 790 m (Figure 4).

Figure 4: Aerial view of the central portion of the Raft River geothermal site indicating the location of the tracer injection well and the two closest production wells.

2008 Tracer Test

Injection of water (940 gpm) into RRG-5 began on March 3rd, 2008. Three hundred pounds (136 kgs) fluorescein was added to RRG-5 29 days later on April 3rd. The tracer was injected as a concentrated solution of fluorescein that was gravity fed into the RRG-5 from two plastic totes in less than 20 minutes. Water samples were collected at various intervals from RRG-1, RRG-2 and RRG-4 for the following 45 days. Fluorescein was recovered in wells RRG-1 and RRG-4 but was not seen above background concentrations in well RRG-2. Pumping rates for wells RRG-1 (1080 gpm), RRG-2 (890 gpm), RRG-4 (2130 gpm) and RRG-7 (950 gpm) were fairly constant during the tracer test.

2010 Tracer Tests

Two sequential conservative tracer tests were conducted in 2010 as part of an evaluation of thermal reactive field tracer test study. Water injection in RRG-5 (450 gpm) begun on June 16th, and 100 kg fluorescein disodium salt was added to the injected water five days later on June 21. After an additional 30 days, 100 kg of 2,6-naphthalend disulfonic acid sodium salt was added to the water being injected into RRG-5.

Water samples were periodically collected for 170 days at production wells RRG-1 and RRG-4. The samples were collected in 250 ml amber glass jars and stored on-site at 4 deg C. Pumping rates from the production wells were fairly constant during the tracer sampling (RRG-1 1060 gpm, RRG-2 0 gpm, RRG-4 2190 gpm, and RRG-7 1260 gpm). In addition, the pumping rates from the production wells, with the exception of RRG-2, were very similar to those during the 2008 tracer test.

CHEMICAL ANALYSIS METHODS

2008 Tracer Analysis

Published data on the 2008 tracer injection test is limited. Fluorescein concentrations as a function of time were obtained from digitizing figure 2.13 in the Holt (2008) report to obtain the data set for subsequent analyses.

2010 Tracer Analysis

Water samples (250 ml) were periodically collected from the Raft River site and stored at 4 deg C with minimum exposure to light. Selected samples were then analyzed for naphthalene sulfonate and fluorescein concentrations.

Naphthalene 2,6-disulfonic acid sodium salt

The HPLC method used by Rose *et al*. (2002) was modified to analyze Naphthalene 2,6-disulfonate. This analytical technique is based on ion pair chromatography. Tetrabutyl ammonium phosphate (TBAP) was used as the ion pairing agent. The HPLC analyses used a Jasco HPLC system with PU-2089S Plus pumps, CO-2065 Plus Intelligent column oven, AS-2057 Plus Intelligent autosampler, a FP-2020 Plus fluorescence detector, MD-2018 Plus photo-diode array detector and ChromNAV software. GL Sciences reversed-phase C-18 column, ODS-4, 25 cm x 4.6 mm, 5 µm at 35 ºC was used with a direct 25 µL injection volume for all samples. Methanol and water (25:75) with 3.17 mM Na_2HPO_4, 6.21 mM KH_2PO_4, and 5 mM TBAP at a flow rate of 1.0 mL min^{-1} was used isocratically with the fluorescence detector with a run time of ~50 minutes. The excitation wavelength was set at 225 nm and emission wavelength at 342 nm (Rose *et al.*) with a gain of 100 and attenuation of 8. With an injection volume of 25 μL, concentrations as low as 1 ppb or less could be detected with this method.

Fluorescein disodium salt hydrate

All samples were analyzed for fluorescein (as fluorescein disodium salt) with a FluoroLog Spectrofluorometer and SpectrAcq software. Samples were analyzed using an excitation wavelength of 485.00 nm and an emission wavelength of 528.00 nm. Appropriate calibration standards were prepared from the injected sodium fluorescein salt and stored in bottles wrapped in foil to prevent possible photo-degradation. Standards were run prior to the first sample and at regular intervals throughout the session.

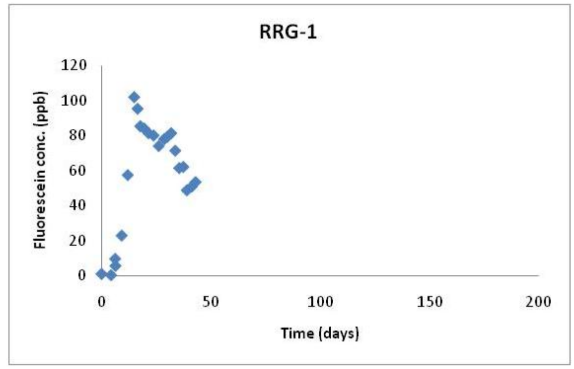
Some stability issues arose during the analyses that have likely overestimated the absolute value of the concentration. Mass balance of the injected amount of fluorescein as calculated by measuring the concentration of fluorescein in the injected solution overestimates the know mass of fluorescein by 36%. We are currently investigating the source of this deviation. Fluorescein values reported in this paper should be considered preliminary for mass balance calculations.

RESULTS

Tracer concentration are plotted as function of time in each of the wells to illustrate the tracer breakthrough at each well for each of the three tests. Concentration breakthrough figures have not been corrected for tracer recirculation. Tracer recirculation is not as big as an issue for this data set since the injected water was diluted with other geothermal pumped water that did not have any tracer. Analysis of the mass balance of the tracer were corrected for recirculation.

2008 Tracer Test Results

Figure 5 illustrates the fluorescein concentration of water samples collected at wells RRG-1 and RRG-4 as a function of time after tracer injection into RRG-5. The fluorescein breakthrough curve is somewhat smoother in well RRG-4 than RRG-1. Fluorescein concentrations in RRG-4 are also approximately 3 times greater than in RRG-1. Sampling results were only reported for approximately 45 days for both days and therefore do not illustrate the tailing end of the breakthrough curve.



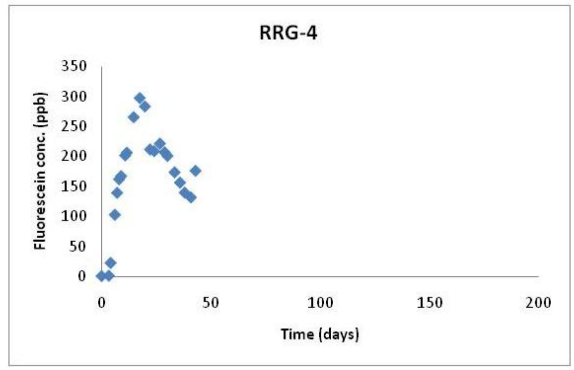


Figure 5: Concentration of the 2008 fluorescein concentration for wells RRG-1 and RRG-4 as a function of time.

2010 Tracer Test Results

The fluorescein breakthrough curves for the 2010 test (Figure 6) were much smoother than the 2008 data (Figure 5). Despite our belief that we are overestimating the fluorescein concentrations for 2010, the 2010 peak values (figure 6) are lower than those reported for 2008 (figure 5). Peak concentration in RRG-4 is approximately four times greater than those measured in RRG-1. The shape of the tracer breakthrough can be described by a log-normal distribution function. Water samples were collected over a period of 179 days.

Naphthalene sulfonate breakthrough curves for the second tracer test conducted in 2010 are presented in figure 7. Well RRG-1 data shows more scatter in the concentration near the peak concentration than seen in RRG-4. Peak concentration are the lowest for the three tracer tests and exhibit the same four to one ratio as seen for the 2010 fluorescein test.

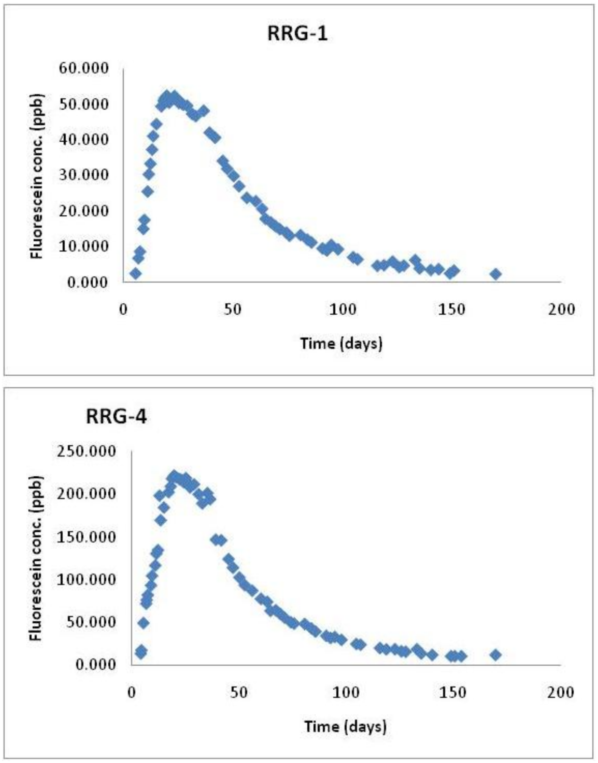


Figure 6: Concentration of the 2010 fluorescein concentration for wells RRG-1 and RRG-4 as a function of time.

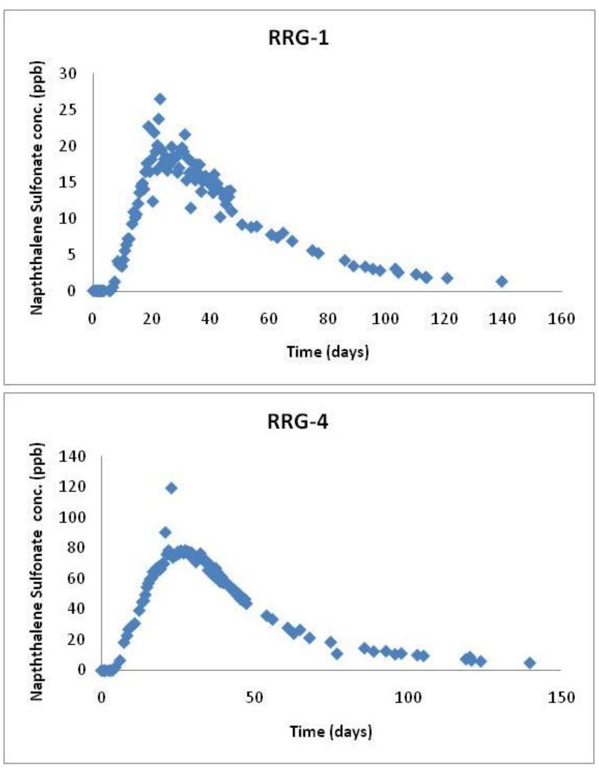


Figure 7: Concentration of the 2010 naphthalene sulfonate concentration for wells RRG-1 and RRG-4 as a function of time.

DISCUSSION

To compare the three tracer tests in more detail, the concentration of the tracer in each well was normalized to the apparent peak concentration for that tracer. In cases where the peak concentration had possible extraneous values, five values around the apparent peak concentration were averaged for the normalization.

Comparison of 2010 Results from Different Wells

Figure 8 illustrates the shape of the normalized concentration versus time for fluorescein for the 2010 tracer test. Breakthrough curves describe the advective and diffusive properties of the flow pathways between the point of injection and the location of the tracer sampling. Despite the fact that RRG-4 was being pumped at approximately twice the rate of RRG-1, the two breakthrough curves are remarkably similar. This similarity could suggest that the tracer BTC shape is mostly controlled by structure near RRG-5 or that the characteristics of reservoir along flow pathways between the injection and the two production wells are similar.

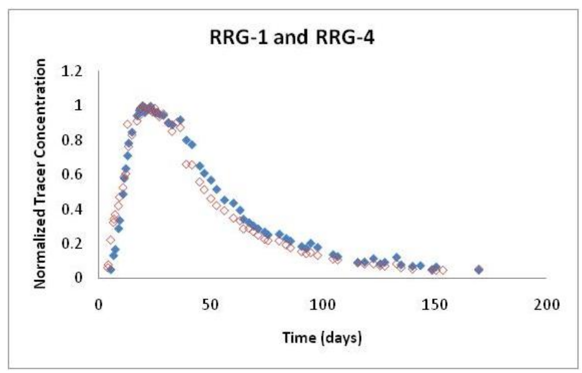


Figure 8: Fluorescein concentration in wells RRG-1(open red symbols) and RRG-4(solid blue symbols) as a function of time since injection.

2010 Tracer Comparison Same Well

Figure 9 illustrates the breakthrough curve for the fluorescein and the naphthalene sulfonate for the 2010 tracer tests in well RRG-4. These two tests were conducted 30 days apart under nearly identical flow conditions. Again the two normalized tracer curves are nearly identical with a possible slightly earlier arrival for the fluorescein. The interpretation suggests that any cooling of the geothermal reservoir during the 30 days of injection of 55 deg C water at 450 gpm did not significantly change the flow characteristics of the reservoir.

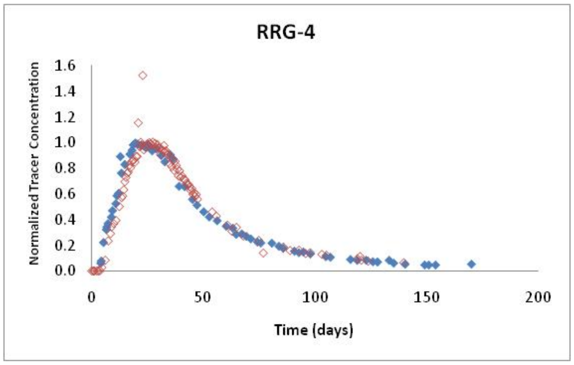


Figure 9: Fluorescein (solid blue symbols) and Naphthalene Sulfonate (open red symbols) concentrations in well RRG-4 as a function of time since injection.

2008 – 2010 Tracer Comparison

Due to the variation in the magnitude of concentration data and the incomplete capturing of the late time, the 2008 tracer breakthrough curve is difficult to interpret by itself (Figure 5). The concentration "spikes" could be interpreted as a series of individual breakthrough from a few non-connecting fractures. However, geothermal systems commonly show a single hump tracer breakthrough curve due to the highly fractured nature of these reservoirs (Horne and Rodriguez, 1981). Breakthrough data from Raft River 2010 tracer tests (Figures 6 and 7) all show a single hump breakthrough. Since the 2010 data exhibits a smooth curve we can interpret the spikes in the 2008 data as simple analytical noise and not multiple superimposed breakthrough curves.

Figure 10 illustrates the fluorescein tracer concentration as a function of time for both RRG-1 and RRG-4. The main differences between the tests was that a slightly greater amount of fluorescein was injected in 2008 than 2010 (136 vs. 100 Kg) and the water injection rate was approximately twice that of the 2010 test.

The initial breakthrough and general shape of tracer breakthrough curves appear to be similar. There is some indication that the 2008 tracer exhibits less spreading but the noise in the 2008 data and the incomplete data collection to describe the late time arrival adds significant uncertainty to this speculation.

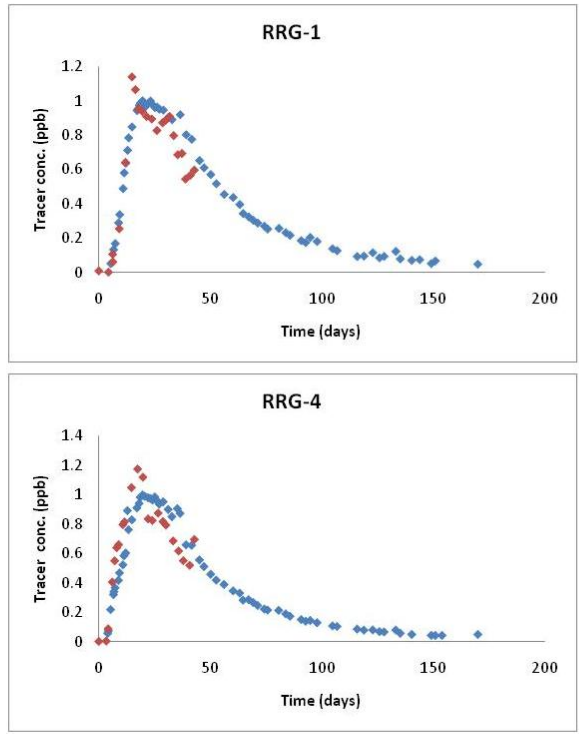


Figure 10: Comparison of fluorescein concentrations as a function of time since injection for wells RRG-1 and RRG-4 (solid blue symbols are for the 2008 test and solid red symbols are for the 2010 test).

Tracer Mass Balance

A second way to examine the tracer data is by plotting the mass of tracer recovered in each production well. First, the measured concentrations are corrected for tracer recirculation through the injection well. These corrected concentrations are then multiplied by the production well flow rates to determine the mass rate entering the well at any time. Finally, these values are normalized by the total amount of mass that was injected into the reservoir to allow for easier comparison of the three tracer tests.

Figure 11 illustrates the normalized mass fraction recovered in RRG-4 as a function of time for the three tracer test. All three tracer tests show initial arrival at approximately the same time. Data for the two 2010 test have a similar shape suggesting that the tracer experience a similar flow path but the total mass fraction recovered was much less for the naphthalene sulfonate than the fluorescein tracer. This result may be due to potential fluorescein measurement analytical errors as discussed earlier.

The 2008 mass fraction recovery curve exhibits an earlier breakthrough with less spreading than the 2010 data. The earlier arrival would be consistent with the larger injection rate during the 2008 tracer test. The less tailing of the curve could also be interpreted as less mixing in the reservoir or could be simply an artifact of extrapolation of the 2008 fluorescein breakthrough data.

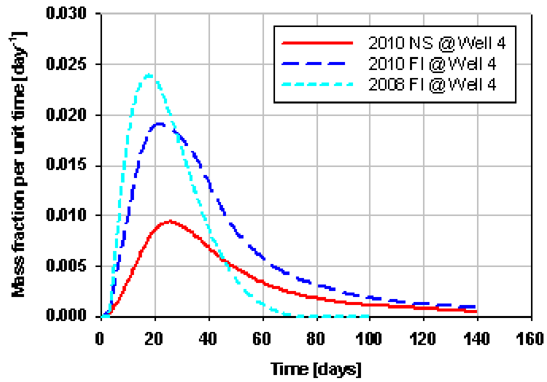


Figure 11. Exit time distribution curves for three conservative tracer tests conducted at Raft River.

Table 1 lists the mass fraction of tracer recovered in RRG-1 and RRG-4 for the three tracer tests. The mass fraction recovered can be interpreted as the fraction of the injected water that is captured by each production well. Total mass fractions less than one, can be interpreted as either some injected water is transported outside the production well cone of influence or that some of the tracer sorbed or biodegraded during transport. Both fluorescein and naphthalene sulfonate are believed to be conservative tracers. The discrepancy between the 2010 fluorescein and naphthalene sulfonate total mass recover suggest an error in one of our analytical measurement methods.

Table 1: Mass fraction of tracer recovered in Raft River production wells.

	RRG-1	RRG-4	Total
2008 Fluorescein	0.12	0.67	0.79
2010 Fluorescein	0.11	0.91	1.02
2010 Naphthalene disulfonate	0.06	0.45	0.51

Flow-Capacity Curves

The flow-storage diagram was developed to estimate the sweep efficiency in layered media. As described by Shook (2003), these diagrams can be used semi-quantitatively to describe the percentage of flow originating from what percentage of the pore volume. Curves that lie closer to the one-to-one line suggest a more homogeneous fracture reservoir that has fractures of equal aperture and length. Interpreted in this manner, the curves illustrated in Figure 12 suggest that the 2010 flow regime was consistent between the two tests. The comparison of the 2008 to the 2010 curves suggests that the flow regime during the 2008 test was more homogenous than during the 2010 test. This difference could be due to the different injection rates during the two tests or potential reservoir flow path evolution due to the cold water injection.

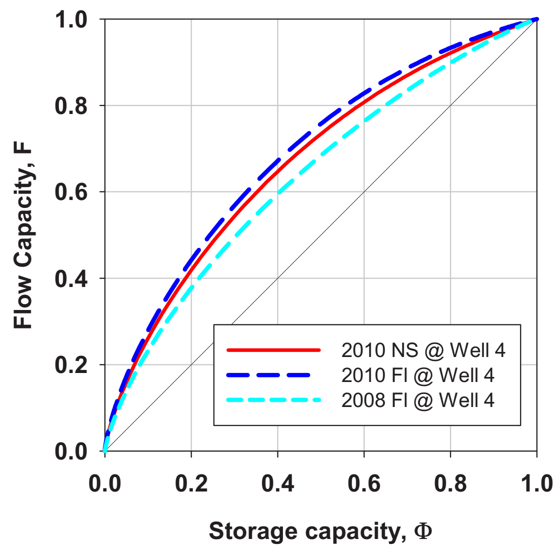


Figure 12. Flow capacity, F, vs. storage capacity, Φ, curves for three conservative tracer tests conducted at Raft River.

SUMMARY

Three conservative tracer tests have been conducted through the Bridge Fault fracture zone at the Raft River Geothermal (RRG) site. All three tests were conducted between injection well RRG-5 and production wells RRG-1 (790 m distance) and RRG-4 (740 m distance).

Preliminary analyses of the tracer breakthrough curves suggest the flow pathways are similar in their flow properties across this section of the reservoir. The consistent arrival of a single hump BTC suggests the reservoir is composed of many fractures. The higher tracer recoveries in RRG-4 suggest a more direct connection to well RRG-5 than RRG-1 and 5.
The smooth tracer concentration data from 2010 suggest that the variation in the 2008 data is likely analytical noise and not the superposition of a few fractures. Similar tracer breakthrough curves for the fluorescein and the naphthalene sulfonate suggest no change in flow pathways during the first 30 days of cold water injection. A possible change of the flow pathways maybe evident between the 2008 and 2010; however, this difference could be due to the lack of a complete breakthrough curve and the greater

injection rate used during 2008. All results should be considered preliminary due to potential issues with the analytical methods used to analyze the tracer concentrations.

ACKNOWLEDGEMENT

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