Tracer Testing to Characterize Hydraulic Stimulation Experiments at the Raft River EGS Demonstration Site

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ABSTRACT

A series of three tracer tests was conducted over a 3.5-year period as part of the Raft River EGS Demonstration Project in order to characterize the evolution of fluid flow processes resulting from the hydraulic stimulation of the target injection well RRG-9. Injectivity increased very little in RRG-9 as the result of hydraulic stimulation experiments over a 300-day period but increased significantly as brine was injected continuously over the subsequent three years. The tracer tests revealed that fluid flow patterns evolved over time along the injection/production pathway with tracer breaking through progressively earlier and to more wells over the duration of the testing.

1. Introduction

Permeability can be enhanced in EGS reservoirs through a combination of hydraulic, thermal and chemical stimulation processes. During hydraulic stimulation, elevated pore pressure serves to reduce the effective normal stress on pre-existing planes causing fractures optimally oriented to the contemporary stresses to open in shear. This allows for increased flow along the activated fractures. As cold, fresh water subsequently flows through those fractures, the combined processes of thermal contraction and mineral dissolution continues to enhance permeability. Thus, while hydraulic stimulation is the primary process that serves to increase fracture permeability, additional processes such as thermal contraction and mineral dissolution operate over time to enhance flow through these fractures. And, as will be shown here, those thermal and chemical processes can have a much larger effect than the initial hydraulic stimulation.

Due to their excellent thermal stability, detectability, affordability and nontoxicity, the naphthalene sulfonates have gained worldwide acceptance for use as tracers for tagging reinjection fluids in geothermal, groundwater and petroleum reservoirs (Rose et al., 2001). They have likewise been successfully used in numerous EGS demonstration projects including Soultz (Sanjuan et al., 2006), Coso (Rose et al., 2002; Rose et al., 2005; Rose et al., 2006), Desert Peak (Rose et al., 2009; Rose and Clausen, 2017), and Cooper Basin (Ayling et al., 2015).

The first documented low-pressure stimulation of an impermeable geothermal well was conducted at the Coso geothermal field (Rose et al., 2005; Rose et al., 2006). Coso well 34A-9 was drilled to a depth of approximately 9,000 ft in 1993 into the hottest portion of the field's east flank. Cold steam condensate was injected intermittently into this hot but tight well over a period of approximately two weeks. At the beginning of the two-week period, the well could accept only 40 gpm with a wellhead pressure of 100 psi. At the end of the period, the well was accepting 800 gpm with a vacuum at the wellhead. A subsequent flow test showed that it could produce approximately 3 MWe. Since there had been no formal hydraulic fracturing, the success of 34A-9 was attributed entirely to thermal and chemical stimulation processes.

Following a workover of 34A-9 almost a decade later, a follow-on stimulation experiment was conducted in 2004 for the purpose of evaluating the effect of low-pressure injection on further changes in permeability. At the start of the test, separated brine was injected under vacuum into the wellbore for one week at a rate of approximately 2,000 gpm. The injection flow rate eventually dropped and stabilized at about 800 gpm. Significant microseismicity accompanied the injection experiment (Julian et al., 2005). Tracer testing confirmed a strong connection between 34A-9 and neighboring production well 38-9 (see Figure 1).

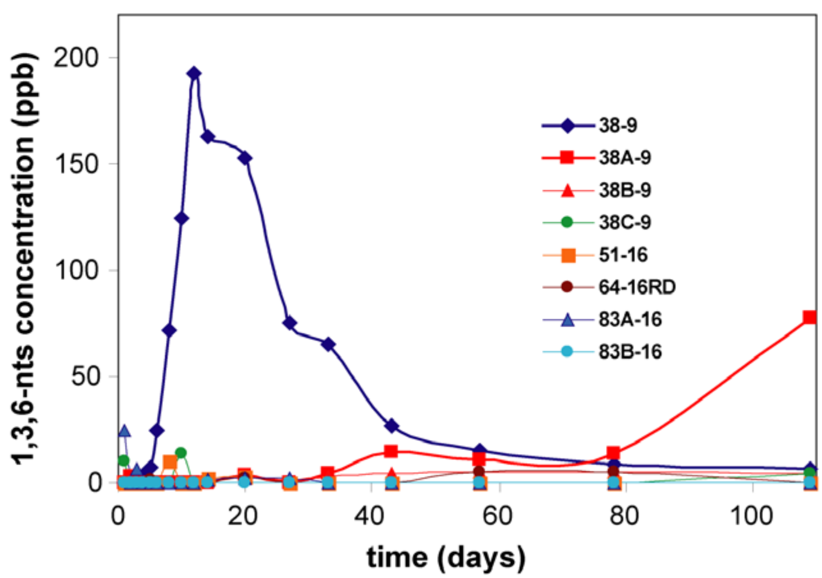

Figure 1. Following the low-pressure stimulation Coso injection well 34A-9 was subsequently placed online. A tracer test revealed a strong hydraulic connection with neighboring production well 38-9.

2. The Raft River EGS Demonstration Project

The Raft River geothermal field is located in southern Idaho approximately 100 miles northwest of Salt Lake City, Utah (Figure 2). The resource was discovered in the 1950's when ranchers encountered hot water while drilling irrigation wells. Between 1974 and 1982 the Energy Research and Development Administration (ERDA) and later the Department of Energy explored and developed the field as a geothermal demonstration project. A summary of the activities that were conducted under this program is provided by NREL (Open EI) and Bradford (2016). U.S. Geothermal Inc. acquired the Raft River field in 2002 and began to produce power commercially in 2008. The field generates about 11 MWe using 150^{o}C water from four production wells: RRG-1, RRG-2, and RRG-4 and RRG-7. The northwest wells produce from the Precambrian Elba Quartzite. RRG-7 produces from the underlying quartz monzonite. These wells cumulatively produce 5,000 gpm, with individual wells producing between 850 to 2,200 gpm. Prior to the stimulation of RRG-9, the spent fluid was injected into RRG-3, 6, and 11 and occasionally RRG-5.

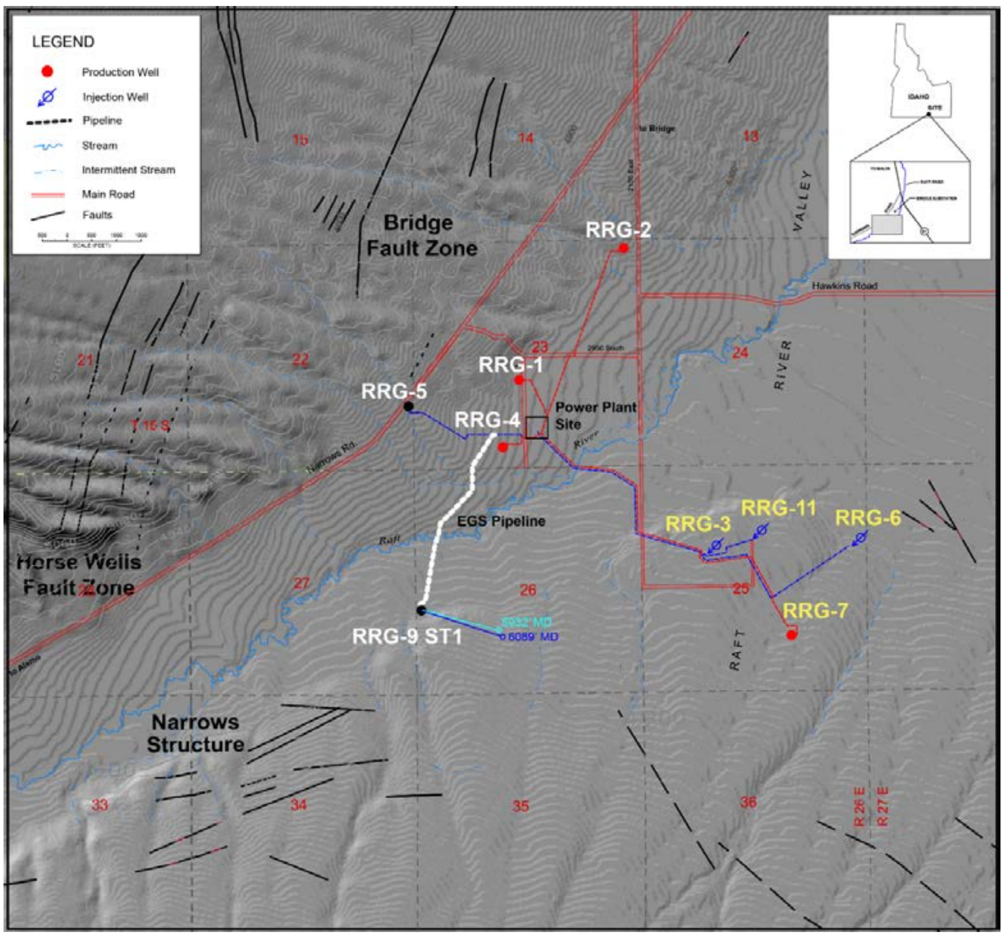

Figure 2. The Raft River geothermal field. Production wells and production pipelines are shown in red. Injection wells and injection pipelines are shown in blue. The RRG-9 wellhead is shown in black, the well trajectories in dark and light blue. The 10-inch pipe line connecting it to the power plant as a dashed white line. Modified from (Williams and others, 1982).

The structural geology of the region is complex, reflecting the effects of two major Cenozoic tectonic events. The earliest event, between about 42 and 25 Ma resulted in the formation of the Albion-Raft River-Grouse Creek metamorphic core complex involving the Precambrian basement rocks, plutonism, extension, and normal faulting. Formation of the Raft River Basin began at 13.5 Ma. The structures produced by this early event are covered by youner volcanic and volcaniclastic deposits and cut by faults related to Basin and Range tectonism (Konstantinou and others, 2012). The Basin and Range faults exposed in the surficial deposits trend northerly north of the production wells and northeast northwest to the southeast (refer to Figure 2). The majority of the eighty-two fractures identified in the open hole section of RRG-9 ST1 are dominantly north-trending and steeply dipping (Bradford and others, 2013, 2015b). Temperature, televiewer and distributed temperature sensor surveys indicate permeability is limited to the northeas-trending fracture zone in the Elba Quartzite at 5,645-5,660 ft. MD.

Geochemical investigations by Ayling and Moore (2013) show the reservoir is strongly compartmentalized. They identified four distinct fluids; two within the Precambrian reservoir rocks and two representing shallow groundwaters. Reservoir fluids from the northwest (RRG-1,2,4,5) are characterized by lower salinities than those from the southeast (RRG-3,6,7,9,11). Based on these data, Ayling and Moore (2013) concluded the northwestern and southeastern portions of the field are separated by a low permeabilty shear zone within the Precambrian basement, which they termed the Narrows Zone.

2.1 The Stimulation of Well RRG-9

EGS Target Stimulation Well RRG-9 was drilled at the southern end of the field to test the extent of the thermal anomaly. It encountered a temperature of 140^{o}C but did not produce commercial quantities of geothermal water. As part of the Department of Energy’s (DOE) Enhanced Geothermal System Demonstration Program, RRG-9 was selected for testing the efficiency of thermal and hydraulic stimulations to improve its productivity. RRG-9 ST1 was drilled to 5,932 ft and cased to 5,551 ft, leaving 381 ft. of open-hole below the casing shoe (Moore, 2012). The well penetrated 5,152 ft. of Quaternary and Tertiary volcanic and volcaniclastic rocks before encountering the Precambrian basement. It encountered 600 ft of the Elba Quartzite above the quartz monzonite between 5300 and 5900 ft.

The Raft River EGS Demonstration Project consisted of three hydraulic stimulations of RRG-9 followed by a long continuous injection of recycled brine into the well over a period of approximately 1400 days (Bradford and others, 2013, 2014, 2015a,b, 2016). A series of tracer tests served to document the evolution of fluid-flow processes. The first stimulation was conducted shortly after the well was completed using a single pump truck. During this stimulation, groundwater was pumped into the well at flow rates ranging from 11 to 756 gpm. A maximum wellhead pressure of 1,150 psig was achieved. Following the stimulation, the well was shut in for approximately 1 year to accommodate construction of the 10-inch injection pipeline from the plant to the well. Upon completion of the permanent injection line, continuous injection was initiated in June 2013 (day 0 in Figure 3). RRG-9 could accept only approximately 20 gpm, indicating that essentially no permanent injectivity had been created during the first stimulation.

The second stimulation of RRG-9 was conducted in August 2013 using small agricultural pumps. A maximum flow rate of 330 gpm was measured, but following the stimulation (approximately day 70 in Figure 3), a steady rate of approximately 140 gpm was measured at a line pressure of 275 psi.

The third stimulation was conducted in April 2014, with maximum pressures and flow rates of 1,150 psi and 1,260 gpm, respectively. Following that stimulation (approximately day 300 in Figure 3), a steady flow rate of 200 gpm was measured with an injection line pressure of about 275 psi. Since the third stimulation, the injection rate into RRG-9 has increased steadily by a factor of approximately 7 to its current level of 1400 gpm. The increases in injectivity resulting from the three hydraulic stimulations that were completed during the first 300 days of the project were relatively insignificant compared to the increase in injectivity that was achieved by continuous injection at low line pressures during the subsequent three years.

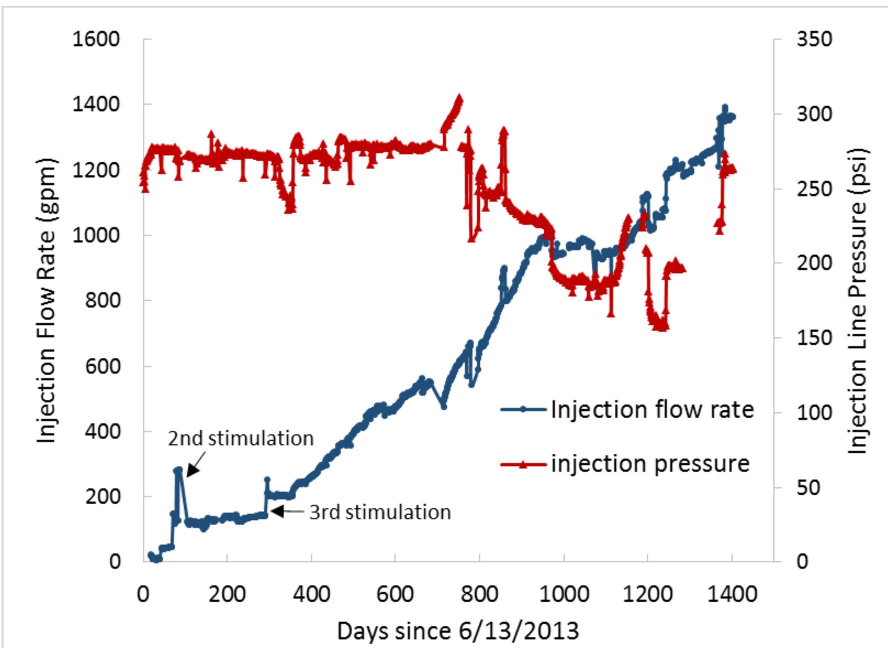

Figure 3. Injection flow rate and injection line pressure during 1400 days following the initial hydraulic stimulation of RRG-9.

2.2 Tracer Testing of RRG-9

A series of tracer tests was initiated on September 9, 2013 in RRG-9 and then continued over a period of approximately 3.5 years. The tracer designations, injection dates and tracer masses are listed in Table 1. All production wells were subsequently sampled and analyzed for tracer concentrations over the same time period.

Table 1. Tracer designations, injection dates, masses and brine injection rates for the tagging of Raft River Injection Well RRG-9.

Tracer Designation	Injection Date	Mass Injected (kg)	Brine Injection Rate (gpm)
1,3,6-naphthalene trisulfonate	September 9, 2013	100	120
2-naphthalene sulfonate	January 7, 2015	100	278
1,5-naphthalene disulfonate	February 11, 2016	100	935

2.2.1 Tracer returns from RRG-9 to RRG-4

Shown in Figure 4 are plots of the return curves of the three tracers from RRG-9 to RRG-4 over the 3.5-year duration of the testing. This is the only well in which all three tracers were observed. It is also the well in which the highest concentrations of tracers were observed. Note that the x axis represents the time in days since the injection of the first tracer, 1,3,6-nts, on September 9, 2013.

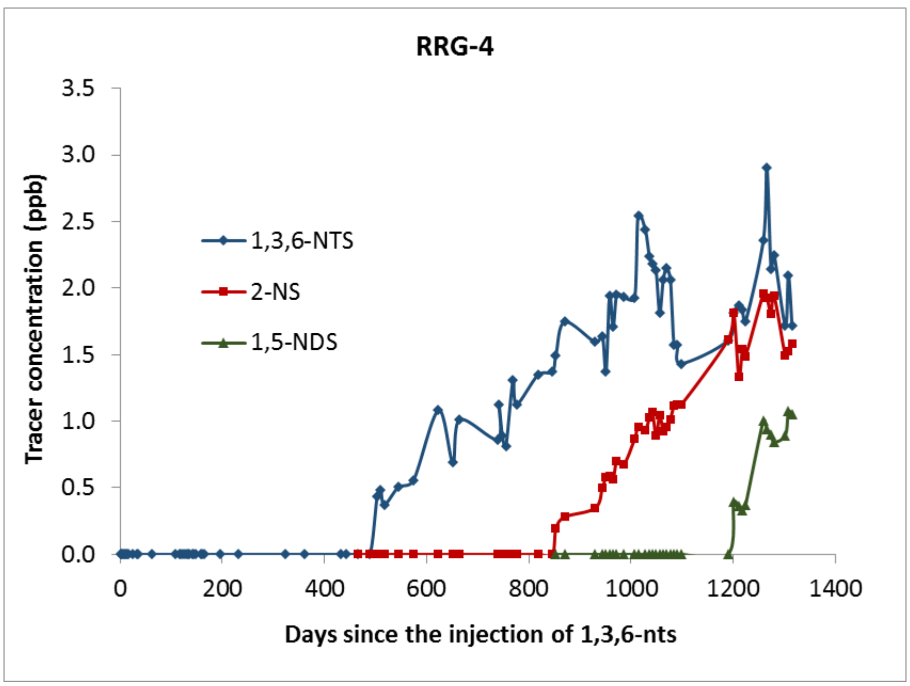

Figure 4. Returns of the three naphthalene sulfonate tracers to RRG-4 as functions of time since the injection of the first tracer over the 3.5-year duration of the tracer testing. The tracer 1,3,6-nts was injected on day 0; 2-ns on day 486; and 1,5-nds on day 885.

Shown in Figure 5 is a replotting of the tracer returning to RRG-4 according to the time since the injection of *each* tracer. It is evident from this plot that the time for the first-tracer arrival is advancing with each tracer as the brine injection rate increases over the 3.5-year duration of the test. A calculation of the mass returned and percentage of mass returned to RRG-4 for each tracer during the 3.5-year duration of the tracer test is shown in Table 1.

Table 1. Calculation of mass returned and percentage of mass returned to well RRG-4

Tracer	Mass Returned (kg)	% Returned
1,3,6-naphthalene trisulfonate	13.7	13.7
2-naphthalene sulfonate	5.90	5.90
1,5-naphthalene disulfonate	1.02	1.02

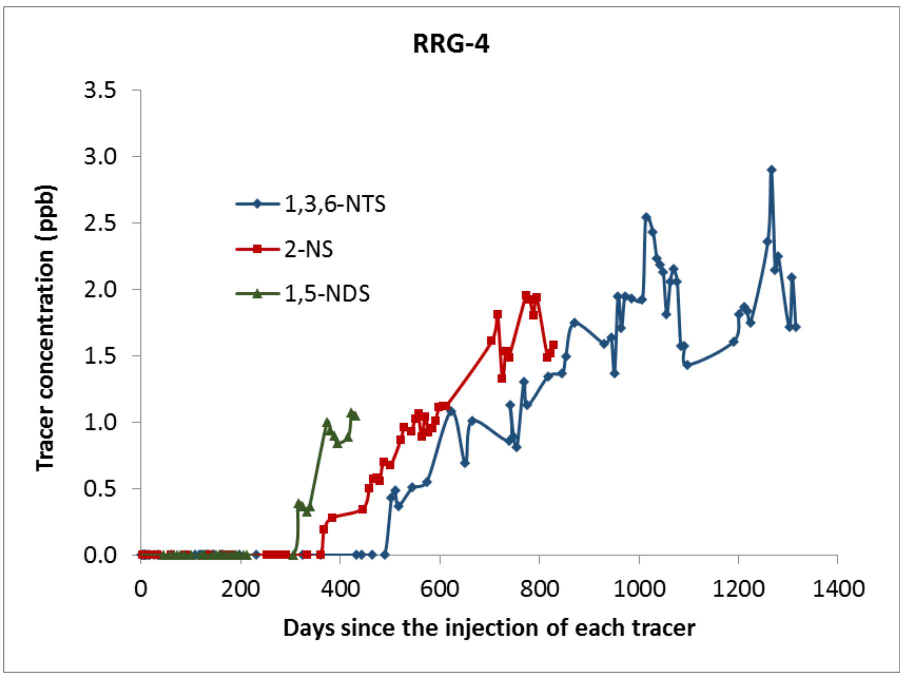

Figure 5. Returns of the three naphthalene sulfonate tracers to RRG-4 as functions of time since the injection of *each* tracer over the 3.5-year duration of the tracer testing. The first arrival of each tracer is progressively advanced with each tracer test as the fracture-flow paths evolve and as the brine injection rate increases.

2.2.2 Tracer returns from RRG-9 to RRG-1

Shown in Figure 6 are plots of the return curves of the three tracers from RRG-9 to RRG-1 over the 3.5-year duration of the testing. RRG-1 is the only well besides RRG-4 in which tracer was consistently observed. Shown in Figure 7 is a replotting of the tracer returning to RRG-1 according to the time since the injection of *each* tracer. It is apparent from this plot that the 1,3,6-nts, which was the first tracer used, did not appear in well RRG-1 until approximately 970 days after its injection into RRG-9. When the test was repeated, however, the second tracer (2-ns) arrived in RRG-1 approximately 460 days after being injected. Over the course of this second year of injection, a new pathway had evolved between RRG-9 and the field that did not exist when the first test was conducted.

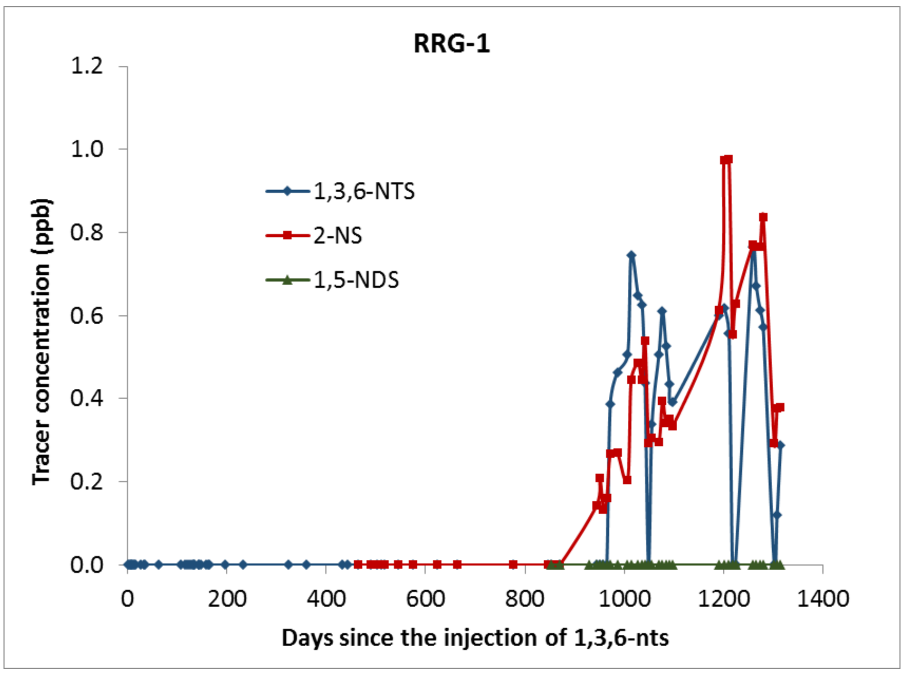

Figure 6. Returns of the three naphthalene sulfonate tracers to RRG-1 as functions of time since the injection of the first tracer (1,3,5-nts) over the 3.5-year duration of the tracer testing.

The tracer concentrations plotted in figures 6 and 7 are very low and close to the detection limit of approximately 0.100 ppb. Nevertheless, the concentrations of 1,3,6-nts appear not to be growing but fluctuating between about 0.4 and 0.8 ppb. This may indicate that the 1,3,6-nts curve is an ‘echo’ and results from its production from RRG-4, since some of the fluids produced from RRG-4 are quickly and continuously reintroduced into the field through various injection wells.

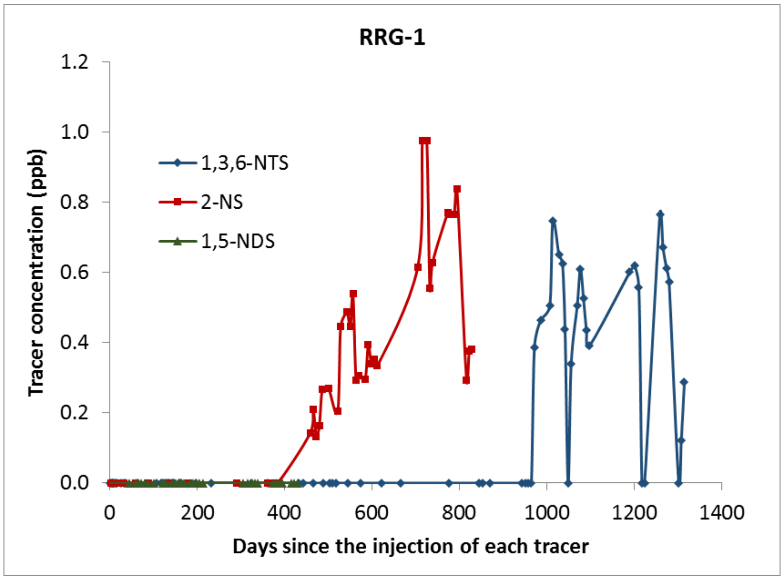

Figure 7. Returns of the three naphthalene sulfonate tracers to RRG-1 as functions of time since the injection of *each* tracer over the 3.5-year duration of the tracer testing.

Table 2. Calculation of mass returned and percentage of mass returned to well RRG-1

Tracer	Mass Returned (kg)	% Returned
1,3,6-naphthalene trisulfonate	0.94	0.94
2-naphthalene sulfonate	1.05	1.05
1,5-naphthalene disulfonate	0.00	0.00

Shown in Figure 8 are plots of tracers detected in samples taken from the reinjection line as functions of time since the injection of each tracer.

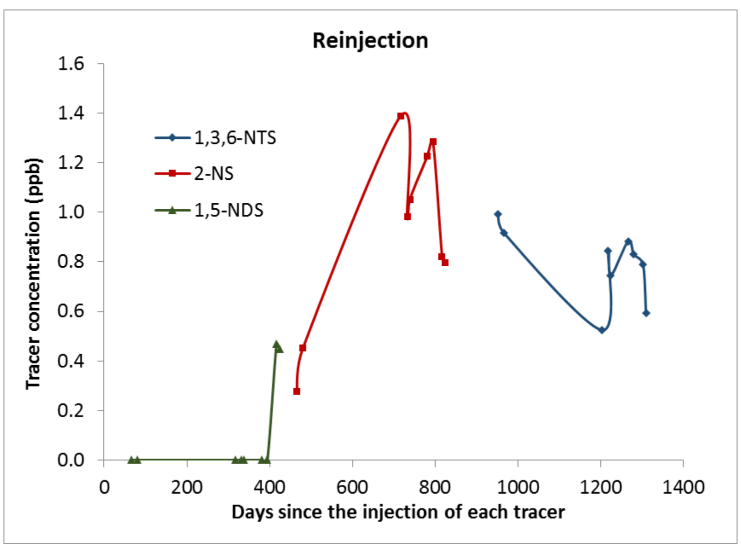

Figure 8. Concentrations of the three naphthalene sulfonate tracers measured in the reinjection fluids as functions of time since the injection of *each* tracer over the 3.5-year duration of the tracer testing.

3. Conclusions

Whereas hydraulic fracturing can have dramatic short-term effects on well injectivity, the effects of thermal and chemical stimulation processes can be significant if injection is continued under low wellhead pressures over long time periods. Three short, open-hole hydraulic stimulation experiments at relatively low wellhead pressures resulted in only modest injectivity gains to Raft River injection well RRG-9. However, significant improvement in injectivity accompanied continuous injection of brine at low wellhead pressure (<300 psi) over the subsequent three years. Tracer testing over a 3.5-year period revealed the evolution of new fracture-flow patterns and increasingly shorter fluid-residence times between RRG-9 and production wells within the field.

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