Multiple Zone Geothermal Stimulation Case Study: Fluid Diversion Using Thermo-Degradable Zonal Isolation Materials

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Keywords

Geothermal stimulation, hydroshearing, production improvement, diverters, temperature improvement, DTS monitoring

ABSTRACT

In both conventional geothermal projects and in EGS, the flow rate from each production well is a critical component of project economics and has a direct effect on the Levelized Cost of Electricity (LCOE). By focusing our efforts in geothermal technology on improving production and injection rates through stimulation, we can mitigate exploration risk and expand the base of geothermal power production. AltaRock has performed four stimulations to date using Thermo-degradable Zonal Isolation Materials (TZIM) to block existing permeable zones and created multiple stimulated fracture systems in conventional geothermal and EGS reservoirs. The TZIM stimulation conducted in a liquid dominated mid-temperature reservoir was able to enhance multiple zones in the target well and increase production flow rate as well as overall production temperature.

Introduction

Geothermal and EGS stimulation have historically involved the stimulation of a single zone of fractures around an existing well bore in order to increase well productivity. During stimulation, the fractures that are most optimally oriented in the remote stress field will likely slip first when the injection pressure causes a reduction of the normal to shear stress ratio on the fracture surface. When this ratio falls below the sliding friction coefficient, the fractures will slip, this is also known as hydroshearing. Once the first zone is stimulated, it is difficult to apply additional pressure to cause other zones with less optimally oriented fractures to hydroshear without inhibiting flow to the first stimulated zone.

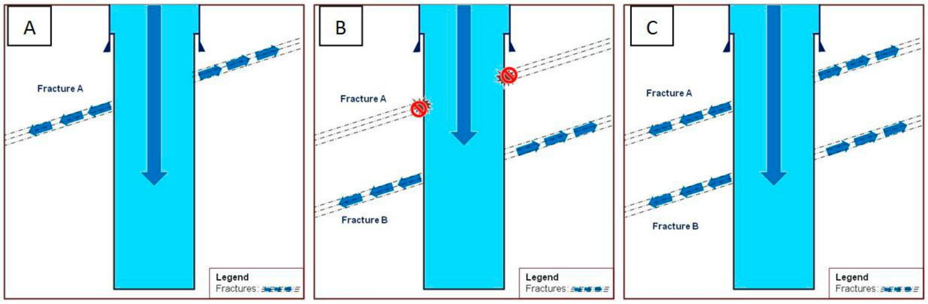

Figure 1. Stimulation of a single fracture zone (A), stimulation of second fracture zone after diverter application to first fracture zone (B), and well with multiple fracture sets after TZIM degradation.

The stimulation of multiple fracture sets in a single wellbore without the use of mechanical isolation devices will enhance well productivity without increasing operational risks. To stimulate multiple fracture sets in a single well requires hydraulic isolation of each fracture network after it has been stimulated. To provide hydraulic isolation for the stimulation of multiple fractures a diverting agent can be used. AltaRock Energy, Inc. developed and field tested a variety of proprietary diverters. Figure 1 illustrates the conceptual model of hydraulic isolation by using TZIM. After an initial stimulation of the first fracture zone (Figure 1A) a TZIM pill is mixed and pumped into the well to temporarily seal the fracture network from accepting additional fluid (Figure 1B). Additional pressure is then applied to the well and a second zone of fractures (Fracture B), which required a higher hydroshearing pressure than the first zone, can now be stimulated. After multiple fractures are stimulated injection is discontinued and the well bore is allowed to reheat to static temperatures, which causes the TZIM material to thermally degrade. This leaves all stimulated fractures open for circulation and flow during the operation of the wellfield (Figure 1C).

TZIM System Development

A number of diversion systems were considered during early developmental stages. The particulate material system was chosen due to its ability to seal off fractures through bridging near the wellbore. Each TZIM treatment can be custom designed by changing the particle size distribution to effectively seal fractures with varying apertures and permeability. The treatment sufficiently lowers the existing permeability and allows for additional pressure buildup in the wellbore to initiate hydroshearing of new zones. The degradation characteristics of TZIM allow the materials to remain sufficiently intact during injection, and maintain a seal in the wellbore during the length of the subsequent stimulation treatment(s). Once the stimulation treatment ends the diverter particles could be removed by either falling to the bottom of the well once the differential pressure holding them in place is removed, by flowing back with fluid from the fractures once the well is opened up and flowed, and/or due to thermal degradation of the TZIM as the well rapidly heats back up to geostatic temperatures.

The advantages of a particulate diverter system include:

- Ability to seal fractures at the wellbore face.
- The material can be placed without interrupting the stimulation pump operations.
- Placement of material does not require a drilling rig or mechanical packers, reducing cost and risks.
- Effectiveness of diversion can be measured though the use of fiber optic temperature monitoring, a downhole pressure monitoring tool, and/or the use of a conventional temperature logging tool.
- If insufficient sealing is noted, additional TZIM can be pumped to affect an adequate seal.
- TZIM can be selected to degrade completely once the well heats up after stimulation so that there is no risk of formation damage.
- Degradable materials are easy to permit and no mechanical intervention is required post stimulation.

Field Demonstration History

Four TZIM field demonstrations have been conducted to date. Field trial in 2010 and early 2011 in a high-temperature, steam dominated reservoir showed that TZIM can successfully isolate existing permeable zones, even with slotted liners already in place (Petty et al., 2011). These demonstrations successfully improved an existing injector by pushing injection deeper and improved an existing producer by increasing long term productivity by up to 68% (Petty et al., 2012).

TZIM was also used to successfully stimulate multiple zones in an EGS well at the Newberry Volcano EGS demonstration (Petty et al., 2013). Well injectivity increased 18 fold and transformed a non-usable well into a potential injector.

TZIM Stimulation in a Liquid Dominated Field Case Study

AltaRock conducted water injection stimulation on a low temperature geothermal well drilled in a liquid dominated field in 2012. TZIM was used to temporarily block off existing shallow permeable zones in order to build-up wellhead pressure and open up deeper fractures through hydroshearing.

Prior to stimulation three zones exhibited permeability, as indicated by the static temperature profile (Figure 2). Zone 1 starts just below the casing shoe and consists of a brittle clastic unit. Stratigraphic columns provided by the operator identified the top contact of the clastic unit as a thrust fault with abundant clay, as noted in the mud log. Temperature monitoring of this zone revealed a strong down flow that was likely contributed by nearby injectors that caused cooling of the overall production fluid. While 400°F temperatures are noted at total depth, the stable production temperature of this well (~224°F) matches the static temperature observed in Zone 1.   Zone 2 encompasses the transition between predominantly limestone to predominantly dolomite. Zone 2 is also the most permeable, as shown by large temperature deflection at 6500'. The stimulation target is located in the higher temperature Zone 3 which is dominated by metamorphic rock. There are small gradient changes on the temperature profile that may indicate some permeability at these depths. The processed (XRMI) image log for the well identified numerous fractures in the metamorphic section. The goal of the stimulation was to temporarily block off highly permeable fractures with low temperatures in Zone 1 and 2 with AltaRock's TZIM technology and enhance the permeability of Zone 3 through cold water injection stimulation in order to turn the well into a producer with economical flow rates and temperatures.

The stimulation was designed to increase fluid pressure in the wellbore sufficiently to cause shear-slip on pre-existing fractures but not high enough to cause tensile fracture of the borehole walls by exceeding the minimum principal stress. In order to achieve the stimulation pressures and flow rates, two positive displacement pumps aligned in parallel were rented for the stimulation. The combined achievable flow rate from the pumps is 1000 gpm, with a maximum allowable injection pressure of 1000 psi. In addition, a Distributed Temperature Sensor (DTS) was deployed to monitor downhole diversion in real time. Tracer injection and microseismic monitoring were also implemented to gauge the effectiveness of the stimulation. The stimulation water supply was provided by two sources: plant re-injection and local ground water well. The two sources were mixed near the wellhead in large steel tanks and average stimulation fluid temperature ranging 100-150°F.

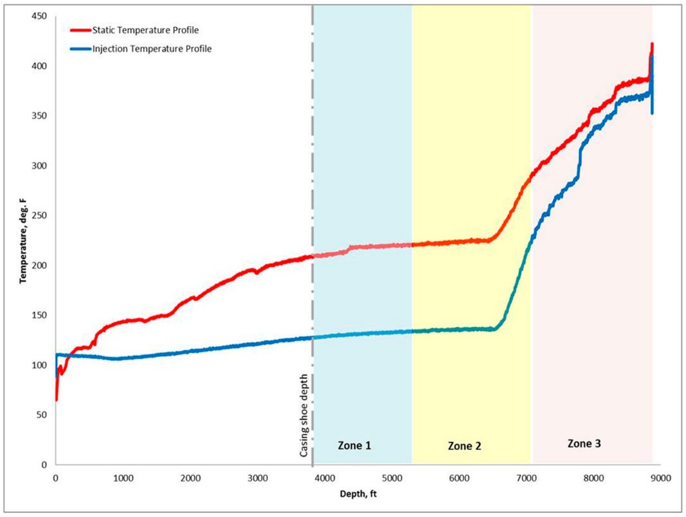

Figure 2. Static (Red) and injecting (Blue) profile pre-stimulation showing existing permeable zones.

Stimulation Approach and Results

The first task during the stimulation was to conduct a step-rate pump test to determine the baseline productivity prior to stimulation. Post productivity pump test, the downhole line shaft pump was removed in preparation for the stimulation. After staging the necessary stimulation pumps, piping and equipment, a step-rate injectivity test was conducted on 5/5/12 to calculate the baseline injectivity. The ratio between the baseline productivity and injectivity are used to estimate the productivity improvements post stimulation. Flow rates were adjusted to record three different steady state wellhead pressures for all pump tests. The average productivity was calculated to be 1.4 gpm/psi and the baseline injectivity was calculated to be 2.14 gpm/psi. First tracer solution 1,5 naphthalene disulfonic acid disodium salt (1,5 NDS) was also injected at the end of the test. Daily samples were collected at all nearby producers for tracer concentration analysis.

After the injectivity test, the first batch of TZIM was injected in order to seal off shallow permeable fractures in Zone 1 and Zone 2. Before TZIM injection, the well was permeable enough to accept 864 gpm at 217 psi wellhead pressure (WHP). WHP increased immediately as a result of TZIM plugging while maintaining a constant injection rate. WHP slowly decreased overnight as new fractures opened up in Zone 3. The DTS profile (Figure 3) showed additional cooling was achieved below 6500' after TZIM injection. The temperature gradient plot (Figure 4) reveals that the zones accepting fluid after TZIM injection are between 6700-7000', 7800-8000', 8300' and 8700'. The first phase of stimulation/diversion lasted 3 days. Four different batches of TZIM were injected, totaling approximately 1700 lbs. The stimulation was paused on 5/7/12 due to extended pump mechanical issues. An interim injectivity test conducted post TZIM degradation showed 10-12% improvement in injectivity, and the decision was made to perform the necessary repairs in order to conduct a second stage of stimulation/diversion.

After necessary pump repairs, the stimulation resumed on 5/31/12. TZIM was injected immediately post pump start-up to again block off shallow permeable zones. After 6 pills of TZIM, the wellhead pressure reached 350 psi and declined overnight while injection rate maintained around 1000 gpm. DTS monitoring showed further cooling below 6500' and additional zones began taking fluid post TZIM injection after 760 hours. The Phase II temperature gradient plot (Figure 4) indicated temperature in Zone 2 decreased as more TZIM batches were injected, and fluid loss in Zone 3 became more apparent as stimulation progressed. Several new stimulated fractures were indicated near 7600', 7750', 7900' and 8100'. The stimulation concluded on 6/6/12 and a total of 12 TZIM pills were injected. Prior to shutting in the pumps, the final tracer (2,6 NDS) was injected.

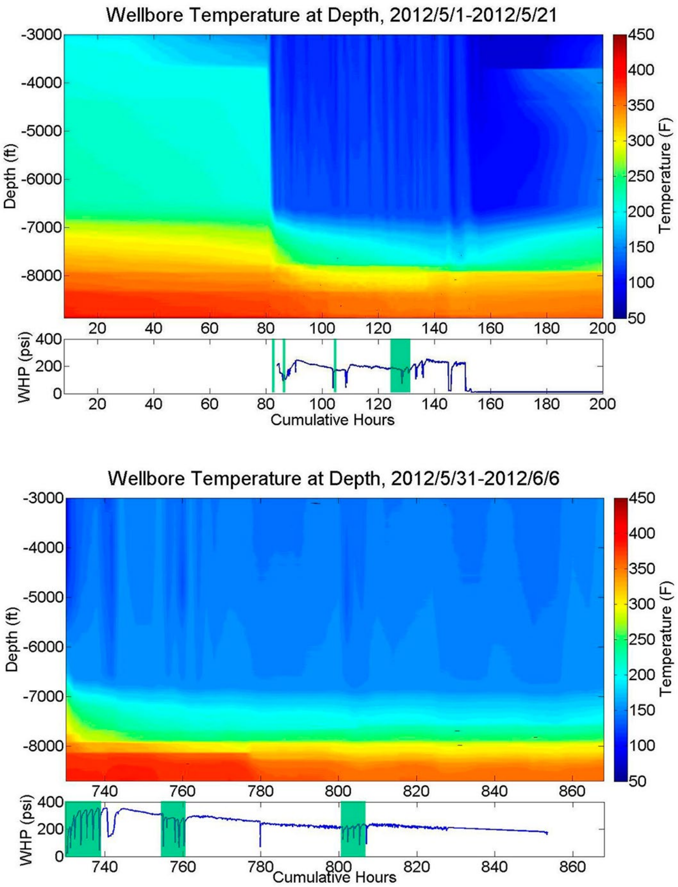

Figure 3. Downhole temperature from 3000′ to TD progression during Phase I (top) and Phase II (bottom) stimulation. TZIM injection marked in green. Corresponding WHP shown below each temperature graph.

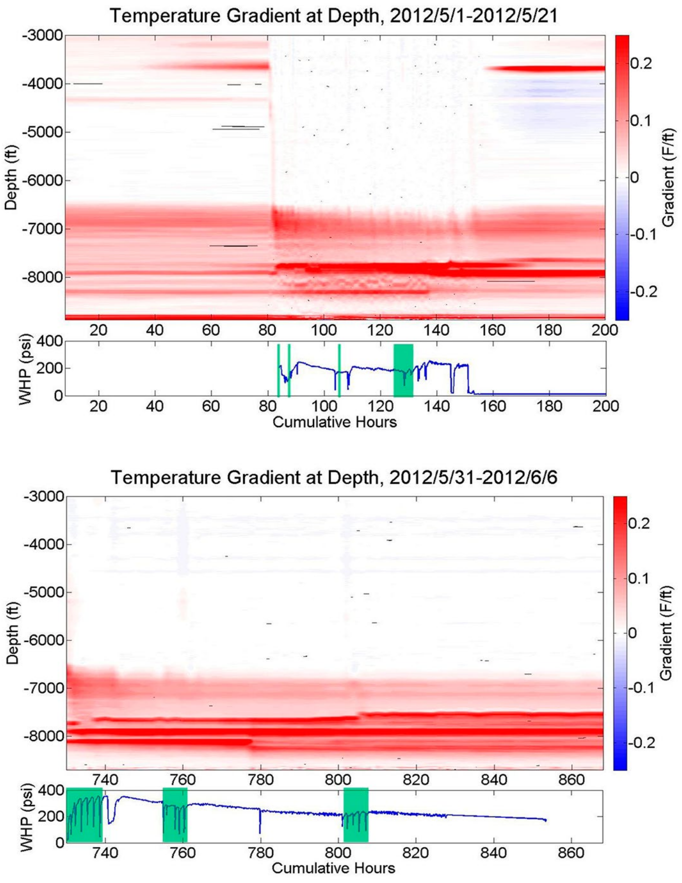

Figure 4. DTS temperature contour plot showing cooling over time during Phase I (top) and Phase II (bottom) stimulation. TZIM injection marked in green. Corresponding WHP shown below each temperature graph.

Microseismic Monitoring

A network of eight geophones and digital recorders were installed to monitor this stimulation. The data was downloaded by AltaRock personnel and shipped to Geotech instruments for processing during the stimulation. Through the stimulation time period, six seismic events were detected within the aperture of the network. Three out of the six events located occurred during the second phase stimulation. One of the events plotted on a seismograph is shown below in Figure 5. This was the smallest event detected (M=-0.7), and was still detected on all eight stations. A more recent experience of micro-seismic monitoring during stimulation from Newberry (Cladouhos et al., 2013) showed that borehole seismic stations are three times more likely to locate seismic events than surface stations. However, conclusions can be made that events located here are occurring as a result of the TZIM stimulation.

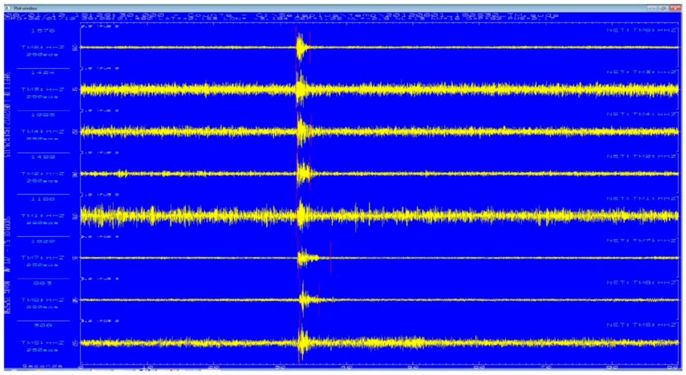

Figure 5. Seismograph for M=-0.7 event on 6/1/12. The vertical component is shown for each station

Tracer Testing

Two tracers, naphthalene disulfonate 1,5 and 2,7 (1,5 NDS and 2,7 NDS) were injected, and daily samples were collected in all production wells and nearby hot springs. The results of the tracer study showed the producer (Producer 1) adjacent to the stimulation well is most connected to the test well. The location of Producer 1 with respect to the stimulated well and field injectors (Injector 1 and 2) is shown in Figure 6, and the breakthrough curves for the two tracers in Producer 1 are shown in Figure 7 which indicates a notable difference between the two tracer concentrations.. 1,5 NDS peaked at 145 ppb while 2,7 NDS peaked at 95 ppb approximately one month post stimulation. The reduced amounts observed in tracer returns indicate the flow path between the stimulated well and Producer 1 was altered when fractures were plugged by TZIM.

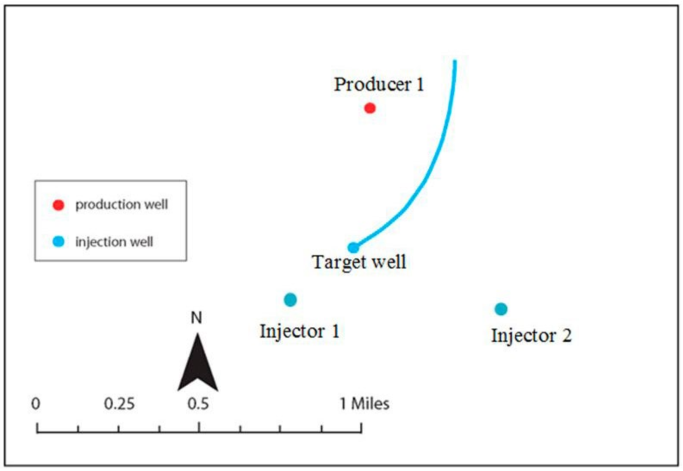

Figure 6. Field map illustrating wells closest to the stimulated well.

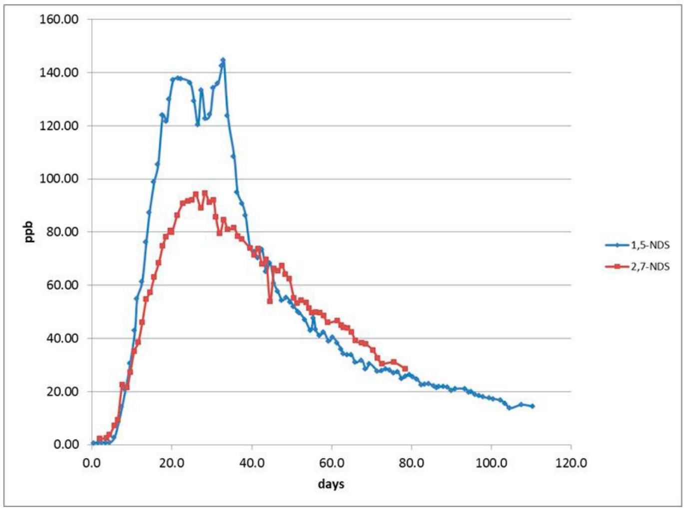

Figure 7. Tracer concentrations in Producer 1, showing 1,5 NDS detected in Blue and 2,7 NDS detected in Red.

Stimulation Improvements

A post stimulation injection test was conducted one month later to ensure complete TZIM degradation. The three step injectivity test showed over 30% improvement in injectivity with the well accepting 865gpm at 116 psi WHP and average injectivity of 2.89 gpm/psi. This improvement will result in higher production flow rates from the test well without causing additional drawdown. The final DTS profile (Figure 8) demonstrates the zones improved were deep and higher in temperature. The difference between the injection and static temperature surveys were used to quantify

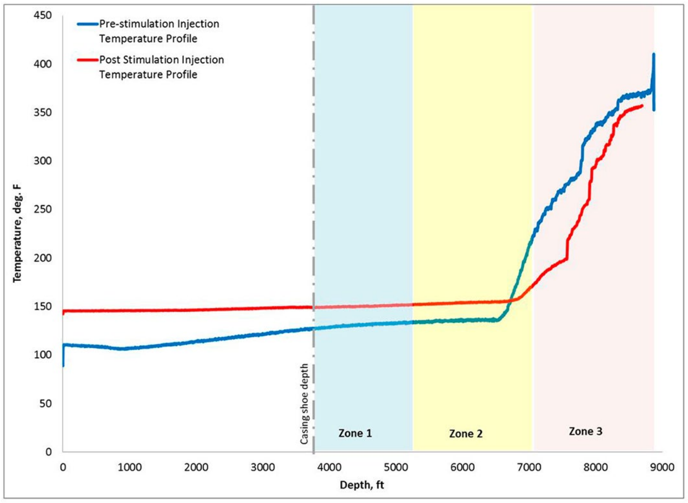

Figure 8. Pre-stimulation injecting profile (Blue) compared with post stimulation injecting profile (Red).

the flow and temperature enhancement per zone as a result of the stimulation. The estimated final production temperature after heat up may increase up to 40 degrees. The improved temperature and flow rates are expected to more than double the well's power production capability. A higher capacity production pump for the stimulated well is schedule for installation in 2013. Upon successful installation, a final step-rate production flow test will be conducted.

Conclusions

TZIM was successful in blocking shallow permeable zones and diverting stimulation deeper downhole to enhance multiple fractures in a low temperature producer without the use of packers. This stimulation successfully transformed an idle well into an economical producer with relatively low costs and low risks.

Two new production zones were created as a result of injection stimulation, and stayed open post stimulation.

Existing permeable zones below 6500' improved due to injection stimulation.

The stimulation improved the overall injectivity by approximately 30%.

The improvement will result in higher production temperature with the mixed flowing temperature ranging from 245F-260°F compared to 220°F pre-stimulation.

Intellectual Property Statement

AltaRock holds a portfolio of patents, patent applications, licenses and related proprietary intellectual property regarding its diverter and stimulation technology, materials and methods.

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