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AN EGS STIMULATION EXPERIMENT UNDER LOW WELLHEAD PRESSURES

Peter Rose, Jess McCulloch, Mike Adams, and Mike Mella

Energy and Geoscience Institute at the University of Utah
423 Wakara Way suite 300
Salt Lake City, Utah, 84108, USA
e-mail: prose@egi.utah.edu

ABSTRACT

A stimulation experiment was conducted involving Coso injection well 34A-9 as part of the DOE-funded Coso/EGS project. When the well was first drilled, its measured temperatures were among the highest ever recorded within the Coso field, but its permeability was poor. Steam condensate was then injected into the well, resulting in significant and immediate injectivity improvements. 34A-9 was subsequently used for several years as a steam condensate injector, but was shut in due to leaks in the shallow casing. Upon repairing the liner, a second stimulation test was conducted in August 2004, again resulting in injectivity improvements. Significant microseismicity was measured in the vicinity of the well during the early stages of injection. Tracer testing was conducted during a subsequent circulation test, revealing excellent communication with a neighboring production well. The potential for mineral scaling in the reservoir adjacent to 34A-9 was simulated for injection fluids of various compositions. The maximum dissolution of silica and calcite was calculated based upon injection-fluid chemistry and injection flow rate into 34A-9 between 1999 and 2003.

INTRODUCTION

During the past three decades, a number of research efforts around the globe have been directed towards developing EGS technologies under the various titles of Hot Dry Rock, Hot Wet Rock, Deep Heat Mining, Enhanced Geothermal Systems, and Engineered Geothermal Systems. The first of these projects was conducted in the United States, followed by others in the United Kingdom, Germany, France, Japan, Sweden, Australia and Switzerland. Vuataz (2001) reviewed the EGS papers presented at the 2000 World Geothermal Congress. More recently, an extensive EGS reference database has been compiled (Vuataz and Cattin, 2004).

The east flank of the Coso geothermal field is an excellent setting for testing Enhanced Geothermal System (EGS) concepts (see Figure 1). Fluid temperatures exceeding 300°C have been measured at depths of less than 10,000 ft, and the granitic reservoir is both highly fractured and tectonically stressed. However, some of the wells within this portion of the reservoir are relatively impermeable. High rock temperatures, a high degree of fracturing, high tectonic stresses and low permeability are the qualities that define an ideal candidate-EGS reservoir. With a grant from DOE, a team of scientists and engineers from Coso Operating Company, Geomechanics International (GMI), the Navy Geothermal Program Office, the USGS, Kansas State University, the Energy and Geoscience Institute and Q-con was formed for the purpose of developing and evaluating an approach for the creation of an EGS within the Coso east flank reservoir.

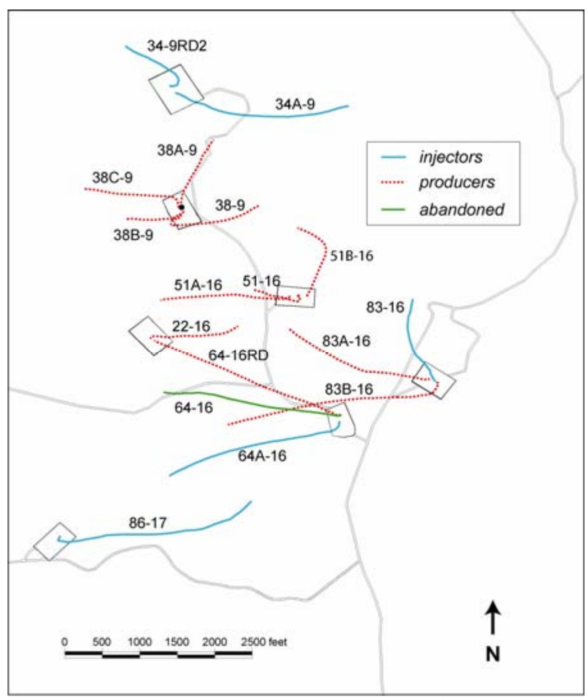

Figure 1. Locations and trajectories of wells within the east flank EGS study area of the Coso geothermal field.

PROGRAM OBJECTIVES AND APPROACH

The objective of the EGS project at Coso is to stimulate one or more low permeability injection wells through a combination of hydraulic, thermal and chemical methods and to hydraulically connect the well(s) to at least one production well. Thus, the objective is not only to design and demonstrate an EGS on the periphery of an existing geothermal reservoir, but to understand the processes that control permeability enhancement. The primary analytical tools used include borehole logs for imaging fractures and determining regional stresses, petrographic and petrologic analyses of borehole cuttings, petrophysical measurements of core samples, geophysical methods including microseismology and magnetotelluric (MT) studies, structural analysis, fluid-flow modeling, and geochemical modeling. Lessons learned at Coso will make it possible to design and create an EGS wherever appropriate tectonic, thermal and hydraulic conditions exist, thereby allowing geothermal operators to greatly extend their developmental reach beyond the relatively few naturally occurring hydrothermal resources.

This project is currently in the fourth of five years. The first year consisted of an analysis of existing data with an emphasis on characterizing the stress state of the Coso east flank and identifying candidate injection wells for hydraulic and thermal stimulation. Subsequent efforts focused on preparations for the creation of an EGS doublet between injection well 34-9RD2 and a newly drilled production well, 38C-9 (see Figure 2).

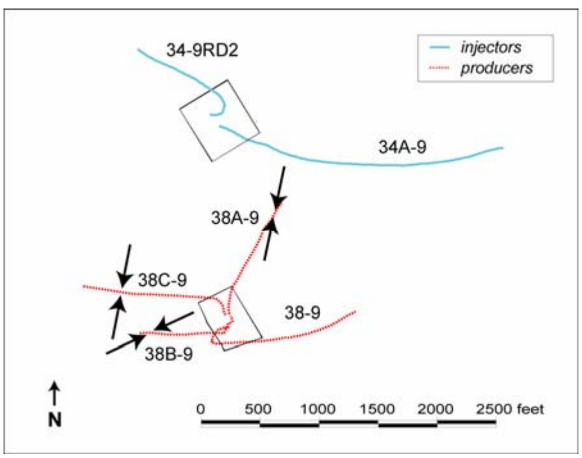

Figure 2. Plan view of the northern section of the EGS study area showing the wellhead locations and trajectories of wells 34-9 and 38-9. Also shown are the average SHmax azimuths for the three production wells 38A-9, 38B-9, and 38C-9 as determined from drilling induced tensile fractures imaged within the wellbores.

The injection well 34-9RD2 will be redrilled and hydraulically stimulated in 2005 (year 4) with the objective of creating permeability between it and production well 38C-9.

STIMULATION OF COSO WELL 34A-9

A stimulation experiment was conducted on Coso well 34A-9 in order to test the effects of injecting cold separated brine under high-flow, low-pressure conditions and to test many of the tools that have been developed in preparation for the hydraulic stimulation of other Coso wells.

Petrography and Petrology of Well 34A-9

Petrographic and petrologic studies of drill cuttings from Coso wells indicate that the reservoir has had a long and complex thermal history. Propagation and stimulation of fractures, particularly those that have been active during recent episodes of geothermal activity, can be expected to play a critical role in reservoir development. Thus an understanding of mineral parageneses and lithologic controls on fracturing is needed for understanding the effects of hydraulic stimulation in hot tight wells.

Analyses of thin sections and fluid inclusion measurements indicate that faults that were recently conductive can be distinguished from older, sealed faults. These studies have documented an early widespread episode of quartz, epidote and chlorite mineralization related to regional metamorphism of dioritic basement rocks that was followed by the intrusion of granitic rocks that are relatively unaltered and only weakly fractured. Younger veins related to recent geothermal activity and recharge by meteoric waters are dominated by minor quartz and later blocky calcite and hematite. It is possible that the calcite-filled fractures will preferentially fail in shear and become hydraulically conductive during stimulation experiments. However, shear failure itself does not guarantee subsequent increased permeability, since some faults may reseal upon failing in shear.

Careful petrographic and petrologic analyses were conducted on cuttings obtained during the drilling of well 34A-9. Shown in Figure 3 is a summary of rock type and vein mineralogy as a function of depth for injection this well. The rock in the deeper, more relevant portion of the well (between about 6,000 and 9,000 ft) consists mostly of biotite-granodiorite and hornblende-biotite-quartz-diorite, interspersed with minor sequences of metasediments and granite.

Injection History of Coso Well 34A-9

34A-9 was drilled to a depth of approximately 9,000 ft in 1993 with the trajectory shown in Figure 2.

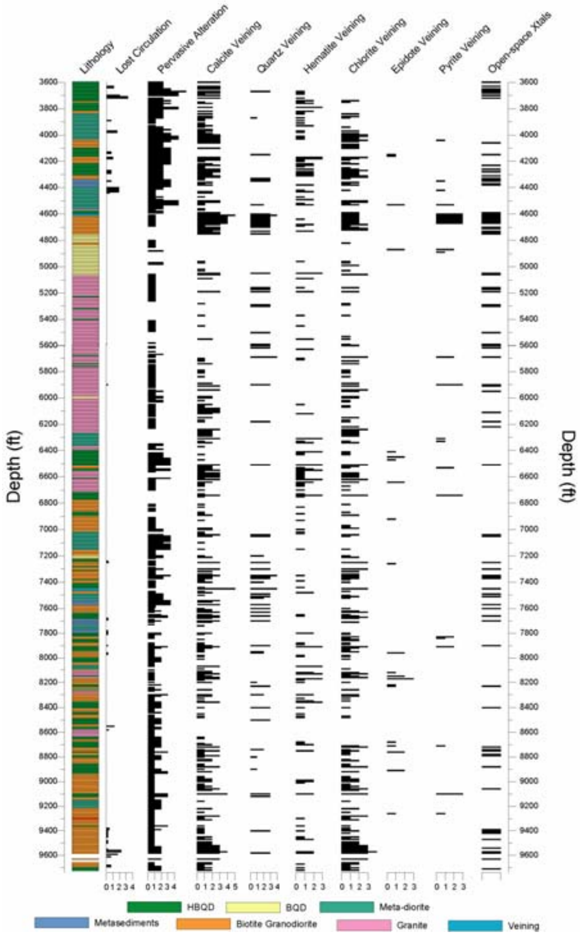

Figure 3. Summary of rock type and vein mineralogy as functions of depth for injection well 34A-9.

The well was drilled into the hottest portion of the East Flank but had low productivity due to low permeability. Coso Operating Company then conducted a series of low pressure stimulation experiments with the intent of increasing the productivity of the well. They injected cold condensate intermittently 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. Significant microseismicity was observed during the periods of injection.

34A-9 was then allowed to flow and its output was determined to be approximately 3 MWe. Whereas this represents a very significant and successful EGS result, the study was never documented and reported in the open literature. Likewise, the operators did not record and correlate much of the associated hydraulic, petrologic, geophysical and geomechanical data.

Repair and Low-Wellhead-Pressure Stimulation of 34A-9

34A-9 was used as an injection well for several years, but was shut-in due to a leak that developed at the top of the 9 5/8” casing. As a result of the leak, most of the injected fluid entered the reservoir at shallow depths rather than at greater depths where it was needed to provide reservoir-pressure support. It was therefore necessary to cement a 7-in casing ‘tie-back’ across the top of the 9 5/8” liner. The well would then be subjected to a series of tests to determine if injection of cold brine under low wellhead pressures could produce sufficient permeability to allow 34A-9 to be returned to service as an injection well. The well would be considered successfully stimulated if it could sustain an injection flow rate of at least 750 gpm with a wellhead pressure of 100 psi or less.

A stimulation experiment was conducted in 34A-9 in August, 2004 for the purpose of evaluating the effect of low-pressure injection on changes in permeability. Since the fluid level in 34A-9 was drawn down before the initiation of the experiment by approximately 3,000 ft, simply filling the wellbore would result in downhole pressure increasing by approximately 1300 psi. If some of the fractures intersected by the 34A-9 wellbore were optimally oriented and critically stressed, then such an increase in downhole pressure would result in shear failure with concomitant increases in permeability.

Prior to the initiation of the test, a helium-filled capillary tube was inserted into the wellbore to a depth of 3500 ft for the purpose of measuring downhole pressure. Pressure was also monitored at the wellhead and within the pipeline supplying the wellhead. Separated brine at a temperature of 260^{o}F was injected into the wellbore for one week at a rate of approximately 2,000 gpm. Brine having a temperature of 160^{o}F was subsequently injected at a rate decreasing from about 1600 to about 800 gpm over approximately five weeks. Significant microseismicity accompanied the injection experiment (Julian et al., 2005).

These data show that significant permeability improvements can be realized in wells stimulated under mild conditions. The stated objective of achieving 750 gpm at less than 100 psi wellhead pressure was achieved by a large margin. It must be noted, however, that the stimulation experiment summarized in this section was preceded by long periods of injection of steam condensate between 1994, when the well was first stimulated, and August of 2004, when the second stimulation experiment was conducted.

Tracer Testing of the Newly Stimulated 34A-9

In order to determine the fate of fluids injected into the newly stimulated 34A-9, a tracer test was initiated on 1 September, 2004. In this test, 100 kg of the tracer 1,3,6-naphthalene trisulfonate was injected as a pulse. The neighboring liquid-producing east flank wells were subsequently sampled and analyzed for the tracer. Figure 4 shows a plot of 1,3,6-naphthalene trisulfonate returns to the sampled wells. The return curve confirms that the stimulation of 34A-9 resulted in a very strong hydraulic connection to the neighboring well 38-9, with a slower but significant and building return to 38A-9.

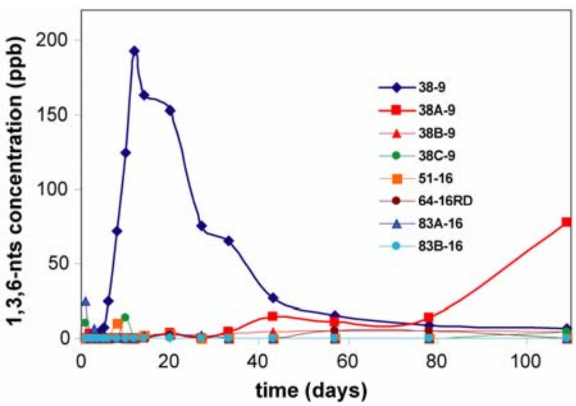

Figure 4. Tracer returns from tagged injection well 34A-9 to several Coso east-flank production wells.

Precipitation and/or Dissolution upon Injection

The scaling potential of various water compositions injected into 34A-9 was evaluated. A scenario was modeled in which each of four different waters—groundwater, acidified brine, a brine-condensate mixture, and steam condensate—was mixed with reservoir water. The heating of the mixtures to reservoir temperatures was simulated using the reaction path modeling program REACT (Bethke, 1994). Reservoir water was titrated into the injectate while the temperature was raised from 100^o to 275^{o}C. The final ratio of injected to reservoir water was 1:1. More details of these simulations are given in Adams et al. (2005).

Figure 5 shows the maximum amount of scale that would form from acidified brine (Fig. 5b) if quartz precipitated at temperatures below 200^{o}C. However, quartz is slow to precipitate at these temperatures (Rimstidt and Barnes, 1980). Amorphous silica is more likely, but the practice of acidifying injectate at Coso is designed to delay precipitation of this mineral until temperatures are reached at which the fluid is less saturated in amorphous silica. This applies to brine-condensate mixtures and pure condensate as well (Figs. 5c and 5d, respectively).

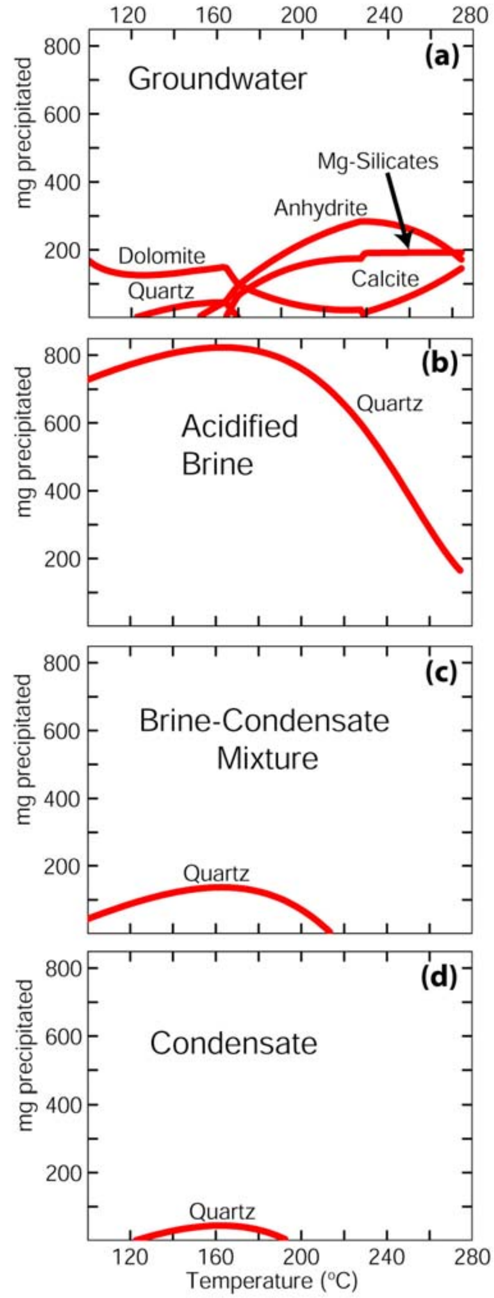

Figure 5. Chemical simulation in which different injectate compositions are mixed with reservoir water while being heated. Quartz precipitation is shown for comparison, although its actual precipitation is chemically inhibited.

Groundwater would clearly produce the most scale because of its relatively high concentrations of Ca, Mg, and SO_4 (Fig. 5a). Precipitation from groundwater injected into the Coso field is discussed further in Adams et al. (2005).

These simulations do not consider reaction of injectate with reservoir vein minerals. Dissolution of minerals along fractures was examined using a very simple model in which the maximum solubilities of calcite and quartz were calculated using REACT. The amount of mineral that could be dissolved was then calculated from the difference between the maximum-solubility concentrations and the measured calcium and silica concentrations in the injectate. The resulting concentrations were combined with flow rate data and integrated over the range of available data, which span the years 1999-2003 (Figure 6).

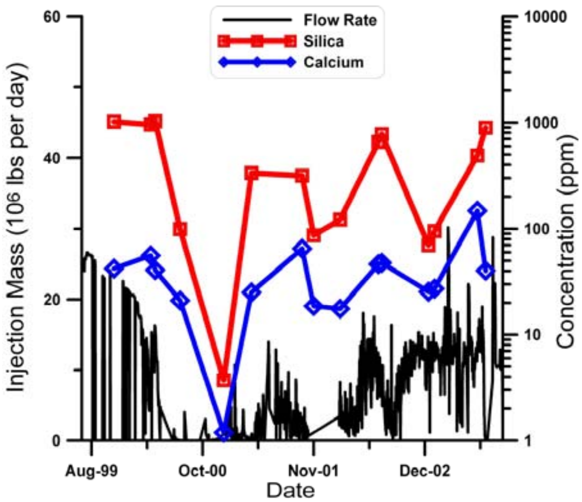

Figure 6. Injection data for well 34A-9 between 1999 and 2003. The black line shows the injectate flow rate, whereas the red and blue curves indicate the concentrations of silica and calcium in the injectate, respectively.

These calculations indicate that the waters may have dissolved as much 170 m^3 of quartz and 60 to 190 m^3 of calcite during the four years. The quantity of quartz dissolved is almost certain, since it does not depend on pH or the temperature gradient near the injection well. Calcite dissolution, in contrast, is very dependent on the temperature gradient near the well bore and the amount of mixing with reservoir water. It will dissolve near the well bore because of its retrograde solubility and then deposit away from the wellbore as temperature increases (Durst and Vuataz, 2001). Quartz, in contrast, will dissolve continuously as the water heats, but the amount will be greatest at the higher temperatures because of the logarithmic dependence of the solubility on temperature. Thus, dissolution of calcite may have the greater effect on increasing injectivity because of its proximity to the well bore, even though a greater volume of quartz is dissolved.

SUMMARY AND CONCLUSIONS

A stimulation experiment was conducted on Coso injection well 34A-9 as part of the DOE-funded Coso/EGS project. Significant improvements in injectivity resulted from this stimulation, which was achieved under low wellhead pressure. Microseismicity was measured in the vicinity of the well during the early stages of injection, with many of the earthquakes occurring between the 34A-9 and an adjacent well 38-9. A tracer test was conducted during a subsequent circulation test, revealing that excellent hydraulic communication had been established between these two wells. A petrographic and petrologic study was conducted on 34A-9 for the purpose of identifying rock types and alteration mineralogy.

The potential for mineral scaling in the reservoir adjacent to 34A-9 was simulated for injection fluids of various compositions. Groundwater would clearly produce the most scale because of its relatively high concentrations of Ca, Mg, and SO_4. The maximum dissolution of silica and calcite in the reservoir adjacent to 34A-9 was modeled based upon injection-fluid chemistry and injection flow rate into 34A-9 between 1999 and 2003. These calculations indicate that the waters may have dissolved as much 170 m^3 of quartz and between 60 to 190 m^3 of calcite during the four years.

ACKNOWLEDGEMENTS

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