The Coso EGS Project—Recent Developments

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ABSTRACT

An Engineered Geothermal System (EGS) field experiment will be conducted to hydraulically stimulate injection well 34-9RD2, located on the east flank of the Coso geothermal reservoir, with the objective of increasing the injection rate of this well to 750 gpm at a wellhead pressure of 100 psi or less. The stimulation of this well is expected to create hydraulic communication with the recently drilled production well 38C-9, which is directly south of 34-9RD2. We summarize the results of fracture and stress analyses based upon borehole image logs of 38C-9; petrographic and petrologic analyses of cuttings from both the injection well 34-9RD2 and the production well 38C-9; and plans for the redrilling and stimulation of 34-9RD2.

Introduction

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.

Key to the creation of an EGS is an understanding of the relationship between natural fracture distribution, fluid flow and the ambient tectonic stresses that exist within the resource. Once these relationships are determined, we will proceed to design a hydraulic stimulation experiment of an east-flank injection well as the first step in the creation of a heat exchanger at depth. We will quantify the success of our experiment through hydraulic, microseismic, geomechanical, and geochemical measurements.

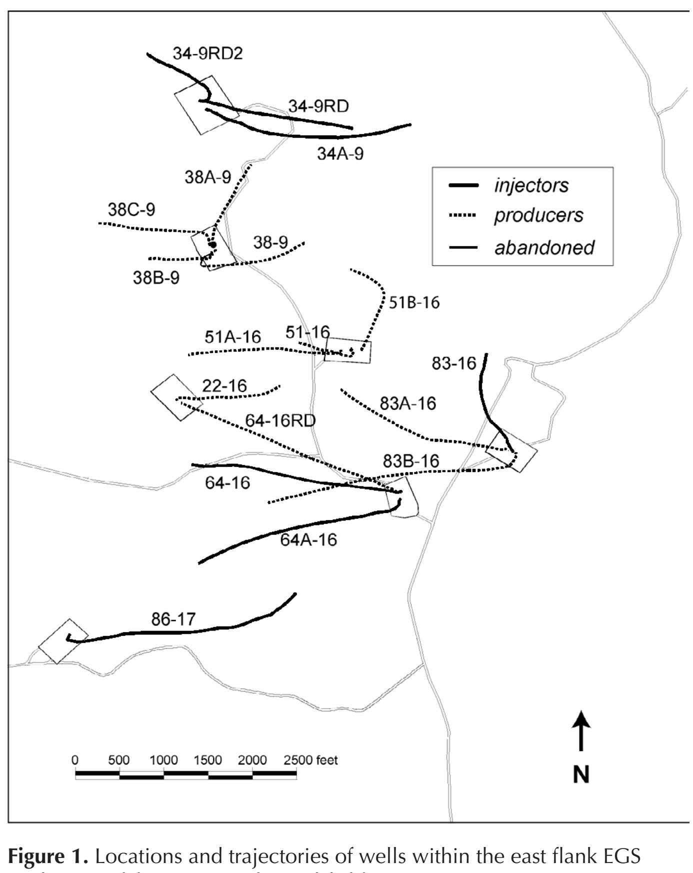

Figure 1. Locations and trajectories of wells within the east flank EGS study area of the Coso geothermal field.

The Coso/EGS 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 this well to at least one production well. Our 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 that we will use include borehole logs to image fractures and determine regional stresses, petrographic and petrologic analyses of borehole cuttings, petrophysical measurements of core samples, geophysical methods including microseismology and magneto-telluric (MT) studies, structural analysis, fluid-flow modeling, and geochemical modeling. We believe 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 high-grade hydrothermal resources.

We are currently in the third year of a 5-year project. The first year consisted of an analysis of existing data, largely from several east flank wells (see Figure 1), in order to characterize the stress state of the Coso east flank and to identify candidate injection wells for hydraulic, and thermal stimulation. Subsequent efforts focused on the creation of an EGS doublet between injection well 34-9RD2 and a newly drilled production well, 38C-9 (see Figure 2). The injection well 34-9RD2 will be redrilled and hydraulically stimulated in 2004 (year 3) with the objective of creating permeability between it and production well 38C-9.

Geomechanics

Barton et al. (1998, 1995) have shown that optimally oriented, critically stressed fractures control permeability in areas of active tectonics. Likewise, we suspect that critically stressed and optimally oriented fracture sets are likely to be the most responsive to stimulation on the east flank of the Coso geothermal field. A knowledge of the local stress tensor is needed to determine the proximity of natural fractures to frictional failure and therefore, to determine their role in reservoir permeability. A detailed analysis is required in order to develop a geomechanical model of the reservoir and to determine which fractures are optimally oriented and critically stressed for shear failure. The geomechanical model includes the pore pressure (P_p), the uniaxial compressive rock strength (C_0), and the magnitudes and orientations of the most compressive (S_1), intermediate (S_2), and least compressive (S_3) principal stresses. These are derived from in situ pore pressure measurements, laboratory rock strength tests, wireline log data, minifrac test results, and observations of wellbore failure. Only through fracture and wellbore-failure analyses of image data, correlated with petrographic analyses, can we understand the effects of subsequent stimulation experiments upon increases in fracture permeability.

Well 38C-9 is the first of two new wells planned for an Enhanced Geothermal System in the Coso east flank area. This well is intended to be the production leg of the EGS doublet. Well 38C-9 datasets were analyzed to characterize fracture orientations and stress magnitudes and orientations in order to identify the subset of critically stressed planes that act to maintain permeability within the reservoir. These results will be incorporated in the 34-9RD2 stimulation design. The image analysis for 38C-9 shows a preponderance of moderate- to steeply dipping fractures, dipping either to the northeast or northwest, similar to results from other wells in the area.

The orientation of drilling-induced tensile fractures and a single borehole breakout indicate an S_{Hmax} azimuth of 11º ±17º in well 38C-9 (Figure 2). This is parallel to the S_{Hmax} azimuth observed in well 38A-9, but differs somewhat from that observed in two other EGS study wells, 38B-9 and 83-16. Hydraulic fracturing stress tests demonstrate that the magnitude of S_{hmin} is relatively low (about 0.63 of the vertical stress) but slightly above that predicted for normal faulting failure. However, borehole failure analysis and simple frictional faulting theory indicate that this value of S_{hmin} and approximate bounds on S_{Hmax} are consistent with crustal strength being controlled by strike-slip faulting. A hydraulic fracturing stress test in a deeper interval of 34-9RD2 will constrain the stress model further. Fracture failure analyses using the improved Coso stress model indicate that strike-slip faulting can be achieved on optimally oriented fractures with pressures less than 500 psi above ambient, whereas pressures between 500 and 1,000 psi above ambient are required to achieve slip through normal faulting (Sheridan and Hickman, 2004).

Petrologic Relationships

Petrologic studies of Coso indicate that the reservoir has had a long and complex thermal history. Propagation and

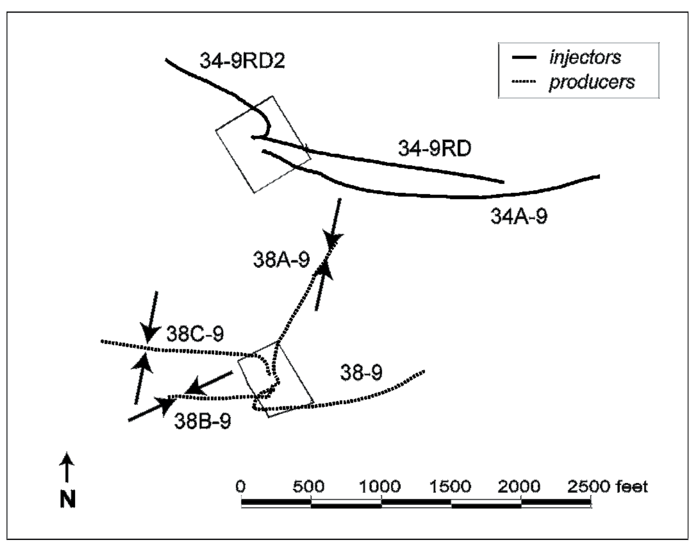

Figure 2. Plan view of the northern section of the EGS study area showing the wellhead locations and trajectories of wells 34-9 and 38-9. Also shown are the average S_{Hmax} azimuths for the three production wells 38A-9, 38B-9, and 38C-9 as determined from drilling induced tensile fractures imaged within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

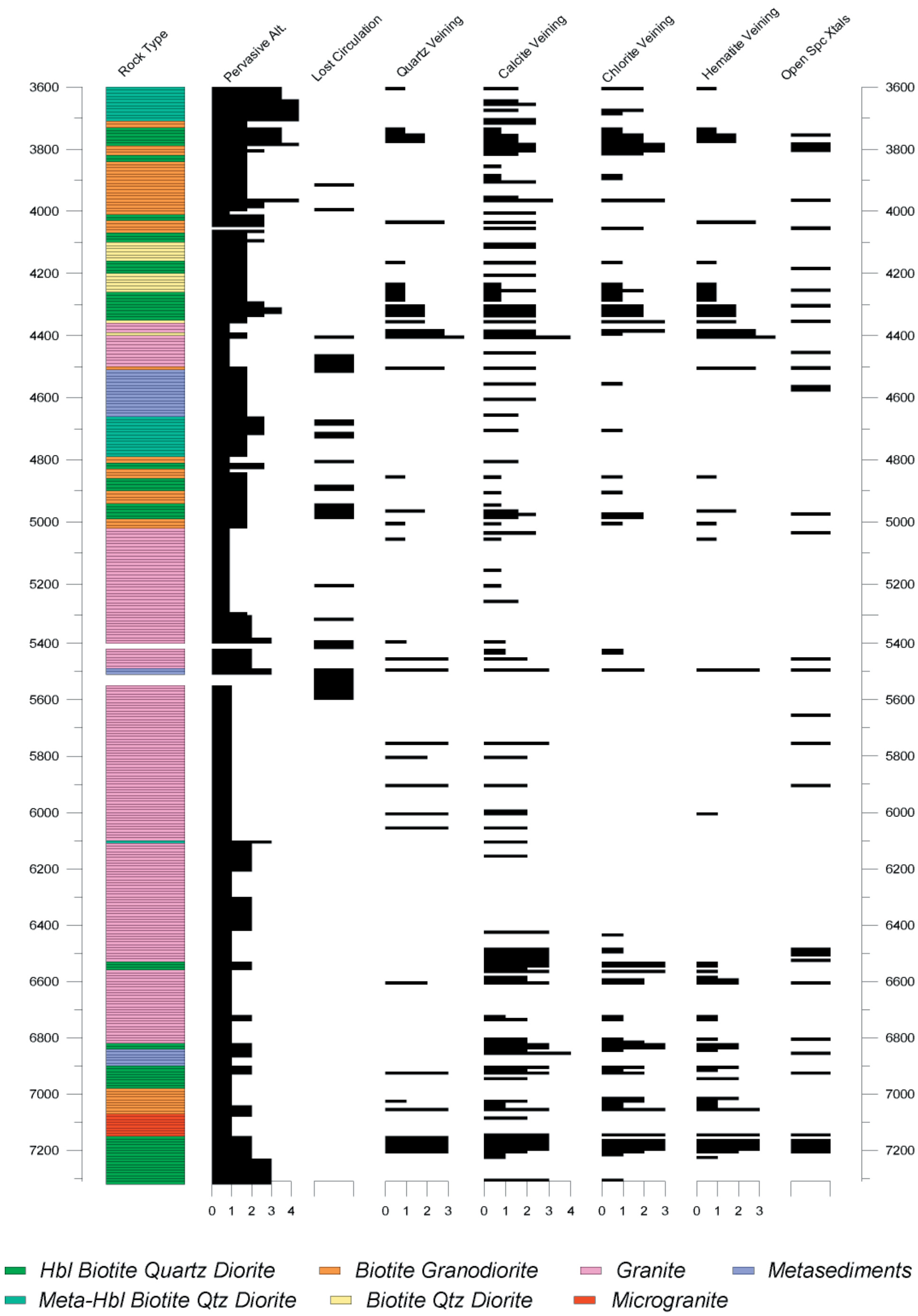

Figure 3. Summary of rock type and vein mineralogy as functions of depth for injection well 34-9RD2.

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 are 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 the stimulation experiments conducted in well 34-9RD2. This possibility will be tested during the 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 wells 34-9RD2 and 38C-9. Shown in Figure 3 is a summary of rock type and vein mineralogy as a function of depth for injection well 34-9RD2. These analyses include only the region adjacent to the proposed open-hole section. The large granite interval between about 4400 ft and 6800 ft is the largest section of granite observed in any well studied within the east flank compartment. This granite, as elsewhere is less altered, and less fractured than the older dioritic rocks into which it has intruded.

Figure 4, overleaf, shows a similar cross-section of rock types and alteration minerals in the targeted production leg of the EGS doublet, 38C-9. The predominant rock types are hornblende-biotite-quartz-diorite and the closely related meta-hornblende-biotite-quartz-diorite. There is, however, a considerable thickness of granite and microgranite, which presumably occurs as dikes and sills. The petrology and petrology of this well is representative of the production wells within the east flank compartment, with the exception that it contains considerably more quartz veining.

Preparation of Injection Well 34-9RD2 for Stimulation

Before initiating the hydraulic stimulation experiment, we will deepen the injection well 34-9RD2 by 500 ft. First, the 7-in liner that currently spans the depth between 3,350 ft and 7,600 ft will be removed. A suite of logs to measure pressure, temperature, and spinner (PTS) data as well as density, poros-

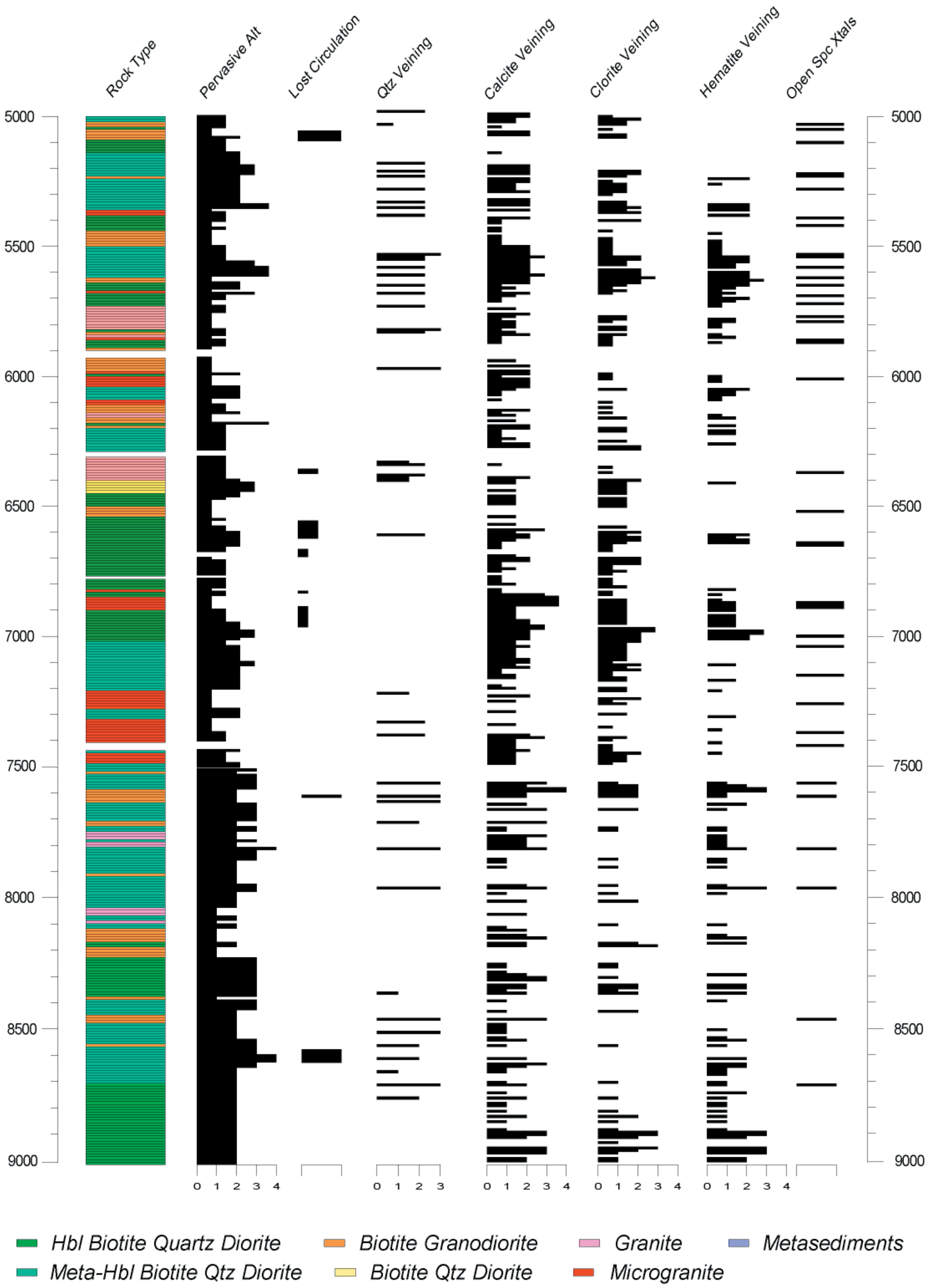

Figure 4. Summary of rock type and vein mineralogy as functions of depth for production well 38C-9.

ity, and resistivity will then be run. In addition, a Schlumberger Formation Micro Scanner (FMS) log and a high-temperature borehole televiewer log will be run over the open-hole section. These latter two logs will serve to characterize the dip and azimuth of existing fracture sets and to image existing borehole breakouts. An analysis of data collected from the various logs will serve to augment our understanding of the fracturing and stresses within the rock volume surrounding the wellbore, which is crucial to our understanding of the subsequent stimulation experiment.

After cementing lost circulation zones, a new 7-in liner will be installed and cemented from the surface to the casing shoe at 7,600 ft. A 10-ft section will then be drilled using a 6.125-in bit and a mini-hydrofrac test will be conducted with the objective of measuring the minimum horizontal stress (S_{hmin}) at this depth. Drilling will proceed with the extraction of 30 ft of core between approximately 7,610 ft and 7,640 ft, followed by the drilling of the remainder of the 500-ft open-hole section. Cuttings will be collected at 2-ft intervals and spot core will be retrieved between 8,070 ft and the total depth of 8,100 ft.

A second suite of logs (PTS, density, porosity, resistivity, FMS, and borehole televiewer) will be run unless precluded by high borehole temperatures. Whereas the deepened open-hole segment may be too hot for the deployment of many of the logging tools, we expect that we will be able to deploy the borehole televiewer, which has been temperature-hardened to withstand temperatures up to 275°C.

Finally, an injection test will be conducted using the rig pumps in order to characterize the injectivity of the well over the 500-ft open-hole section. Data obtained from this test will be used to finalize the design of the stimulation experiment.

Stimulation of Injection Well 34-9RD2: Preliminary Design

Upon completion of the preparation and redrilling of the target injection well, a massive hydraulic stimulation experiment will be conducted. The objective of this experiment is to hydraulically stimulate the formation adjacent to 34-9RD2, and achieve an injection rate of 750 gpm at a wellhead pressure of 100 psi while developing hydraulic communication with surrounding wells. Achievement of this objective would result in an increase in production of approximately 5 MWe.

Our approach to permeability enhancement within the Coso east flank follows from our concept that increases in pore pressure will allow for stress relief and the creation of shear failure along fractures that are optimally oriented and critically stressed. In addition, we expect that a significant fraction of these fractures will be self propping due to asperities along the fault surfaces. In hard, fractured rocks, this approach has advantages over 'hydro-frac' techniques employed in conventional oilfield stimulations. Primarily, it allows for permeability enhancements in a much larger volume due to increased fracture reopening both along the length of the open-hole section and at greater distances away from the wellbore.

Since conventional oil-field stimulations typically target the creation and extension of a single fracture or a small number of fractures, they can be accomplished with a relatively small fluid volume over a relatively short duration, using a flow-rate constraint. In order to stimulate a large volume of rock and thereby create a large-volume heat exchanger, it is necessary to inject a large fluid volume over relatively long durations. In addition, such stimulations require the achievement of high initial fluid pressures in order to initiate shear failure in fractures along the entire length of the open-hole section. High initial pressures can be achieved either by injecting at very high flow rates and/or by initiating the flow process with heavy brine, thereby increasing the down-hole hydrostatic pressure gradient. High initial pressures result in the stimulation of a broader spectrum of fractures and fracture orientations as fractures are made to slip simultaneously. Alternatively, increasing flow rate and pressure in a slow and stepwise fashion always favors only the shallowest and most optimally oriented fractures.

Although the initial pressures must be high, they should not be so high as to exceed the minimum horizontal stress of the reservoir, which would result in the creation of near-wellbore tensile fractures. Sheridan and Hickman (2004) calculate that the onset of shearing within Coso well 34-9RD2 is expected between 500 and 1000 psi overpressure, with S_{hmin} at approximately 5,000 psi within the targeted open hole segment. Figure 5 reveals a possible stimulation strategy. Flow is initially ramped to a target level that exceeds the requirement for the onset of shearing, but that is less than the minimum horizontal stress (5,000 psi downhole) and less than the wellhead constraint of 3000 psi. The flow rate will be adjusted to maintain the pressure at this level during an extended period, during which microseismic sensing will be conducted in order to monitor the creation of a fracture network away from the wellbore.

If the initial target pressure is deemed insufficient to result in an appropriate level of fracturing, the pressure will be increased in a stepwise fashion as shown in Figure 5 until the rate of fracturing is sufficient or until the maximum wellhead constraint is reached. If necessary, the minimum horizontal stress would be breached, resulting in the onset of tensile fracturing. Jung and Weidler (2000) have shown that the creation of such 'mixed fracture' systems can produce very favorable heat exchangers, since complex interactions between induced tensile fractures and natural fractures can result in a kind of self-propped hydro-frac. The creation of tensile fracturing in the early stages of the stimulation, however, is not desirable, since such fractures are likely candidates for the development of dominant flow channels at the expense of a broader and more evenly dispersed fracture network.

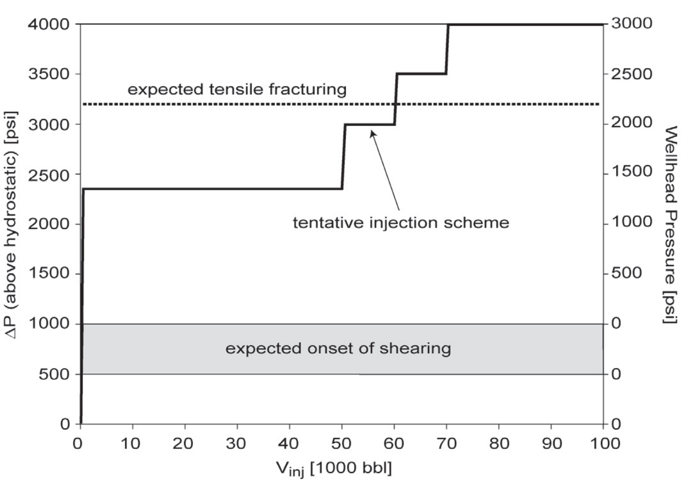

Figure 5. Possible strategy for the stimulation of injection well 34-9RD2.

Conclusion and Summary

We are in the final preparation stages for the stimulation of the tight injection well 34-9RD2 on the east flank of the Coso geothermal reservoir. A preliminary fracture/stress analysis shows that a significant number of fractures intersecting this wellbore are optimally oriented for shear failure and that slip could occur with wellhead overpressures between 500 and 1000 psi. Petrologic and petrographic studies of 34-9RD2 and the planned production leg of the EGS doublet, 38C-9, are complete. They show that 34-9RD2 intersects a large interval of relatively unfractured and unaltered granite just above the targeted open-hole section, whereas the 38C-9 wellbore intersects mostly the diorites that are observed in other Coso-east-flank production wells. This latter well exhibited more quartz veining, however, as compared to other east-flank production wells.

A preliminary plan for the workover, redrilling, and stimulation of 34-9RD2 is complete. It includes the replacement of the 7-in liner, a mini-hydrofrac test to measure the minimum horizontal stress, numerous wellbore logging and imaging tests, the drilling of a 500-ft open-hole section and the retrieval of two 30-ft spot cores. The stimulation is expected to be conducted at downhole pressures that do not exceed the minimum horizontal stress, S_{hmin}, and at flow rates that do not exceed 750 gpm. However, the duration of the injection experiment and total injection volume are expected to be significantly greater than those in conventional oilfield hydrofracs.

Acknowledgements

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