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OVERVIEW OF THE NORTHWEST GEYSERS EGS DEMONSTRATION PROJECT

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ABSTRACT

An Enhanced Geothermal System (EGS) Demonstration Project is currently underway in the northwest Geysers. The project goal is to demonstrate feasibility of stimulating a deep high-temperature reservoir (HTR) (up to 750 ^{o}F, 400 ^{o}C). Phase I of the EGS Demonstration, Prestimulation, has been completed, which included initial site characterization and well recompletions. Two previously abandoned wells, Prati State 31 (PS-31) and Prati 32 (P-32) were reopened and deepened to be used as an injection and production well pair to stimulate the HTR. The deepened portions of both wells have conductive temperature gradients of 10 ^{o}F/100ft (182 ^{o}C/km). Phase II of the EGS Demonstration, Stimulation, commenced in October 2011 with injection into P-32. Analysis of preliminary data of the reservoir response to injection is included.

INTRODUCTION

The Enhanced Geothermal System (EGS) Demonstration Project is located in the Northwest Geysers where a high temperature reservoir (HTR) up to 750 ^{o}F (400 ^{o}C) has been identified. The HTR underlies a normal temperature reservoir (NTR) where temperatures are in the vicinity of about 465 ^{o}F (240 ^{o}C). The EGS Demonstration Area was originally explored in the 1980s with a number of exploration wells that were never produced. These exploratory wells were abandoned in 1999 because of problems caused by high concentrations of non-condensable gases (NCG) and highly corrosive hydrogen chloride gas condensate in the steam produced from the HTR. The EGS Demonstration is in an area where the HTR is relatively shallow and the abandoned wells are sufficiently deep to penetrate the upper portion of the HTR (Figure 1). Two of the previously abandoned wells, Prati State 31 (PS-31) and Prati 32 (P-32), were reopened, deepened and recompleted for direct injection and stimulation of the HTR.

The intent of the EGS Demonstration is to show that the permeability of the HTR can be stimulated by fracture reactivation when cool water is injected into very hot rocks at low flow rates (1000 gpm, or less) and low pressures (about 10 MPa, or less). Water injection into the HTR is also anticipated to lower the concentrations of NCG and volatile chlorides, as well as provide sustainable steam flow to nearby steam production wells. This project was also originally motivated by evidence for an inadvertently created EGS at depths of 3 to 5 km in the HTR about 3 miles southeast of the EGS Demonstration (Stark, 2003).

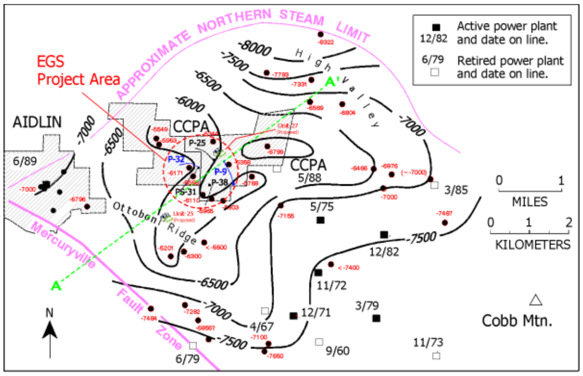
The Northwest Geysers EGS Demonstration Project is funded by the US Department of Energy's (DOE) Geothermal Technologies Program and Geysers Power Company (Calpine) and is a collaborative effort between scientists and engineers at Calpine and Lawrence Berkeley National Laboratory (LBNL).

The project is organized into three phases:

- Phase I: Pre-stimulation
- Phase II: Stimulation and Analysis
- Phase III: Long Term Data Collection, Monitoring, and Reporting

During Phase I, a concise stimulation plan was developed based on a detailed geological model, analysis of historical data, and pre-stimulation modeling. A set of stimulation scenarios were presented by Rutqvist et al. (2010) from a coupled thermal, hydraulic, and mechanical (THM) model developed at LBNL.

Phase II of the project commenced in October 2011 with injection of tertiary-treated wastewater from the City of Santa Rosa into the HTR via P-32. Injection is expected to continue until October 2013.



Contoured elevation in feet (msl datum) of top of high temperature reservoir.

Figure 1. Northwest Geysers steam field and elevation of top of high temperature reservoir. Cross section AA' shown in Figure 2.

This paper summarizes field work completed during Phase I including: site preparation, wellbore readiness, and baseline testing and preliminary results from Phase II including analysis of the early response to injection.

GEOLOGICAL SETTING

The EGS Demonstration Area is part of an undeveloped 10 square-mile area of the Northwest Geysers, between the Calpine Aidlin Power Plant and the Calpine Ridgeline Power Plant (Units 7 & 8). In this area the HTR is at its shallowest depth and has been identified from pressure-temperature logs to be at 5500 to 6000 feet below sea level. The rock in the HTR is thermally-altered biotite hornfelsic metagraywacke and intercalated argillite (Figure 2).

The geothermal resource in the EGS area was explored by PS-31 and P-32, and the nearby steam production wells Prati 25, Prati 37 and Prati 38 (Walters et al., 1992). In P-32 the HTR was encountered near a depth of about 8400 ft (2.6 km). Flowing steam temperatures at the bottom of the well were logged at 656°F (347°C) prior to failure of the Pressure-Temperature-Spinner (PTS) tool (Walters et al., 1992). Where PTS logs were available, the calculated enthalpies in the HTR ranged from 1,300 to 1,320 BTU/lb with apparent temperature gradient ranging from approximately 5 to 10 °F/ 100 feet depth increase (Walters et al., 1992). All data from these wells are publicly available at the California Division of Oil Gas and Geothermal.

Whole-rock and steam oxygen-18 data for the wells are published in Walters and Beall (2002), and Walters et al. (1996). The NCG data for the wells were published in Walters and Beall (2002). Additional NCG and isotopic data, demonstrated a well-defined chemical distinction between gases from the NTR and HTR (Kennedy and Truesdell, 1996). A description of the HTR is published in Walters et al. (1992).

In the Northwest Geysers, mapped surface faults and fracture zones (Nielson et al., 1991) may be used to delineate distinctly different reservoir blocks: some reservoir rock blocks are isotopically less-exchanged rocks by meteoric water than the isotopically more-exchanged rocks typically found throughout the Geysers steam fields. Additional whole-rock oxygen-18 analyses collected for the project together with temperature logs showed the presence of conductive temperature gradients that indicated the HTR in the EGS Demonstration Area had not exchanged with meteoric water and therefore was a non-hydrothermal, hot dry rock reservoir.

Pressure data, reservoir modeling, isotopic and NCG data, as well as published analysis of temperature logging by the US Geological Survey indicated that the EGS Demonstration site was relatively younger and partially isolated from the steam reservoir to the south, east, and west. Steam from the HTR contained much higher NCG concentrations, higher pressures than the depleted main Geysers steam fields to the southeast. The high temperatures recorded in the HTR suggested the area is underlain by a recent igneous intrusion, which began cooling 5,000 to 10,000 years before present (Williams et al., 1993).

Structurally, the Geysers reservoir is within the terrane of the San Andreas Fault system and is still strongly influenced by Franciscan-age subduction, Tertiary thrust faulting and high-angle Quaternary faults. Oppenheimer (1986) indicated that seismic sources in The Geysers occur from almost randomly-oriented fracture planes. Lockner et al. (1982) performed experiments to determine the mechanical characteristics of rocks from the Geysers reservoir. They concluded that fracturing and hydrothermal alteration had weakened the rock sufficiently such that the reservoir was only able to support a frictional load.

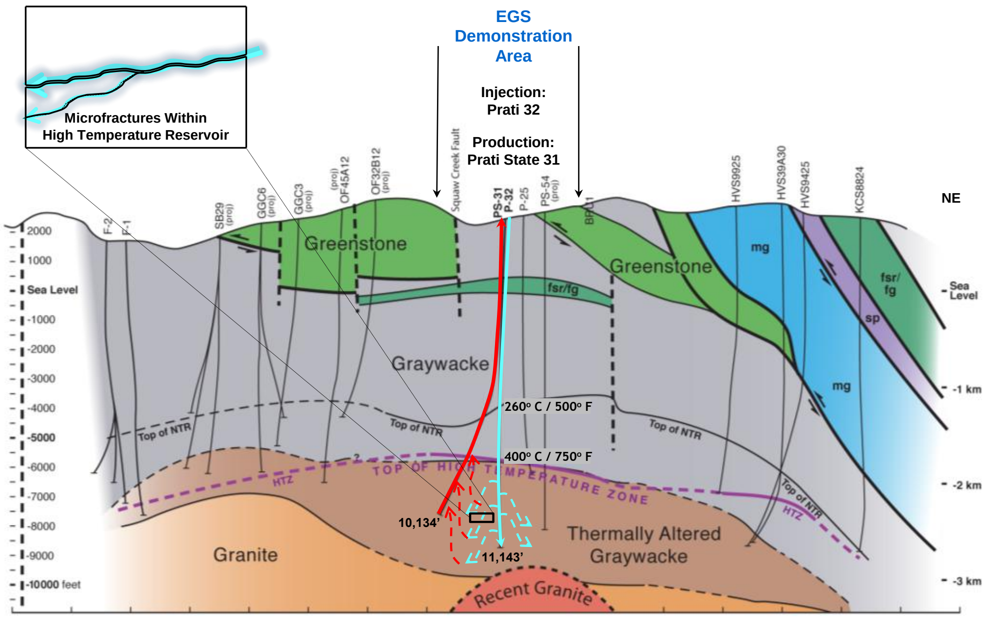


Figure 2. Geologic cross-section of The Geysers and location of the EGS Demonstration Area. Line of cross section is shown in Figure 1.

PHASE I: PRE-STIMULATION

Wellbore Readiness

Two previously abandoned wells, PS-31 and P-32 were reopened and deepened as an EGS production-injection well pair in the HTR. The testing and logging wells indicated there is some localized permeability in the HTR as evidenced by steam entries in the HTR in both wells (Figure 3). The presence of steam entries in the HTR was unexpected because the oxygen-18 data and conductive temperature gradients provided no indication that meteoric water had circulated in the HTR.

Recompletion of Wells

The EGS Demonstration Project initially planned for PS-31 and P-32 to comprise an injection and production well pair, respectively. After deepening the wells, a significant steam entry was identified at 11,000 ft in P-32 with a temperature of 750 °F (Figure 4). The high temperature and apparent permeability resulted in a revised plan to use P-32 as the injection well and PS-31 as the production well.

Figure 4 shows good agreement between the temperature profiles from P-25 and PS-31. These PT surveys confirmed the temperature regime of the NTR at around 450 °F and the underlying HTR indicative of a conductive temperature gradient (10 °F/100ft - 182 °C/km) present in the latter with maximum temperature of about 750 °F at TD.

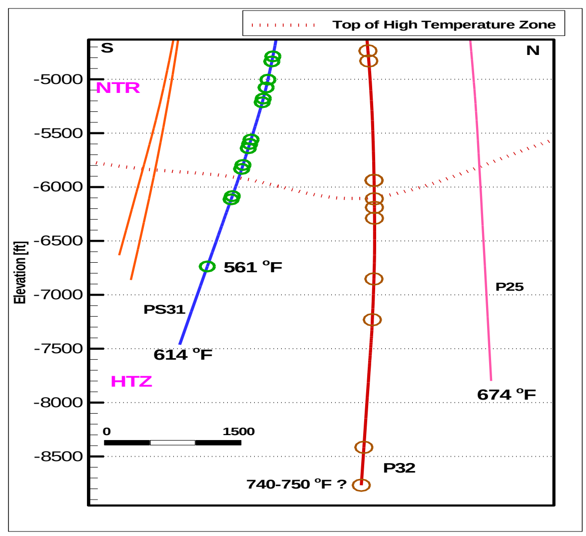


Figure 3. Cold water injected into P-32 (red) is produced from PS-31 (blue). Circles represent steam entries.

The well designs were modified to accommodate the decision to switch P-32 to injection and P-31 to production. P-32 was deepened from 9600 ft to 11,143 ft and a 5-1/2” blank liner was hung from the surface to 8,500 ft (Figure 5). The remaining well was not modified and remains slotted liner from 8,500 ft to TD where injectate is expected to stimulate the HTR, which starts in this area at depths around 7,900 ft.

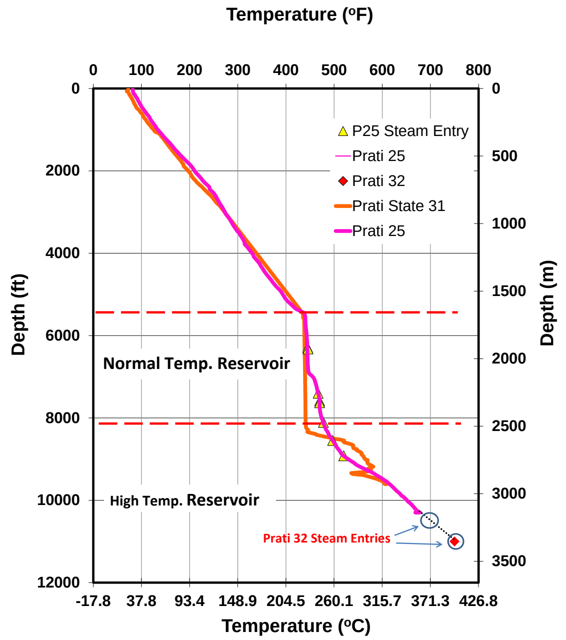


Figure 4. Static Temperature profiles for PS-31, P-25, and P-32 based on pressure-temperature logs

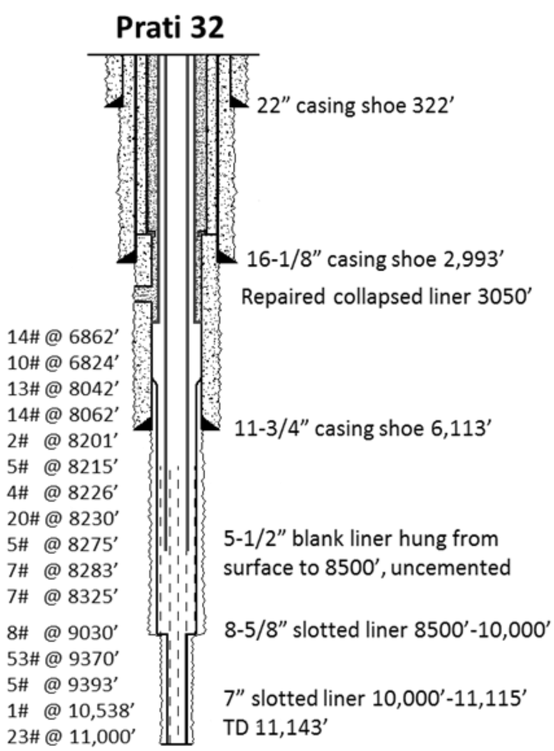


Figure 5. P-32 completion schematic (not to scale).

Initially, PS-31 deepened from 9,000 ft to 10, 034 ft in August 2010 with about 2,000 ft of slotted liner in the HTR. To switch PS-31 over to a production design the overlying blank liner was perforated so the well could communicate with both the NTR and the HTR (Figure 6).

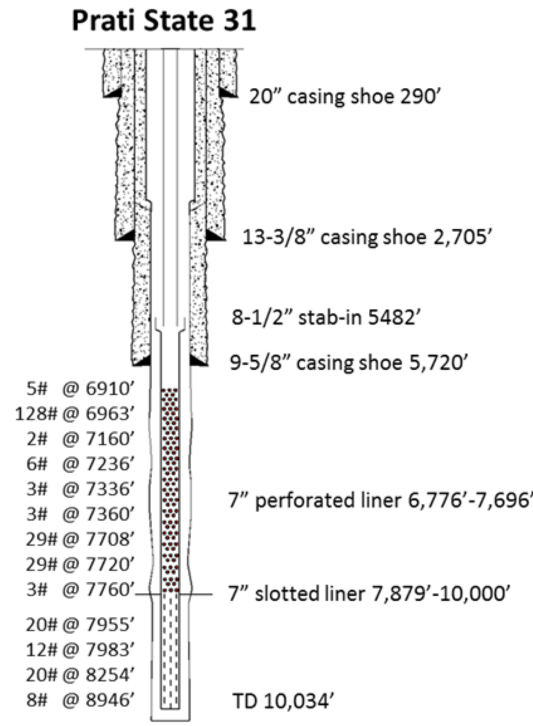


Figure 6. PS-31 completion schematic (not to scale).

The deepening of the EGS injection-pair into the HTR was significantly affected by the high rock temperatures which slowed the rate of penetration while air drilling from a typical rate of 15 to 20 ft/hr to less than 10 ft/hr (Figure 5).

Figure 7. Average bit condition after 300' of typical air drilling in the normal temperature Geysers reservoir (left) and Prati 32 final bit condition after 100' of air drilling to final depth (11,134')in the high temperature reservoir.

Flow Testing

Before recompletion of P-32 as an injector, it was flow tested with a resulting steam flow rate of 84,400 lbs/hr at a normalized pressure of 100 psig, 4 wt% NCG concentrations with 1240 ppmw H_2S, and chloride concentrations in the steam condensate of 135 ppmw.

Three well flow testing campaigns were made in PS-31, the results of which are displayed on Figure 8. The first test was completed on October 13, 2011 before PS-31 was recompleted as a producer. Thus the 3-day isochronal flow test was completed with the NTR behind unperforated blank liner. A flow rate of 42,900 lbs/hr at a normalized pressure of 100 psig with a wellhead enthalpy of 1188 BTU/lb was observed (WHT = 321 F, and WHP = 67psig).

The maximum shut-in well head pressure following the well test was 321 psig. The total NCG concentration in the steam was 4.4 wt% with 1231 ppmw H2S and 135 ppmw chloride concentration in the steam condensate. The PTS log made during this flow test showed superheated steam flowing up the well bore to about 1200 ft depth and saturated steam from about 1100 ft to the surface.

After the perforations were shot in the 7” blank liner from 6,776 ft to 7,696 ft, PS-31 was tested a second time on September 6-7, 2011. PS-31 flowed 52,700 lbs/hr at a normalized pressure of 100 psig. The increased flow rate was attributed to steam entries from the NTR where the blank liner had been perforated.

A third flow test of PS-31 was made September 28, 2011. The flow rate from PS-31 measured during this test was the same as the September 6, 2011 flow rate.

A difference in the pre-perforation PTS logs versus post-perforating logs is that the spinner shows an increase of about 1000 rpm above the top perforation (6776 ft). This is a consequence of an increased flow rate of 10,000 lbs/hr from nine steam entries in the NTR which were covered with 7” blank liner section prior to the perforation job between 6776 ft and 7696 ft.

PHASE II: STIMULATION

Injection into Prati 32 began on October 6, 2011 at 10:20 am. In accord with the usual injection startup procedure for new injection wells at the Geysers, a high initial rate of 1100-1200 gpm was used to collapse the steam bubble in the well bore and nearby formation so that the injected water was drawn into the well and surrounding rock. The high rate was continued for 12 hours then reduced to approximately 400 gpm and maintained for 55 days. Figure 9 shows the early injection history into P-32 and well head pressure (WHP) increases in three offset, shut-in wells PS-31, P-38 and P-25 (Figure 10).

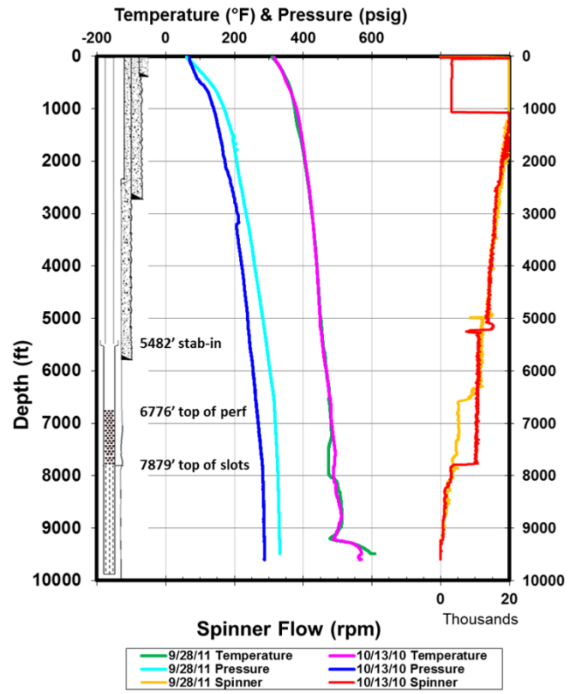


Figure 8. Flowing Pressure-Temperature-Spinner (PTS) logs at PS-31(10/13/10, 9/6/11, and 9/28/11)

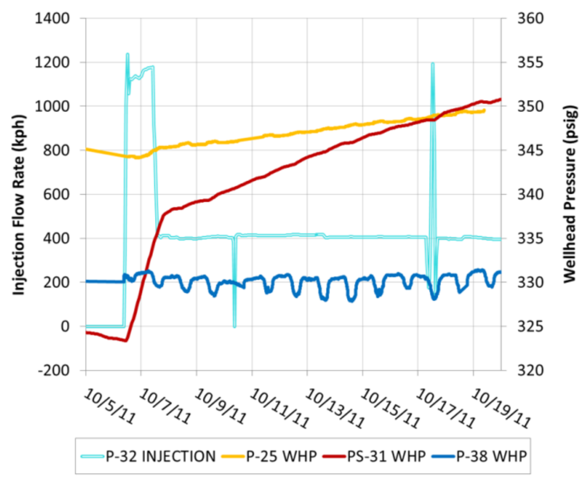


Figure 9. P-32 Injection startup and well head pressures in PS-31 and P-32.

The concentration of noncondensible gas (NCG) in the EGS Demonstration Area prior to injection into P-32 and updated using data collected during flow testing of PS-31 and P-32 are showed in Figure 10.

Also shown in Figure 10 are the locations of MEQs associated with injection at the nearby injection well, Prati-9. Both NCG concentrations and MEQ hypocenter suggest that wells to west (PS-31, P-32, and P-25) were not significantly influenced by injection into Prati 9 (Injection started November of 2007). The latter suggests that PS-31, P-25 and P-32 are partially isolated from the rest of the field. Figure 9 shows that pressure response at PS-31, P-25 is greater than at P-38. It is also important to note that Injection into P-32 has had a stronger effect on PS-31 than P-25 despite that separation distances at TD between P-32 and PS-31 and P-32 and P-25 are roughly the same, 1,723 ft and 1,519 ft, respectively.

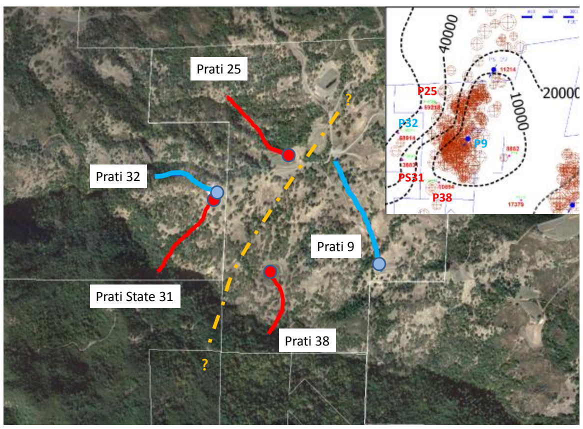


Figure 10. 2010 NCG concentrations in the northwest Geysers and seismicity associated with injection at Prati-9

Since Prati-32 injection began, three injectivity tests have been conducted (10/17/2011, 11/15/2011 and 01/11/2012). Figure 11 shows the pressure, temperature, injection rate and tool depth plotted vs. time during the step-rate injectivity test of 11/15/2011. During this test, the tools were traversed to 7200 ft at approximately 150 ft/min while injecting at approximately 215 gpm. The tools were held at that depth for 15 minute then traversed to the test depth at 50 ft/min while injecting at 600 gpm. Once at test depth the rate was maintained at 600 gpm for an hour before raising it to approximately 900 gpm then to 1200 gpm for an hour each.

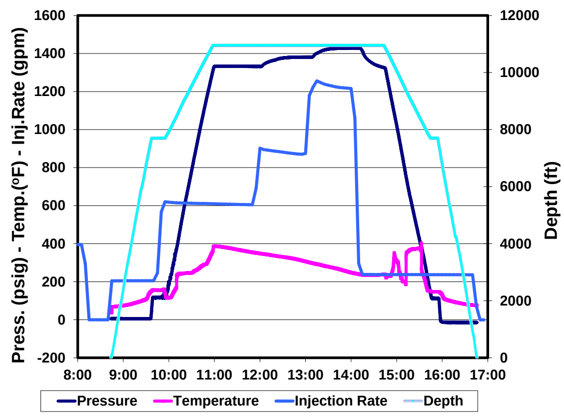


Figure 11. P-32 Step-Rate Injectivity Test 11-15-11. PT Tools Hung at 10,950 feet.

The water levels (depths from the surface) vs. injection rates for the first two tests are shown in Figure 12. These two injectivity tests indicated that the water level had little sensitivity to injection rate and that injectivity did not improve from 10/17/2011 to 11/15/2011. In order to increase stimulation of the deepest entry in the HTR and to increase the overall injectivity at P-32, the injection rate was increased from 400 gpm to 1,000 gpm on 11/30/11.

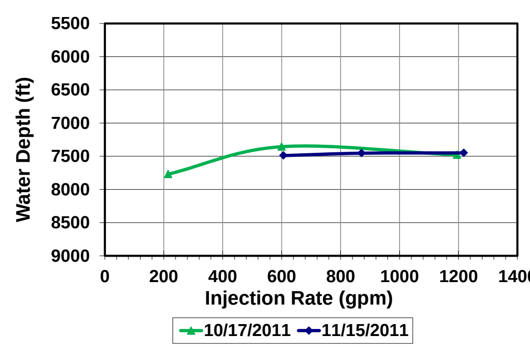


Figure 12. Prati 32 Injectivity

Figure 13 summarizes the effect of injection at P-32 on wells PS-31 and P-25. After the injection was raised from 400 gpm to 1,000 gpm, the rate of pressure increase at PS-31 and P-25 accelerated. It is apparent from Figure 13 that the rate of pressure increase at PS-31 is declining after P-25 was put into production on 12/09/11.

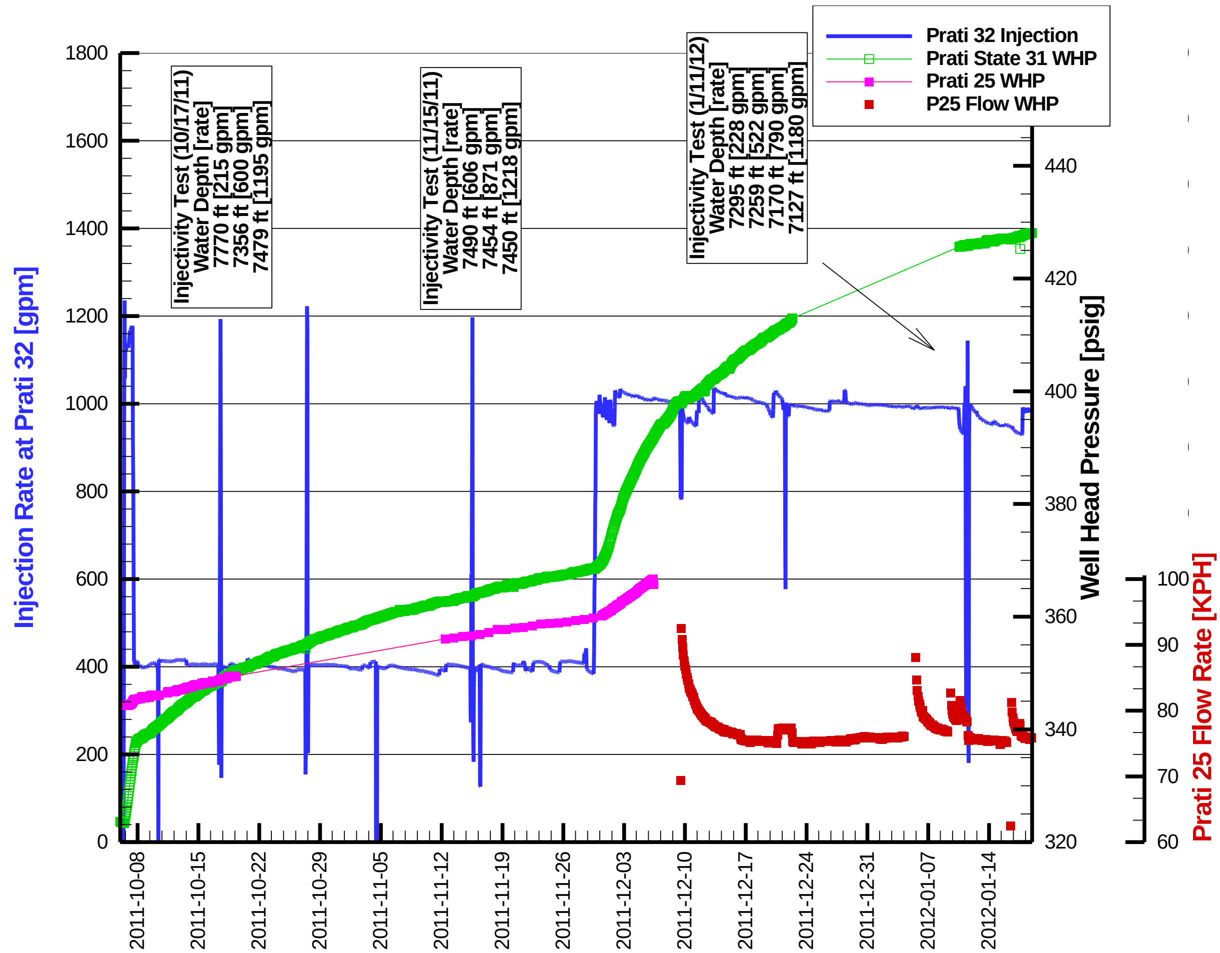


Figure 13. P-32 Injection and well head pressure at PS-31 , P-25.

Early results of the stimulation phase showed that reservoir pressures in this part of the field had substantially increased. Injection in P-32 has generated a rise of reservoir pressure (measure at well head) from 323 to 428 psig at PS-31 and from 345 to 367 psig at P-25. The stimulation in P-32 resulted in an increased of flow at P-25 of 13,000 lbs/hr of super-heated steam. When tested in 5/17/2010, P-25 registered a flow rate of 64,000 lbs/hr at 110 psig well head pressure. Today (1/20/2012), P-25 is flowing 77,000 lbs/hr at 108 psig well head pressure. Injection in P-32 has also resulted in a sharp decreased in NCG at P-25 as indicated in Figure 14 (From 3.7 wt% in 5/2010 to 1.1 wt% in 12/11).

MICROSEISMIC MONITORING

The LBNL seismic monitoring network currently consists of 31 three-component digitally-telemetered seismic stations located within and slightly beyond The Geysers production boundaries. This includes the November 2009 addition of five stations positioned to supplement the existing LBNL and USGS seismic stations, which improved microseismic data collection associated with the NW Geysers EGS Demonstration Project. Recorded seismic events are transmitted to LBNL servers, processed in “real-time” and integrated into the Northern California Seismic Network (NCSN) system (which is part of a much larger and less densely sampled network operated by the United States Geological Survey). Calpine generally accesses the “integrated” online LBNL/USGS dataset for seismicity analysis at The Geysers.

However, for detailed analysis of the NW Geysers EGS Demonstration Project, microseismicity data was acquired directly from a dedicated LBNL database. The seismic databases noted above are archived and available to the public online.

LBNL has also installed a total of 15 temporary three-component seismic stations in two campaigns: (1) 2010: five stations distributed within about 1 mile of the EGS injection well (P-32), and (2) 2011: ten stations installed as a “focused array” to collect specialized data during the start-up of the stimulation. Data from these temporary stations will be downloaded and analyzed at regular intervals. It is intended that these networks will be processed independently as well as a merged dataset with the permanent stations, which provided dense spatial sampling.

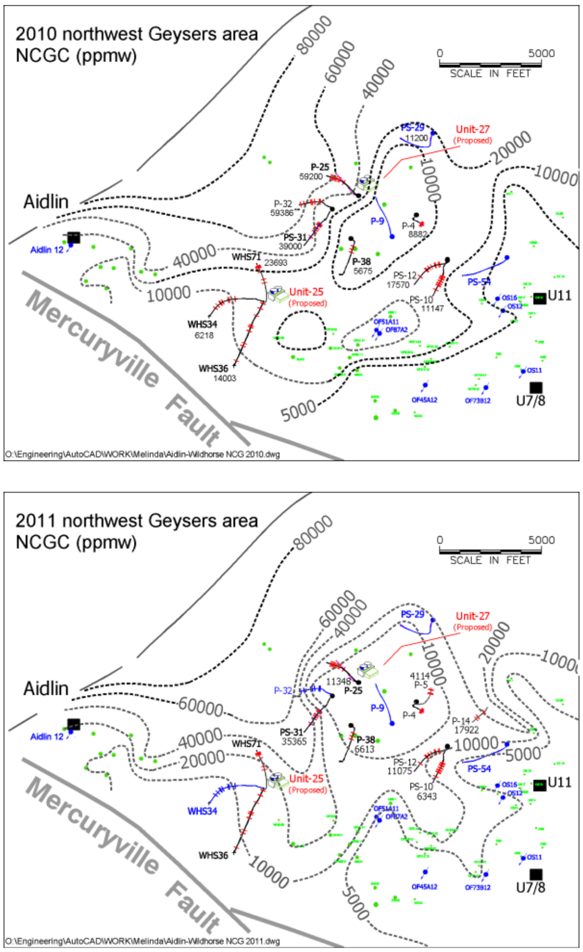


Figure 14. Northwest Geysers NCG concentrations before injection in P-32 (above) and after 2 months after start of stimulation (below)

Detailed microseismicity analysis associated with the EGS Demonstration is being conducted for a volume surrounding the P-32 injection well (dashed box in Figure 15). A summary of preliminary conclusions is as follows:

- A near absence of seismicity was observed within the Prati 32 detailed analysis area prior to injection.
- The frequency of microseismic events generally increases (at least initially) with an injection flow rate increase. The November 29, 2011 increase in flow rate from 400 gpm to 1000 gpm resulted in a significant increase in microseismic event frequency followed by a decline toward previous levels (Figures 16 and 18).
- The majority of early seismicity was relatively near the injection center; significantly more events have occurred to the north/northwest with increasing time, including at least two time/volume-limited “clusters” that appear to indicate fracture reactivation within a previously unaffected volume.
- Recent microseismic events of M 2.53 and M 2.67 were located southwest of the injection center. These events did not trigger strong motion sensors and were not felt in the neighboring communities.
- The average microseismic hypocenter appears to have migrated about 165 ft northward and about 500 ft deeper during the sustained 1000 gpm injection period.
- The average seismic event magnitude has increased slightly from about M 0.9 to about M 1.1.

Seismic event hypocenter development viewed in 3D suggests preferential water movement along a NNW/SSE trending, steeply-dipping zone of higher permeability (Figure 17).

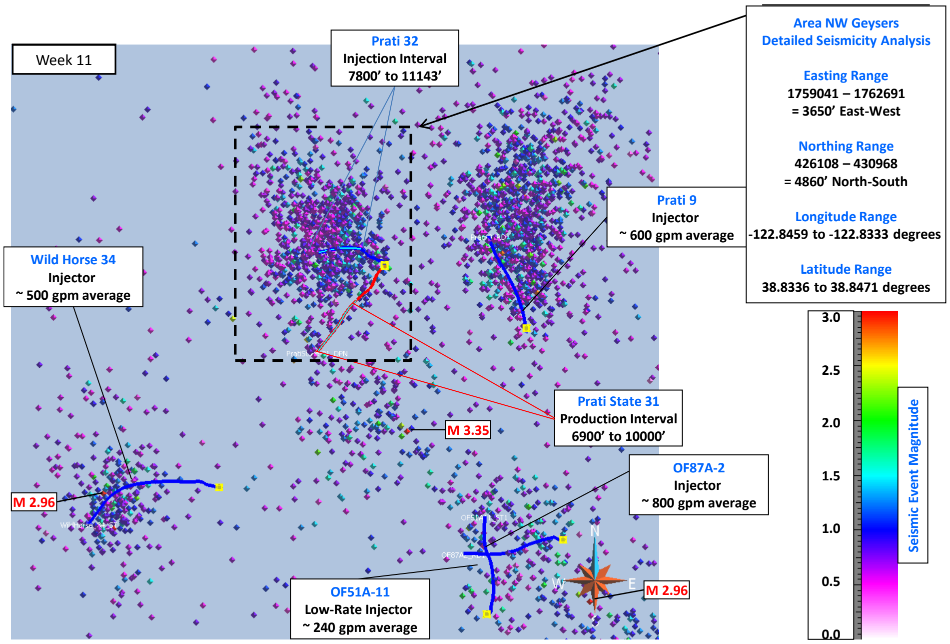


Figure 15. Map view of microseismic events through the initial 75 days of water injection. Injection well locations are blue lines. Microseismic events are diamonds colored and sized by event magnitude.

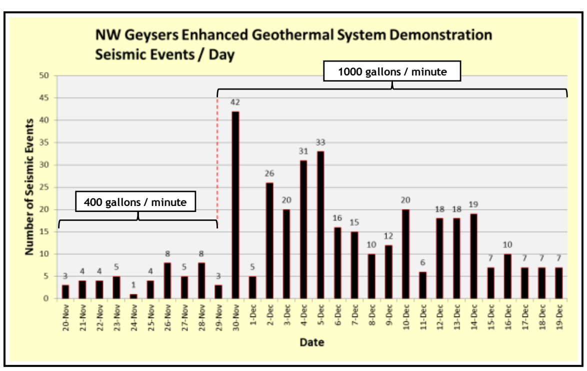


Figure 16. Frequency of seismic events for the period surrounding the flow rate increase. The limited number of events on 1 Dec 2011 is due to a localized telemetry problem

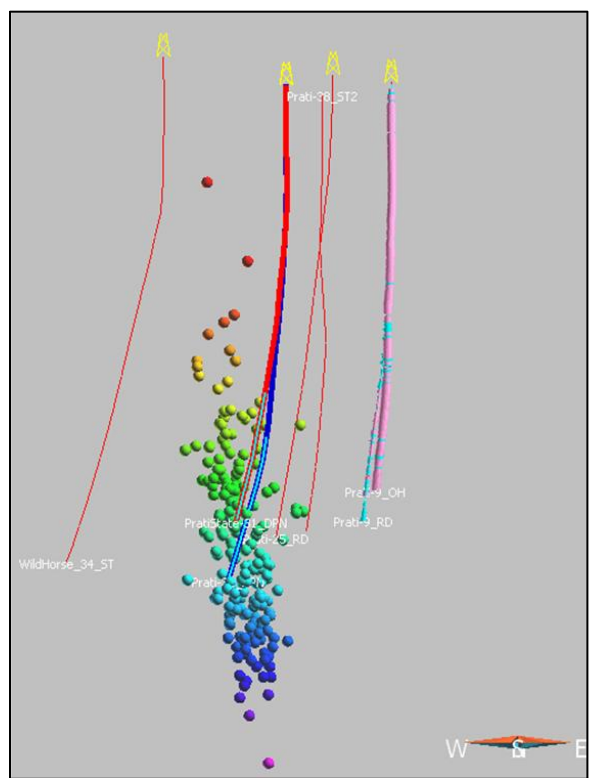


Figure 17. Microseismic events for the initial 75 days. Prati 32 injection interval is light blue segment of blue well track. Note the steeply dipping zone of microseismicity.

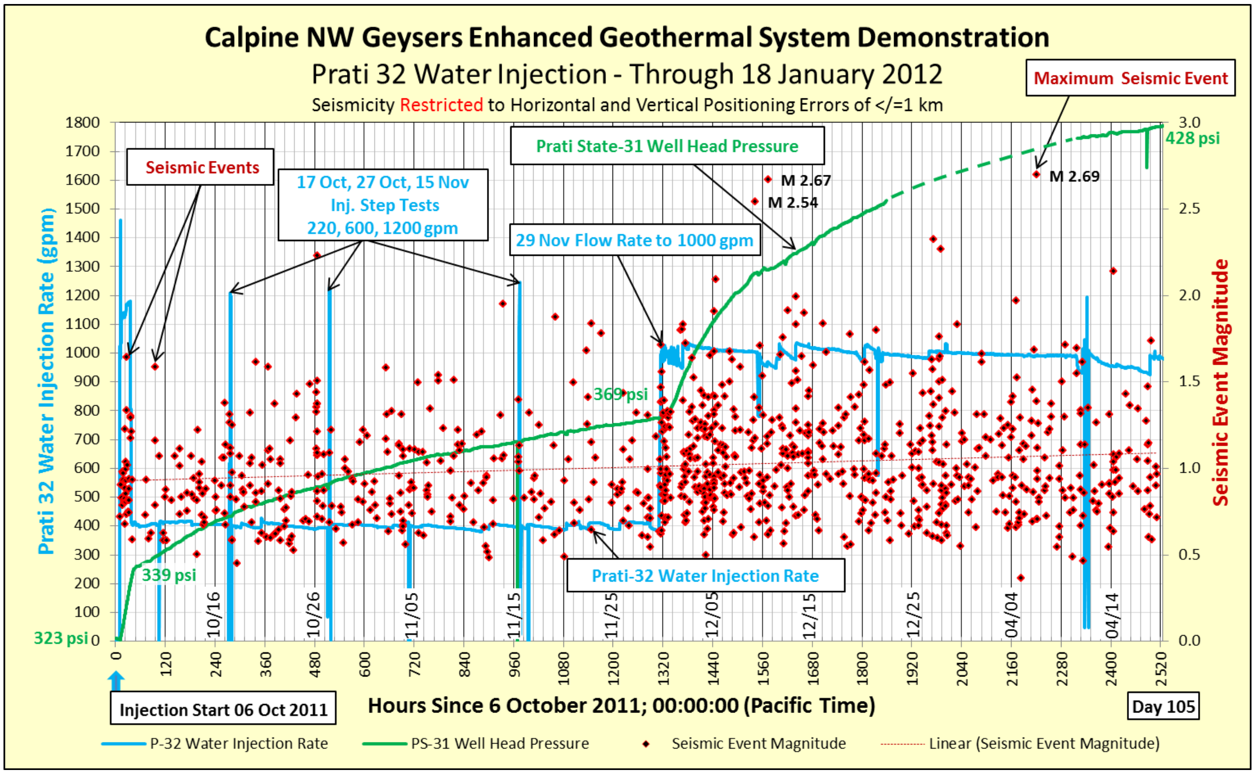


Figure 18. Prati 32 injection rate (blue line), Prati State 31 wellhead pressure (green line)and microseismicity (diamonds) through day 105 of the NW Geysers EGS demonstration.

CONCLUSIONS

Phase I of the EGS Demonstration Project has been completed. Two previously abandoned wells, PS-31 and P-32 were reopened and deepened as an EGS production-injection well pair in the HTR. PS-31 was completed as a production well that can communicate with both the NTR and the HTR. P-32 was completed as an injection well designed to inject water at low pressure and low flow rates in the HTR.

Before recompletion of P-32 as an injector, it was flow tested with a resulting steam flow rate of 84,400 lbs/hr at a normalized pressure of 100 psig, 4 wt% NCG concentrations with 1240 ppmw H_2S, and chloride concentrations in the steam condensate of 135 ppmw. After recompletion of P-31 as an injector, it flowed at 52,700 lbs/hr at a normalized pressure of 100 psig. The maximum shut-in well head pressure following the well test was 321 psig. The total NCG concentration in the steam was 4.4 wt% with 1,231 ppmw H2S and 135 ppmw chloride concentration in the steam condensate.

Injection in P-32 has resulted in a substantial rise in reservoir pressures in the area to values previously observed in the 1980's when the original wells were opened. The stimulation has also caused an increase in the flow rate at P-25 and a considerable reduction in NCG concentrations.

Detailed seismicity analysis is being conducted as an integral part of the EGS Demonstration Project. A dense microseismic detection network provides data for preliminary analysis. The number of seismic events initially increased as a result of increased injection. Also, the epicenter of the seismic cloud appears to have migrated northward and deeper over time.

Injection is expected to continue to October 2013. PS-31, P-32, and other area wells will be continuously monitored and periodically flow tested. Seismic data will also be collected continuously and analyzed on an ongoing basis.

ACKNOWLEDGEMENTS

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