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The Northwest Geysers EGS Demonstrations Project, California Part 1: Characterization and Reservoir Response to Injection

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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 the feasibility of stimulating a deep high-temperature reservoir (HTR) (up to 400°C, 750°F). 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 doublet to stimulate the HTR. The deepened portions of both wells have conductive temperature gradients of 10°F/100ft (182°C/km), produce connate native fluids and magmatic gas, and the rocks were isotopically unexchanged by meteoric water. The ambient temperature meteoric water injected into these hot dry rocks has evidently created a permeability volume of several cubic kilometers as determined by seismic monitoring. Preliminary isotopic analyses of the injected and produced water indicate that 50% to 75% of the steam from the created EGS reservoir is injection-derived.

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1 INTRODUCTION

The Geysers Geothermal field is the world's largest geothermal electricity generating operation and has been in commercial operation since 1960. It is a vapor-dominated geothermal reservoir system that was developed to a maximum installed capacity of 2043 MWe by 1987. Subsequently, a number of peripheral developed areas were abandoned because of resource problems including declining steam pressure, low permeability, corrosive steam and high non-condensible gas (NCG) concentrations. As a result of the high steam withdrawal rates, the reservoir pressure declined until the mid 1990s, when increasing injection rates resulted in a stabilization of the steam production and reservoir pressure. In recent decades operators have been relying heavily on supplemental water injection to sustain its current generation of 825 MWe.

The concept of Enhanced Geothermal Systems (EGS) at The Geysers differs from other EGS programs pursued elsewhere in the world. At The Geysers, EGS projects target areas which contain a significant portion of the recoverable geothermal energy in the system that is currently underutilized. The main focus is on the revival of production from peripheral areas by using water injection to increase reservoir pressure, increase permeability, reduce NCG concentrations and mitigate corrosion. Although this scope is somewhat site-specific, the vast unexploited heat resource and existing infrastructure at The Geysers offers an opportunity for significant short-term EGS generation.

The EGS Demonstration Project is in the northwestern portion of The Geysers geothermal field (Figure 1) where a high temperature reservoir (HTR) with temperatures up to 400°C (750°F) was previously identified (Walters et al., 1992 and Walters and Beall, 2002). The HTR underlies a normal temperature reservoir (NTR) where temperatures are about 240°C (465°F).

The EGS Demonstration Project area was originally explored in the 1980s with three exploration and development wells in the Central California Power Agency (CCPA) steam field. These wells were never produced due to high concentrations of NCG produced from the HTR and were abandoned in 1999 after the CCPA #1 Power Plant was closed for economic reasons and later decommissioned.

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Two of the previously abandoned wells, Prati State 31 (PS-31) and Prati 32 (P-32), were reopened, deepened and re-completed in 2010 for direct injection and stimulation of the HTR. The NTR in the project area is relatively shallow (the base of the NTR is at an elevation of -1800 m mean sea level (m-msl), -6000 feet (ft-msl)) and the project wells are sufficiently deep to penetrate the upper portion of the HTR (Figure1).

The intent of the EGS Demonstration Project is to show that the permeability of the HTR can be stimulated by fracture reactivation to create a diffuse "cloud" of fractures rather than a localized fracture plane when relatively cool water is injected into a very hot rock volume at low flow rates (65 l/s) and low pressures (< 10 MPa). Water injection into the HTR was anticipated to lower the concentrations of NCG as well as to provide a sustainable steam supply for nearby steam production wells. Initiation of this project was also 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 project area (Stark, 2003).

To date, the data shows a strong and favorable reservoir response to the injection, including increases in pressure and flowrate at nearby production wells, and order-of-magnitude decreases in non-condensible gas content of the produced steam. The area stimulated is evidently partially isolated from the main reservoir to the SE, based on data from wellhead pressures, microearthquake monitoring, noncondensible gas concentrations and rock isotope values. The isolation appears to be controlled by a previously-mapped NE-trending fault zone. The EGS injection experiment was not successful in mitigating the corrosive effects of chloride-bearing steam, which resulted in corroded casing of the production well, PS-31.

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

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Phase I: Pre-stimulation. During Phase I, initiated in 2009, a stimulation plan was developed based on a detailed geological model, analysis of historical data, and pre-stimulation modeling (Garcia et al., 2012). 3-D realizations of the main geologic units together with the incorporation of rock properties from previous unpublished core studies (density, permeability, porosity, and rock strength) constituted the input data for the geologic model created near PS-31 and P-32. A set of stimulation scenarios were presented by Rutqvist et al. (2010) and Rutqvist et al. (2015b) from a coupled thermal, hydraulic, and mechanical (THM) model developed at LBNL.

Phase II: Reservoir Stimulation. This phase commenced in October 2011 with injection of tertiary treated wastewater from the Santa Rosa Geysers Recharge Project (SRGRP) into the HTR via P-32 (Garcia et al, 2012). It is important to note that the injection into P-32, as well as all injection at The Geysers, is not pumped and falls from the wellhead under a vacuum of about -0.7 to -0.9 bars (-10 to -13 psig).

Phase III: Long Term Data Collection, Monitoring, and Reporting. This phase will recommence in 2016.

This paper summarizes Phase I field work including wellbore readiness and baseline testing, along with Phase II results including analysis of the reservoir's response to stimulation by injection. An accompanying paper titled, “The Northwest Geysers EGS Demonstration Project, California - Part 2: Modeling and Interpretation” presents the results of coupled thermal, hydraulic, and mechanical (THM) modeling (Rutqvist et al., 2015a, this issue).

2 GEOLOGICAL AND GEOTHERMAL SETTING

2.1 Regional Geology

Structurally, The Geysers geothermal reservoir is within the terrane of the San Andreas Fault system (Figure 1), and is influenced by Mesozoic subduction, Tertiary thrust faulting, and high-angle Quaternary faults. The relative motion between the Pacific Plate and North American Plate has been accommodated by right-lateral strike-slip motion along the San Andreas Fault Zone (DeCourten, 2008). The slip rates within this zone of subparallel, right-lateral, strike-slip faults progressively decrease to the east and created a transtensional tectonic environment between the active Maacama Fault Zone and the active Bartlett Springs Fault Zone. The modern-day Geysers geothermal field is bounded to the southwest by the inactive Big Sulphur Creek – Mercuryville Fault Zone, and to the northeast, by the inactive Collayomi Fault Zone. There are no faults in or adjacent to The Geysers which are known to be active within the last 15,000 years.

Oppenheimer (1986) indicated that seismic sources in The Geysers occur from what appear to be almost randomly-oriented fracture planes. Lockner et al. (1982) performed experiments to determine the mechanical characteristics of rocks from the reservoir at The Geysers. They concluded that fracturing and hydrothermal alteration had weakened the rock sufficiently such that the reservoir rock is only able to support a frictional load.

Within The Geysers the maximum horizontal principal stress is oriented about N26E (Boyle and Zoback, 2014). They used a large set of earthquake focal mechanisms recorded in the Northwest Geysers during the period of January 2005 - May 2012 to determine stress orientations. They concluded that in the Northwest Geysers, fractures appeared to have a N60E direction of strike in the fractured metagraywacke interval comprising the main reservoir, and a bimodal distribution of fractures in the deepest reservoir where the two sets of predominant fractures are N30E and N85E. The corresponding intermediate principal stress is approximately equal in magnitude to the maximum horizontal principal stress and has a vertical orientation.

2.2 Local Geology

The EGS Demonstration project area is part of an undeveloped, 10 square-mile portion of the northwest Geysers geothermal field between the Aidlin Power Plant (Calpine Unit 1) and the

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Ridgeline Power Plant (Calpine Units 7 and 8). In the project area, the HTR is at its shallowest depth (2440 m, 8000 ft) and has been identified from pressure-temperature logs to be at elevations of -1680 to -1830 m-msl (-5500 to -6000 ft-msl) (Figure 1).

Figure 2 is a geologic map showing detailed surface geologic mapping and Quaternary faults in the northwest Geysers. The surface geology of the EGS Demonstration area is part of the Franciscan Assemblage (200 to 80 Ma in age) and mapped in Figure 2 as a greenstone complex (fgs), a relative shallow mélange dominated by metagraywacke and argillite with minor amounts of greenstone and traces of blueschist (fsrgw), and turbidite sequences of metagraywacke and argillite (fgw). Six Quaternary surface faults mapped on the basis of lithologic discontinuities and geomorphic lineaments appear to extend to reservoir depth and divide the northwest Geysers reservoir into compartments separated by hydraulic discontinuities. These are the Mercuryville, Alder Creek, Squaw Creek, Ridgeline, Caldwell Pines and Caldwell Ranch faults which are labeled in Figure 2.

The cross section through the EGS Demonstration area in Figure 3 shows that greenstone and metagraywacke form the caprock over the metagraywacke reservoir. Consequently metagraywacke forms both the caprock and reservoir in the EGS project area; the only difference is that the reservoir metagraywacke is fractured rock through which hydrothermal fluids have passed and the cap rock metagraywacke is not fractured and not hydrothermally altered.

During the course of the EGS Demonstration, a short (4.8 km), northeast-trending fault delineated by detailed surface mapping (by Walters, M., 1985-1990, in: Nielson et al.,1991, and labeled Caldwell Pines Fault in Figure 2) was determined to extend from the surface into the reservoir. This short fault or shear zone appears to create a hydraulic discontinuity (or leaky barrier) between the EGS Demonstration wells and the Caldwell Ranch Project wells (e.g. Prati 38) to the south with a differential reservoir pressure of up to 6.2×10^5 Pa (90 psig) on either side of the fault.

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2.3 Reservoir Geology

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). The HTR in P-32 was encountered near a measured depth of about 2.6 km (8400 ft - referenced to ground surface). Flowing steam temperatures at the bottom of the P-32 well were logged at 347°C (656°F) (Walters et al., 1992). Where pressure-temperature-spinners (PTS) logs were available, the calculated enthalpies in the northwest Geysers HTR ranged from 3020 kj/kg to 3070 kj/kg (1,300 to 1,320 BTU/lb) with an apparent temperature gradient ranging from approximately 15 to 30°C /100m (5 to 10°F /100ft) (Walters et al., 1992).

The six Quarternary faults which form hydraulic discontinuities and compartmentalize the northwest Geysers reservoir also appear to delineate isotopically different reservoir blocks: some reservoir rock volumes are isotopically less-exchanged by meteoric water rather than the isotopically more-exchanged rocks typically found throughout the reservoir at The Geysers. All of the isotopic analyses for the EGS Demonstration Project are presented in the delta notation, δ; as parts per thousand (per mil, or ^{O}/oo) deviation of isotopic ratios $^{18}O/^{16}O$ or D/H, relative to Standard Mean Ocean Water (SMOW). Whole-rock, metagraywacke $\delta^{18}O$ values decrease from +12 per mil at the top of the NTR to +4 of the Geysers reservoir (Moore and Gunderson, 1995 and Walters et al., 1996). Walters and Beall (2002), respectively, confirmed this same relationship of decreasing whole-rock metagraywacke $\delta^{18}O$ values with depth in the High Valley area to the east, and the Aidlin area to the west of the EGS Demonstration Area. However, in the EGS Demonstration area, the metagraywacke in the NTR is only weakly exchanged by meteoric water, and new metagraywacke $\delta^{18}O$ values from the deepened PS-31 and P-32 wells are evidence the HTR is apparently not exchanged by meteoric water. That is, the metagraywacke $\delta^{18}O$ values in both the caprock and HTR in the EGS Demonstration area are in the same range (+12.0 per mil). Taken together with the conductive temperature gradients, the

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unexchanged whole-rock metagraywacke $\delta^{18}O$ values are evidence that the created EGS reservoir is in non-hydrothermal, hot "dry" rock.

Figure 4 graphically compares the whole-rock isotopic profiles of metagraywacke $\delta^{18}O$ values typical of Northwest Geysers wells to wells located in the EGS area and Caldwell Ranch project area. Figures 5 and 6 present these data as geologic cross-sections. North of the Caldwell Ranch Fault and Caldwell Pines Fault, the NTR rock in the EGS Demonstration area is only weakly exchanged with meteoric water, and the HTR rock is unexchanged (Figure 5). Here the reservoir rock in the EGS are unexchanged with meteoric water and are in the same range as the caprock compared to the typical Geysers reservoir.

Many early (1977-1985) $\delta^{18}O$ values in the steam condensate throughout the Northwest Geysers, including the EGS project, ranged from 0 per mil to +3 per mil (Figure 7). Positive $\delta^{18}O$ values indicate that the native steam in this area was not significantly influenced by meteoric water and may be connate water (Lutz et al., 2012) (see Section 5.3.1).

Pressure data, reservoir modeling, isotopic and NCG data, as well as published analysis of temperature logging by the U.S. Geological Survey indicates that the EGS Demonstration Area is younger and partially isolated from the NTR steam reservoir to the south, east and west. Steam from the HTR contains much higher NCG concentrations and higher pressures than the depleted NTR steam fields to the southeast of the EGS project. The high temperatures recorded in the HTR suggests to us that the project area is underlain by a recent granitic intrusion (Figure 3), which is estimated to have begun cooling 5,000 to 10,000 years before the present (Williams et al., 1993).

3 PHASE I: PRE-STIMULATION

3.1 Wellbore Readiness

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Two previously abandoned wells, PS-31 and P-32, were reopened and deepened as an EGS production-injection well pair, respectively, in the HTR. Well testing indicated there is some localized permeability in the HTR as evidenced by steam entries in the HTR in both wells (Figure 8).

3.1.1 Recompletion of Wells

The EGS Demonstration Project was initially planned for PS-31 and P-32 to comprise an injection and production well pair, respectively. However, after deepening these wells, a significant steam entry was identified at 3352 m (11,000 ft) in P-32 with a temperature of 400°C (750°F) (Figure 8 and 9). The high temperature and apparent permeability in P-32 resulted in a revised plan to use P-32 as the injection well and PS-31 as the production well.

Figure 9 shows good agreement between the temperature profiles from P-25 and PS-31. These pressure-temperature (PT) surveys confirmed the temperature of the NTR at around 232°C (450°F) and the underlying HTR indicative of a conductive temperature gradient (10°F/100ft depth increase, or 18.2°C/100m) with a maximum temperature of about 400°C (750°F) near the bottom of the well at 3352 m (11000 ft) measured depth.

Conductive high temperature systems underlying typical vapor-dominated reservoirs were previously reported at The Geysers by Drenick (1986), Walters et al. (1988), and Nielson and Moore (2000). At the Larderello-Travale geothermal field, a hydrothermal system similar to The Geysers, the presence of a deep convective high temperature reservoir was originally published by Bertini in 1985. For additional information on the origin of the HTR at The Geysers the reader is referred to Truesdell (1991) and Beall and Wright (2010). The effect of injection and the complex fluid and heat flow processes in HTR have been studied using numerical simulations by Pruess et al. (1987), Truesdell and Shook (1997), Shook (1993) and Pruess et al. (2007). Both Pruess et al. (2007) and Truesdell and

Shook (1997) showed that injection into the HTR has a favorable effect in terms of a reduction of NCG content. Such reduction on NCG content due to injection has been observed throughout The Geysers and also at the EGS site.

The well designs were modified to accommodate the decision to switch P-32 to injection and PS-31 to production: (1) P-32 was deepened from 2926 m (9600 ft) to 3396 m (11143 ft) and a 5-1/2" (inch=") blank liner was hung from the surface to 2590 m (8500 ft) (Figure 10). Below 2590 m (8500 ft) depth, the well was not modified and a slotted liner was installed from 2590 m (8500 ft) to 3398 m (11115 ft) where water is injected at a rate of about 44.2 kg/s (700 gpm) into the HTR. (2) Initially, PS-31 was deepened from 2743 m (9000 ft) to 3058 m (10034 ft) in August 2010 with about 610 m (2000 ft) of slotted liner installed within the HTR. To switch PS-31 over to a production design, the upper portion of the lower blank liner was perforated, allowing the well to communicate with both the NTR and the HTR (Figure 10).

The deepening of the EGS production-injection well 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 5 to 6 m/h (15 to 20 ft/h) to less than 3 m/h (10 ft/h). Figure 11 shows the bit condition after 30.5 m (100 ft) of air drilling P-32 to final depth of 3396 m (11143 ft).

3.1.2 Well and Reservoir Testing

Before recompletion of P-32 as an injector, it was flow tested with a resulting steam flow rate of 10.6 kg/s (84.4×10^3 lb/h (or kph)) at a normalized pressure of 6.9×10^5 Pa (100 psig), 4.5 wt% NCG concentration with 1,322 ppmw H_2S, and chloride concentration in the steam condensate of 47 ppmw. Sharp pressure drops at PS-31 (step changes of approximately 3 psi) during flow testing of P-32, provided early evidence of the degree of connectivity between these two wells (Figure 12).

Three well testing campaigns were made in PS-31, and the corresponding PTS logging results are graphed in Figure 13. The first test was completed on October 13, 2010 before PS-31 was recompleted

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as a producer. Thus, the 3-day isochronal flow test was completed with the NTR behind unperforated liner. A flow rate of 5.4 kg/s (42.9 kph) at a normalized pressure of 6.9×10^5 Pa (100 psig) with a wellhead enthalpy of 2761 kj/kg (1188 BTU/lb) was observed (well head temperature - WHT = 160°C (321°F), and well head pressure -WHP = 4.6×10^5 Pa (67 psig)). The maximum shut-in WHP following the well test was 323 psig. Pressure transient data following the flow test were used to estimate near-well reservoir permeability. Pressure build-up analysis results provided an estimated value of 22,000 md-ft (6.7 Dm) for fracture transmissivity (kh). The kh at The Geysers ranges from 5,000 md-ft to 400,000 md-ft (values based on prior pressure transient analysis performed at The Geysers and from values obtained for the reservoir model). Assuming a 2,000 ft-thick production interval (Figure 10) at PS-31, the resulting permeability is 10 md (1×10^{-14} m^2). The low permeability estimated during the flow test of October 13, 2010 is comparable to values encountered at other wells in the Northwest Geysers. The total NCG concentration in the steam was 4.5 wt% with 1386 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 365 m (1200 ft) depth and saturated steam from about 365 m (1200 ft) to the surface. After the perforations were shot in the 7" blank liner from 2065 m to 2346 m (6776 ft to 7696 ft), PS-31 was tested a second time on September 6-7, 2011. PS-31 flowed 6.64 kg/s (52.7 kph) at a normalized pressure of 6.9×10^5 (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 on 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 1,000 rpm above the top perforation (2065 m - 6776 ft). This is a consequence of an increased flow rate of 1.26 kg/s (10 kph) from nine steam entries in the NTR which were covered with 7 inch blank liner section prior to the perforation job between 2065 m to 2346 m (6776 ft to 7696 ft).

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4 PHASE II: RESERVOIR STIMULATION

Injection into P-32 began on October 6, 2011 at 10:20 am. In accord with the typical injection startup procedure for new injection wells at The Geysers, the well received a high initial injection rate of 70-76 kg/s (1100-1200 gpm). The high rate was continued for 12 hours then reduced to approximately 25.3 kg/s (400 gpm) and was maintained for 55 days. Figure 14 shows the early injection history into P-32 and WHP increases in the three closer and shut-in wells, PS-31, Prati 38 (P-38) and P-25. As with all other injection wells in The Geysers steam field, water is injected into P-32 under gravity (not by pumping) causing the steam in the well bore and nearby formation to collapse which draws the water into the wellbore and surrounding rock under a vacuum. The measured vacuum at the wellhead in Geysers injection wells ranges from -0.7 to -0.9 bars (-10 to -13 psig).

Figure 14 shows that pressure response to P-32 injection at PS-31 and P-25 is greater than at P-38. It is also important to note that injection into P-32 had a stronger effect on PS-31 than P-25 although the separation distances at the total depths of these wells between P-32 and PS-31, and P-32 and P-25, are similar, 525 m (1723 ft) and 463 m (1519 ft), respectively. It is also possible that the influence of P-32 injection might have been felt at depths less than total depth (TD), where PS-31 is closer to P-32.

Since P-32 injection began, five injectivity tests have been conducted (October 17, 2011; November 15, 2011; January 11, 2012; March 6, 2012 and June 18, 2012). Figure 15 shows the pressure, temperature, injection rate and tool depth plotted versus time during the step-rate injectivity test of November 15, 2011. During this test, the tools were traversed to 2195 m (7200 ft) at approximately 46 m/min (150 ft/min) while injecting water at approximately 13.6 kg/s (215 gpm). The tools were then held at 2195 m (7200 ft) depth for 15 minutes. Then the tools traversed to the test depth of 3338 m (10950 ft) at 15 m/min (50 ft/min) while injecting at 39 kg/s (600 gpm). Once at 3338 m (10950 ft), the injection was maintained for approximately one hour at each injection step at rates of 39 kg/s (600 gpm), 56.9 kg/s (900 gpm) and 76 kg/s (1200 gpm).

The water levels (depths measured from the surface) versus injection rates for the first two tests on

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October 17, 2011 and November 15, 2011 are shown in Figure 16. These two injectivity tests indicated that the water level had little sensitivity to injection rate and that apparently injectivity did not improve from October 17, 2011 to November 15, 2011. One possibility is that the nature of the step injectivity tests do not capture the transient behavior of injection as possible a “falling head” (water column) injectivity test will accomplished. 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 25.3 kg/s (400 gpm) to 65.1 kg/s (1000 gpm) on November 30, 2011.

Figure 17 summarizes the effect of injection at P-32 on wells PS-31 and P-25. Early results of the stimulation phase show injection into P-32 caused substantial pressure increases in the reservoir pressure as measured at the PS-31 well head, from 22.3×10^5 Pa to 29.5×10^5 (323 to 428 psig), and from 23.8×10^5 to 25.3×10^5 (345 to 367 psig) at P-25 during the first injection step of 25.3 kg/s (400 gpm) which lasted 43 days. The injection in P-32 resulted in an increased flow rate at P-25 of 1.6 kg/s (13 kph) of superheated steam. When tested on May 17, 2010, a flow rate of 8.1 kg/s at 7.6×10^5 (64 kph at 110 psig) was measured at the P-25 wellhead. By January 20, 2012, P-25 was flowing 9.7 kg/s (77 kph) at 7.44×10^5 108 psig WHP. After the water injection rate was raised from 25.3 kg/s (400 gpm) to 65.1 kg/s (1000 gpm) on November 30, 2011, the rate of the static WHP increases at PS-31 and P-25 accelerated. The maximum WHP recorded at PS-31 was 32.0×10^5 (465 psig). This represents an increase of 9.7×10^5 (140 psig) from pre-stimulation values. It is apparent from Figure 17 that the rate of pressure increase at PS-31 declined after P-25 was put into production on December 09, 2011. In addition to steam production at P-25, reductions of injection rates at P-32 contributed to a decline of static wellhead pressures at PS-31. Figure 17 shows a stair step in the WHP curve at PS-31 on January, 2012. This step coincides with wireline activity (Static PT followed by a flow test) and can be explained as follows. When shut-in, P-31 tends to gas-up at the top of the wellbore (steam circulating inside and releasing CO_2 at the top). Under static conditions, what it is recorded at the surface is the reservoir pressure minus (-) the “weight” of the steam+gas inside the wellbore. During the static PT

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some gas escaped from the wellhead lubricator and evidently the rest of the gas cap was released during the flow test. Calculation of the pressure profile inside the well based on the static PT confirms the assumption that the well was indeed capped by CO_2 resulting in a different well head pressure as if the wellbore were only filled with saturated steam.

During the injection stimulation phase, two flow tests were conducted at PS-31 on January 31, 2012 and June 14, 2012 with resulting flow rates of 9.1 kg/s and 11.8 kg/s (72 kph and 94 kph) respectively. The increase in flow is primarily attributed to the removal of the PS-31 upper liner (Figure 12) as the well was finally converted from an injector to a producer on April 4, 2012. A pressure transient analysis following the flow test of June 14, 2012 indicated that the kh increased to 12.69 Dm (42300 md-ft) from the 6.6 Dm (22000 md-ft) value found when the well was re-opened. This increase is considered small. Nevertheless, it is an indication that permeability has increased at the EGS site, albeit at a low rate.

Following the stimulation injection phase, water injection at P-32 was suspended for a period of 160 days. The wellhead pressure at PS-31 decreased rapidly indicating again that both wells are extremely well connected. PS-31 began steam production on December 5, 2012 which continued until February 13, 2013 when near-surface corrosion of the well casing caused a steam leak. This leak necessitated shutting-in the well. PS-31 will remain shut-in until a corrosion-resistant high alloy or titanium tie-back liner is installed to prevent future corrosion.

5 MONITORING

5.1 Microseismic monitoring

A permanent Lawrence Berkeley National Laboratory (LBNL) seismic monitoring network has operated since October 2003 and currently consists of 32 digitally-telemetered, three-component seismic stations located within and slightly beyond The Geysers production boundaries. The recorded seismic events are transmitted via radio telemetry to an on-site LBNL server, processed in real-time

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and integrated into the Northern California Seismic Network (NCSN). The NCSN is part of a much larger and less densely sampled network operated by the United States Geological Survey (USGS). Calpine's Geysers seismicity analysis generally utilizes this integrated online LBNL/USGS dataset which is archived hourly at the University of California Berkeley's Northern California Earthquake Data Center (NCEDC). For detailed analysis of the Northwest Geysers EGS Demonstration Project, microseismicity data are acquired directly from a dedicated LBNL database. The seismic databases noted above are available to the public online (Figure 18).

Two temporary LBNL three-component seismic monitoring networks were also installed in separate campaigns to monitor the EGS Demonstration Project area. In 2010, five stations were uniformly distributed within about one mile of P-32. In 2011, sixteen stations were installed as a focused array to collect specific data during the start-up of the EGS stimulation. Data from these temporary stations have been downloaded and analyzed in detail at regular intervals. This temporary station data has been processed independently by LBNL experts and also merged with the permanent LBNL station data to provide a dense spatial sampling of the EGS demonstration project area.

Calpine has completed detailed seismicity analysis using the dedicated LBNL database associated with the EGS Demonstration at regular intervals for a volume surrounding the P-32 injection well. The time range for seismicity analysis within this study (unless otherwise noted) is 01 September 2011 through 05 March 2013, primarily due to early 2013 complications with PS-31 well casing corrosion. During the seismicity analysis time range, seven seismic events associated with the EGS Demonstration Project exceeded M 2.50, the largest being a M 2.87 on 31 May 2012 (Figure 19). The energy release of a seismic event is determined by the shear modulus (rigidity), the area of rupture and the slip rate (Hanks and Kanamori, 1979; Aki and Richards, 1980; Segall, 1998). The SW to NE alignment of six of the seven M ≥ 2.50 seismic events along the southeast boundary of the EGS seismicity cluster is believed to represent a fracture zone with slightly increased surface areas. An eighth M ≥ 2.50 seismic event of magnitude 3.74 occurred after the detailed seismicity analysis period on 21 January 2014.

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A near absence of seismicity was observed within the EGS Demonstration area in the 40 days prior to the start of injection in P-32, with only one event of magnitude 0.63 recorded (see Figure 20). The 06 October 2011 onset of injection and steady 400 gpm flow rates produced an anticipated occurrence of low-magnitude seismicity in the vicinity of P-32. The 29 November 2011 transition from 400 gpm to 1,000 gpm flow rates then resulted in a significant increase in microseismic event frequency (from approximately 8 events per day to 42 events per day) followed by a gradual decline in frequency toward previous levels (Figure 20 and 21). In general, the frequency of microseismic events initially increased with an injection flow rate increase and then declined over time. The frequency of seismic events declined significantly almost immediately after an injection flow rate decrease, and returned to nearly background seismicity levels after approximately 80 days at 0 gpm (Figures 20 and 21).

The majority of early seismicity after injection began was relatively near the injection center of P-32. Significantly more events occurred to the north and northwest with increasing time, including several time-limited and volume-limited clusters or linear alignments that appear to indicate fracture reactivation within a previously unaffected volume. Seismic event hypocenter development viewed in 3D time animations suggests preferential water movement along NNW/SSE trending, steeply-dipping zones of higher permeability (Figure 22).

The average hypocenter descended by approximately 3.6 feet per day during approximately 520 days of data analysis (including days 320 to 480 without injection). The rate of descent was highly dependent on injection flow rate, with a maximum descent rate of 14.5 feet per day during the 98 day period of sustained 1,000 gpm injection. A descent rate of 2.7 feet per day then occurred during the subsequent 103 day period of sustained 700 gpm injection (Figure 23). After 270 days of P-32 injection, a time vs. subsea depth graph prepared using the LBNL microseismicity data suggested an apparent deepening of the average hypocenter position within the EGS Demonstration Project area that existed for approximately 18 days. Additional investigations indicated that this phenomenon occurred for the LBNL microseismicity data throughout its Northwest Geysers coverage area. There is no evidence that this is an artifact resulting from a variation in the seismic event processing

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algorithms. However, this apparent deepening seems to be very much subdued to absent for archived Northern California Earthquake Data Center (NCEDC) data. It is possible that the apparent deepening seen on the more highly resolved LBNL microseismicity data may be attributed to reactivation of deeper structures associated with regional tectonics. However, due to concerns with data reliability, no conclusions have been drawn based on data associated with this apparent deepening.

The apparent SW to NE $M \geq 2.50$ seismicity alignment seen to the southeast of P-32 is consistent with a previously mapped northeast-trending surface zone of faulting (Nielson et al., 1991) and a known reservoir pressure boundary (Figure 24). The timing of these $M \geq 2.50$ seismic events does not show a particularly strong correlation with injection rate or injection rate variability (Figures 17 and 20).

A very positive outcome of the EGS Demonstration Project in terms of induced seismicity analysis is an improved understanding of the relationship between Geysers induced seismicity patterns and apparent fluid flow paths and fluid boundaries. The detailed seismicity investigations conducted in association with this project by Calpine Corporation and those completed in collaboration with LBNL (e.g. Jeanne et al. 2014b and Rutqvist et al. (2015a), this issue) all indicate linear alignment of seismicity hypocenters (representing hydraulic discontinuities) that correlate very well with other constraints such as lithology logs, well pressure measurements, well temperature measurements and previous surface mapping (Figure 25).

In January 2013, a shallow, corrosion-induced leak in the casing of PS-31 appeared. Consequently, steam production from PS-31 was halted. The well then received water injection initially at a high rate to condense the steam, and then at 300 gpm to keep the wellhead pressure at a negative value. The transition from 400 gpm water injection at P-32 to 300 gpm water injection at PS-31 occurred on February 13, 2013 and resulted in an immediate shift in the seismicity hypocenters that was entirely consistent with the location of the new PS-31 injection center (Figure 26). Injection into PS-31 continued until March 21, 2013 when the well was suspended, the casing repaired and the wellbore capped by the injection of nitrogen.

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The Gutenberg-Richter Law is an empirical relationship between the magnitude x of a seismic event and the total number of seismic events with magnitudes higher than x (N(x), and is generally expressed as $\log N(x) = a - b*x$ (Gutenberg and Richter, 1942). The constant b is typically close to 1 for natural seismicity, and is typically higher for earthquake swarms (lacking a clear main shock), for increasing material heterogeneity, for aftershocks, and for areas of having a high geothermal temperature gradient (Kulhanek, 2005; Zang et al., 2014). This relationship is generally displayed in a plot of seismic event magnitude vs. log (frequency $M \geq x$). A linear least-squares fit of 1,173 recorded NW Geysers EGS Demonstration Project seismic events with magnitudes ≥ 1.0 has a “b-value” of 1.69 (Figure 27).

5.2 Non-condensible Gas Monitoring

It is known that boiled injectate, or Injection derived steam (IDS) tends to dilute NCG concentrations in The Geysers reservoir and to displace the original reservoir steam Beall et al. (2007). The result is lower NCG and hydrogen sulfide (H_2S) concentrations of produced steam. Stimulation monitoring data show that the NCG concentrations of PS-31 steam, as well as the flow rate and shut-in well head pressures (SIWHP) are controlled by SRGRP water injected in P-32.

To monitor the effects of P-32 injection on the NCG concentrations of steam from the EGS Demonstration area, samples from PS-31 and P-25 were periodically collected after water injection began on November 6, 2001. The high NCG concentrations in PS-31 and P-25 made field sampling problematic and resulted in some suspect samples. Due to the uncertainty in the data, NCG values presented in this report have been averaged.

Figure 28 shows the injection history of P-32 and the NCG concentrations of PS-31 and P-25 before and after injection began. The first post-injection sample collected from PS-31 was during a flow test on January 1, 2012, 117 days after injection had started and during the 1,000 gpm injection period. The NCG concentration in PS-31 steam was 0.3 wt%, a reduction of about 92% from the pre-injection

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concentration of 4.5 wt%. This was the lowest NCG concentration measured at PS-31 during the stimulation. At the end of the 700 gpm injection interval, the PS-31 NCG concentration during a flow test showed a slight increase to 0.45 wt%. After injection into P-32 ceased (August 20, 2012 to January 29,2013), the NCG concentration in PS-31 steam increased and peaked at 1.3 wt%. The increase of NCG concentration is thought to be due to effects of PS-31 beginning production on December 5, 2012 and no injection in P-32. During this period, the well was likely producing lower amounts of low-NCG IDS and drawing in more high-NCG, native reservoir steam. Once P-32 injection restarted, the PS-31 NCG concentration dropped to 0.98 wt% in 14 days. Unfortunately, no additional steam chemistry was obtained from PS-31 because production ceased in January 2013 after a shallow casing leak appeared. The well is currently suspended, pending repairs. Nonetheless, the data obtained clearly indicate a strong correlation between NCG concentration and the injection rate into P-32. It appears that larger amounts of low-NCG IDS are generated in the reservoir and produced at PS-31 as the P-32 injection rate increases. When the P-32 injection rate was reduced to less than about 700 gpm, PS-31 NCG concentrations began to increase. A 1,000 gpm P-32 injection rate resulted in the most significant PS-31 NCG concentration reductions. It has not been possible to test if high-rate injection into P-32 can be sustained long-term without injection break-through occurring.

Figure 28 also shows the NCG concentrations of P-25, located northeast of the P-32 injector (Figure 2). More frequent geochemical monitoring was done for P-25 than PS-31 as it has been connected to a power plant since December 9, 2011. The change in P-25 NCG concentrations in relation to P-32 injection has a very similar response to that measured at PS-31. The NCG concentrations for both wells decreased dramatically after P-32 injection started, leveled out as the injection rate dropped from 1,000 gpm to 700 gpm, and then increased significantly after P-32 injection ceased. The magnitude of the initial NCG concentration decrease after production started was slightly larger for PS-31 than P-25 (92% versus 88%). However, P-25 had a much longer delay in resuming a decreasing trend after the restart of P-32 injection on January 29, 2013. NCG concentrations of PS-31 responded to the injection restart within 14 days, whereas, P-25, responded between days 72 through 139. A comparison of the P-

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25 and PS-31 NCG response suggests a more robust reservoir connection between P-32 and PS-31 than with P-25.

NCG concentrations in produced steam are obtained for all production wells in The Geysers annually. The distribution of NCG concentrations in the greater EGS Demonstration area is shown in the contour map in Figure 29 prior to injection in P-32 and 2 months after the start of stimulation. Note the elongate northeast-southwest NCG low (10,000 ppmw contour) that developed around injector P-9 in 2010. This well has been injecting since late 2007 and developed a large cell of IDS in the reservoir that did not appear to extend into the EGS Demonstration area. Once P-32 injection started, this NCG low enlarged significantly westward and northward. There are currently no existing production wells located to the northwest of the EGS Demonstration area, so it is difficult to accurately determine the area impacted by injection.

5.3 Chloride Monitoring

A chloride concentration of steam above about 1 ppmw is known to have the potential to cause corrosion in surface and near-surface piping, especially when the superheat of steam is ≤40°F. Based on the knowledge of existing north Geysers production wells having chloride concentrations above 1 ppmw, chloride analysis was included as part of the EGS Demonstration geochemical monitoring. It must be noted that steam chloride concentrations can vary widely due to condensate films that can bias results, and trends can be difficult to ascertain. All steam condensate samples were collected with a probe inserted into the center of the wellbore or test pipeline.

During flow testing and production of PS-31, the steam chloride concentrations ranged between a low of 0.67 to a high of 135 ppmw (Table 1). It is apparent that as injection into P-32 progressed, an obvious decrease in chloride concentration did not occur in parallel with the decrease achieved in NCG concentration. Within 10 weeks after PS-31 went into production on December 5, 2013, the casing corroded and developed a hole about 4.6 m (15 ft) below the surface. We suspect that P-32

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injection has not saturated the rock matrix near PS-31, as saturation could possibly scrub or reduce chloride concentrations. As a consequence, dry superheated steam paths may still extend from the HTR into the overlying PS-31 NTR. A caliper log run on June 25, 2012 and prior to PS-31 production showed the casing to be in good condition. A caliper log made after the near-surface leak was discovered, and only 10 weeks after the production of PS-31 began, shows significant corrosion to a depth of 2,500 ft, with a maximum corrosion rate of 100 mil/year (1 mil=0.001 inch) at 305 m (1000 ft) depth. The repair of PS-31 is planned for mid-2016 and includes the installation of a corrosion-resistant high alloy steel (2507) liner to a depth of approximately 1220 m (4000 ft).

5.4 Stable Isotope Monitoring

The relationship between meteoric water flushing and whole-rock oxygen isotope values was integrated into the understanding of the relationship between the HTR and NCG concentration throughout the north-west Geysers (Walters and Beall, 2002). They described an area of the Northwest Geysers (specifically the EGS Demonstration area) where extremely high NCG concentrations (up to 7 wt%) and isotopically heavy ($\delta^{18}O$) reservoir metagraywacke indicate a lack of flushing by meteoric water.

^{18}Oxygen and deuterium (D) are natural tracers which allow the determination of the percentage of injection-derived water versus native water. Because there is a very large isotopic difference in the $\delta^{18}O$ / δD ratio between meteoric water and the native EGS fluid which is at least partially connate water, isotopic analysis has been used to trace the P-32 injection water rather than conventional tracer methods.

The native steam from P-25 and PS-31 had $\delta^{18}O$ values of about +2 per mil and δD values of about -48 per mil when these wells were originally flow tested in the 1980s. These $\delta^{18}O$ values are indicative that the native steam in these areas was not significantly influenced by meteoric

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water. Various geochemical and fluid inclusion studies (Haizlip, 1985; Moore and Gunderson, 1995; Truesdell et al., (1994); Moore et al., 2001; Walters and Beall, 2002; and Lowenstern and Janik, 2003) have concluded that the early steam in these areas was from connate water (sea water trapped in the metagraywacke and argillite reservoir rocks) from the Mesozoic Era (about 150 million years ago). The $\delta^{18}O$ values in Standard Mean Ocean Water (SMOW) have not varied significantly from 0 per mil for the last 150 million years, the approximate age of the Franciscan Assemblage rocks at The Geysers.

The $\delta^{18}O$ values in steam produced from P-25 and PS-31 in 2012 have decreased from about +2 per mil to about -2 per mil and -4.5 per mil, respectively, in 2012. The Santa Rosa Geysers Recharge Project (SRGRP) water injected since 10/6/11 has $\delta^{18}O$ values of -6 per mil and δD values of -38 per mil, very similar to the local meteoric waters in the northwest Geysers. The $\delta^{18}O$ and δD values of local meteoric water, SRGRP water, the original steam produced from the northwest Geysers, and the steam from the EGS Demonstration production wells, PS-31 and P-25 are plotted in Figure 30.

The mixing-line in Figure 30 indicates that by January 2013, only three months after the injection of SRGRP water into P-32 began, about 80 percent of the steam from PS-31 was injection-derived steam (IDS) from SRGRP water and about 45 percent of the steam from P-25 was IDS. Therefore, it is evident that the IDS from SRGRP water injected into P-32 resulted in flushing of the EGS Demonstration reservoir.

Injection into P-32 ceased from August 20, 2012 until January 29, 2013. As a result the $\delta^{18}O$ values in PS-31 and P-25 steam increased about 2 per mil, and the mixing-line indicates that about 45% of the steam from PS-31 is IDS, and 25% of the steam from P-25 is IDS.

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Therefore, like the NCG concentrations, the stable isotope concentrations in the EGS steam are a function of the SRGRP injection rates in P-32.

Three maps for the EGS project area and vicinity are presented in Figures 7 and 31: (1) early (1977-1985) $\delta^{18}O$ values; (2) $\delta^{18}O$ values in the Caldwell Ranch project area acquired in 2010 and early 2011 from recently re-opened and recompleted wells; and (3) $\delta^{18}O$ values acquired in 2012 after P-32 began injecting SRGRP water. These maps show that the $\delta^{18}O$ values of steam in the western half of the Caldwell Ranch project area and the southeastern part of the EGS Demonstration area has been progressively, and substantially, reduced by the injection of SRGRP water at P-32 and P-9: from 0 to +3 per mil before 2010 to -1 to -4 per mil in 2012.

After the injection of SRGRP water into P-9 began in November 2007, the $\delta^{18}O$ values of the steam produced from the western half of the Caldwell Ranch project decreased from the range of 0 to +2 per mil to the range of -1 per mil. It is noted that P-9 water injection did not change the _18O values in the EGS Demonstration area where the heavy $\delta^{18}O$ values ranging from +1 to +3 in the native steam remained unchanged (Figure 31).

6 LESSONS LEARNED FROM STIMULATION

Lessons learned and the successful practices developed in stimulating the reservoir around P-32 are included in this section. The goal of stimulation is to enhance the natural permeability through the injection of fluids (Tester et al., 2006). The creation of an EGS reservoir may be achieved by two methods: (1) high pressure hydraulic fracturing to create new fractures over a very short period of time (hours), or (2) the shear reactivation of pre-existing fractures at relatively low pressures just high enough to cause shear failure over a long time period (months). At the northwest Geysers modeling indicates that shear reactivation of pre-existing fractures is triggered by the combined effects of

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injection-induced cooling around the injection well and rapid (but small) changes in steam pressure as far as half a kilometer from the injection well (Rutqvist et al. (2015a), this issue).

6.1 Community impact and outreach

Project awareness and community support for this project was achieved through public meetings, a dedicated EGS website, access to the Calpine Geothermal Visitor Center (upgraded in 2012) and EGS update presentations at regular intervals.

The Northwest Geysers EGS Demonstration project is located 10.5 and 14.5 kilometers (6.5 and 9 miles), respectively from the Cobb and the Anderson Springs communities. Techniques for the stimulation of geothermal reservoirs are being refined, and it is advantageous for EGS test programs to be sited at a distance from communities. There have been a total of eight seismic events associated with the EGS Demonstration with M ≥ 2.50, the largest of these being an M 3.74 on January 21, 2014 and an M 2.87 on May 31, 2012. The timing of these M ≥ 2.50 seismic events does not show a particularly strong correlation with injection rate or injection rate variability. The M 3.74 event resulted in a geometric mean peak ground acceleration (PGA) value of 11.87 cm/sec^2 (1.2% of gravitational acceleration (g)) at the Anderson Springs Strong Motion Station. According to USGS guidelines, this is consistent with a Modified Mercalli Intensity of IV (light perceived shaking and no potential for damage). The Cobb Strong Motion Station was offline due to a memory card failure, and estimated to have a geometric mean peak ground acceleration in the range of 18.0 to 24.0 cm/sec^2 (1.8 to 2.4% of g), consistent with a Modified Mercalli Intensity of IV (light perceived shaking and no potential for damage). The M 2.87 seismic event, the second largest in the EGS Demonstration area since injection began, resulted in negligible geometric mean PGA values of 1.53 cm/sec^2 (0.16% of g) at Anderson Springs and 1.38 cm/sec^2 (0.14% of g) at Cobb; these PGA values are consistent with a Modified Mercalli Intensity of I (no perceived shaking and no potential for damage).

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6.2 Well Testing and Well Logging

The addition of observation wells to the EGS injection-production well pair, P-32 and PS-31, respectively have proved to be very important to monitoring the EGS demonstration. Static pressure monitoring wells (i.e., WHS-71, P-25, and P-38) outside of the immediate EGS reservoir area provided constraints on the size of the stimulated, EGS reservoir volume. Pressure transient analysis proved to be a valuable tool in assessing the increased permeability near PS-31.

A tight seal of the wireline lubricator at the P-32 well head was not achieved during the initial PT logging and resulted in steam leakage during this survey. As a consequence, the results were noisy and created difficulties during analysis.

High temperature well logging tools are needed to accurately characterize the reservoir before stimulations and to track the stimulation process. The standard injectivity test at The Geysers differs from testing used in other reservoir types. A 'falling head' injectivity test could have provided us with an estimated flow rate of injected fluid getting into the reservoir to better assess the permeability of the well. This type of survey could have benefited from a surface read-out tool. Due to high temperature in the wells we were limited to the use of memory tools for logging. The limitation of 180°C (350°F) for casing caliper tools prevented the use of these to depths more than 600 m (2000 ft)

7 CONCLUDING REMARKS

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. A pipeline was built to carry tertiary-treated waste water from the Santa Rosa Geysers Recharge Pipeline to P-32.

Injection in P-32 has resulted in a substantial reservoir pressure rise in the area compared to values observed in the 1980s. The stimulation has also caused an increase in the flow rate at P-25 and a considerable reduction of the NCG concentration in the P-25 steam. The maximum NCG drop in PS31 and P25 occurred at injection rates of 1000 gpm in P32. Pressure transient analysis of PS-31 flow rate indicates that the kh increased to 42,300 md-ft (12.69 Dm) following stimulation from the 22,000 md-ft (6.6 Dm) value found when the well was re-opened. This increase is considered small but it is an indication that permeability has increased at the EGS site, albeit at a low rate.

Comprehensive seismic data collection and analysis has been an integral part of the EGS Demonstration Project, primarily utilizing the LBNL field-wide permanent seismic monitoring network, along with two program-specific temporary LBNL seismic monitoring networks. A seismicity cluster began to develop almost immediately after P-32 water injection was initiated, and data analysis indicates; (1) the opening of new permeability zones defined by seismicity that are confined in time/space; (2) preferential water movement NNW (N130) trending along tilted zones of permeability; (3) limited water flow to the southeast and northeast which correlates with surface faulting; (4) the downward progression of seismicity indicating deeper permeability stimulation, particularly at the 1,000 gpm injection rate; and (5) increased seismicity associated with an injection rate increase, followed by a significant decrease in event frequency.

Injection is expected to continue through 2017. PS-31, P-32, and other area wells will be continuously monitored, periodically flow tested or injection tested, and sampled for geochemistry. Seismic data will also be collected continuously and analyzed on an ongoing basis.

ACKNOWLEDGMENTS

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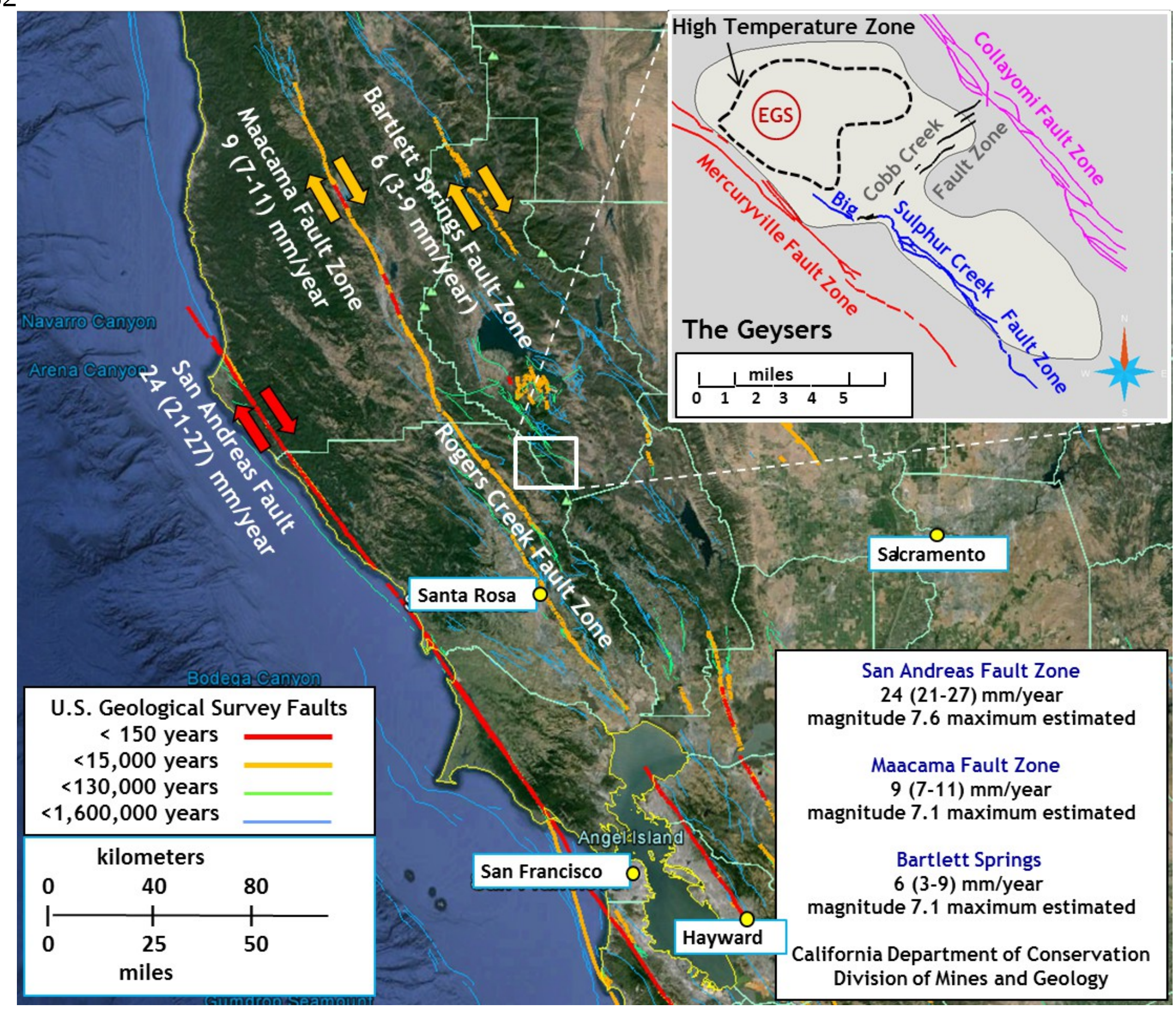

Figure 1: The San Andreas Fault System, including the Maacama / Rodgers Creek Fault Zone and Bartlett Spring Fault Zone. Only faults with activity in the previous 15,000 years are displayed (California Division of Mines and Geology, 1996). The inset map shows the location of the EGS Demonstration Project and the surrounding high temperature region of the northwest Geysers.

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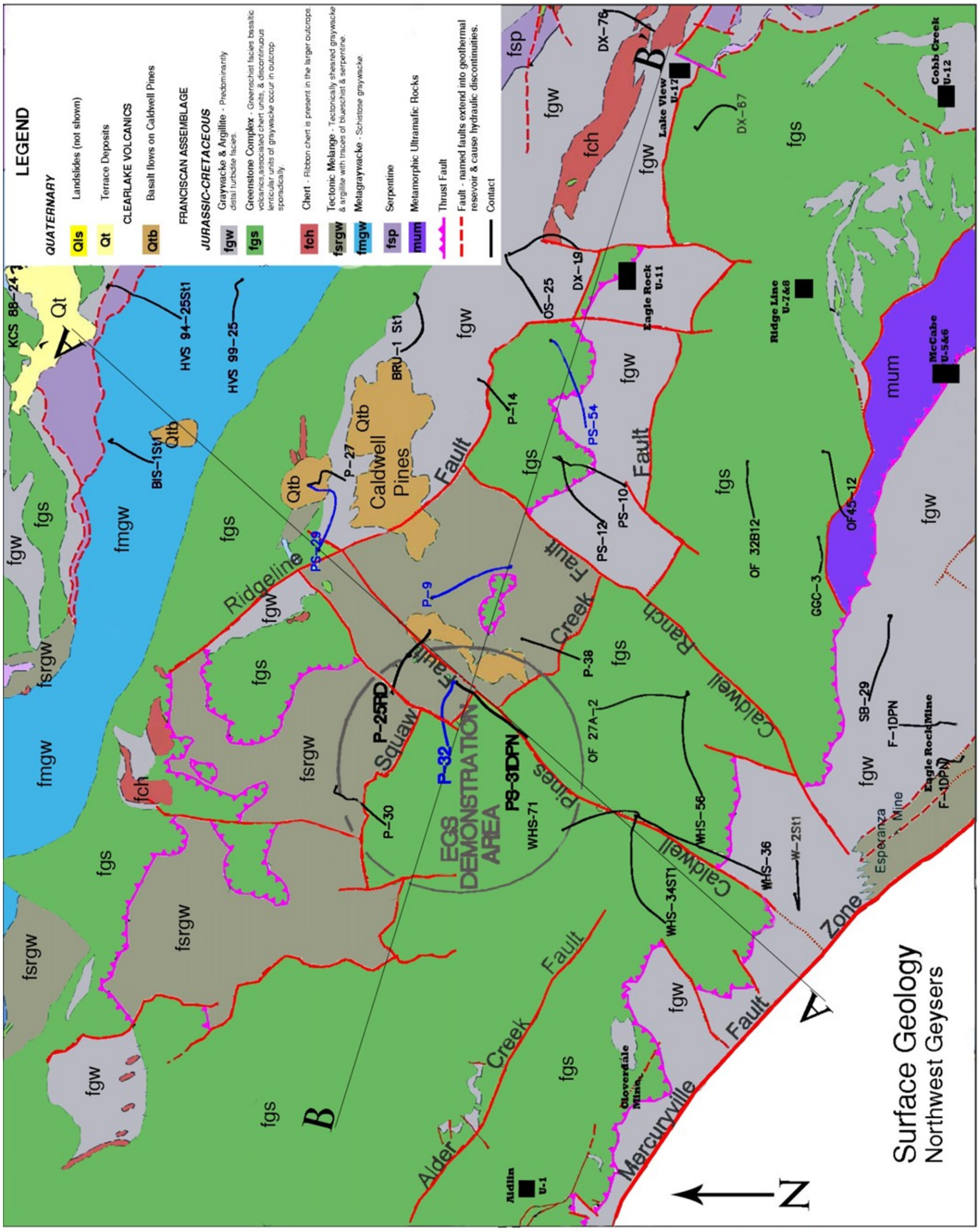

Figure 2: Surface geology of the Northwest Geysers EGS Demonstration Area. Surface faults in the Northwest Geysers which are coincident with hydraulic discontinuities in the reservoir are labeled in red. The hydraulic discontinuity between the EGS Demonstration Area and Caldwell Ranch project is attributed to the Caldwell Pines Fault shown above. The locations of geologic cross-section (A-A') and rock isotope cross sections (A-A’ and B-B’) are shown in Figures 3, 5 and 6).

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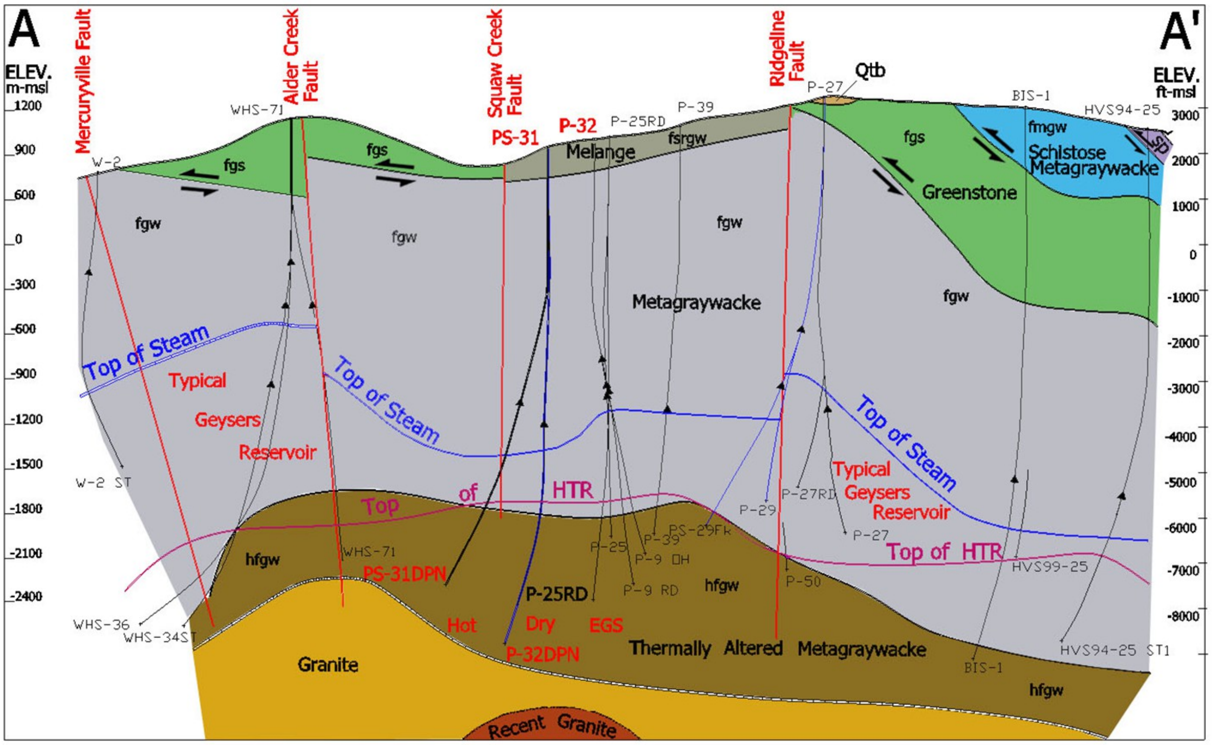

Figure 3: Geologic cross-section (A-A') of the Northwest Geysers and location of the EGS Demonstration Area. Line of cross section is shown in Figure 2

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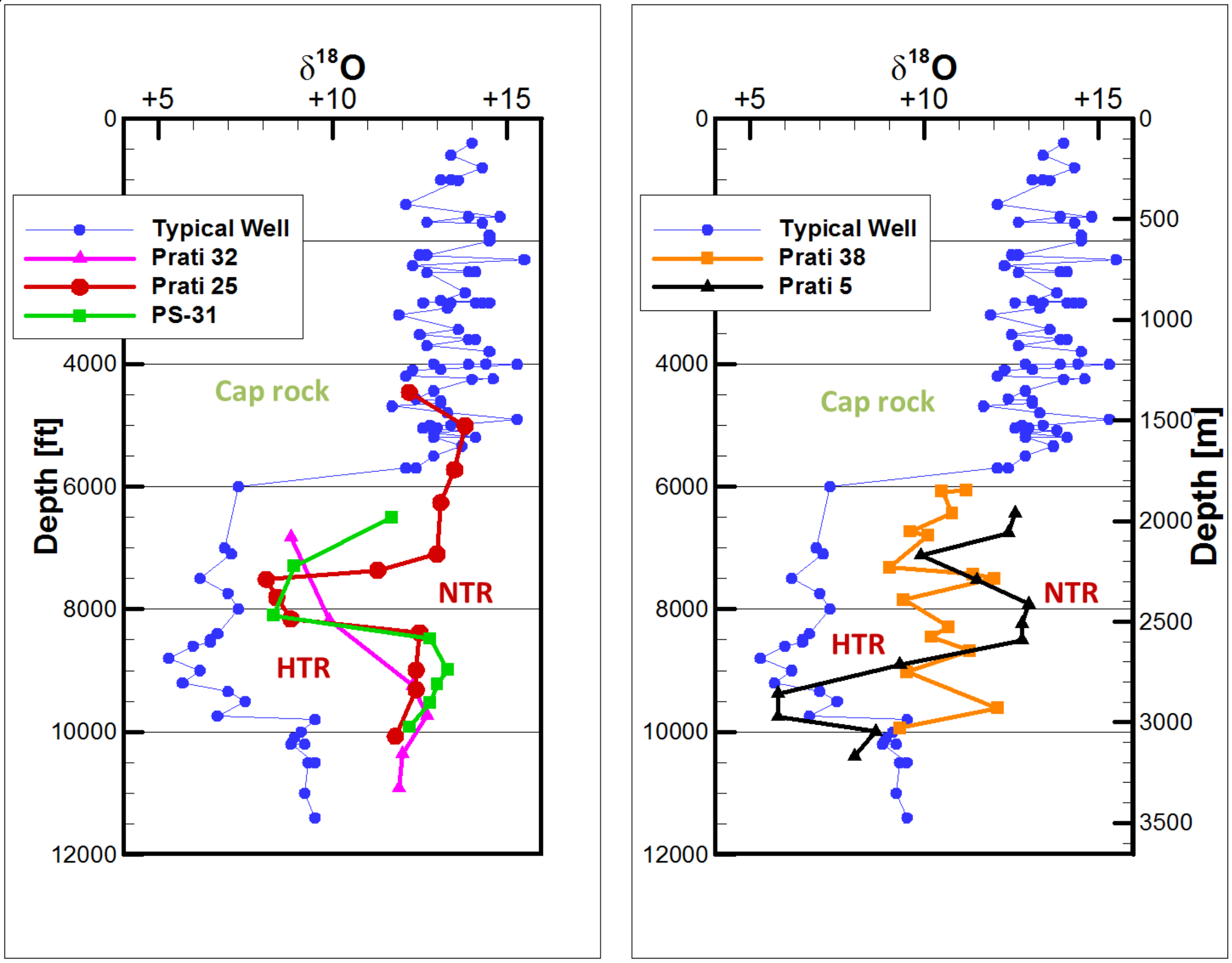

Figure 4: Whole-rock $\delta^{18}O$ values for the Northwest Geysers are plotted versus depth. The graph is for the EGS Demonstration reservoir wells shown in color and a typical Northwest Geysers reservoir well. The Typical Well plot (shown in gray above) is a composite of NTR wells that surround the EGS Demonstration area. Note that the HTR rocks in the Caldwell Ranch, which are in a different reservoir compartment than the EGS wells, are exchanged with meteoric water. (After Lutz et al. (2012))

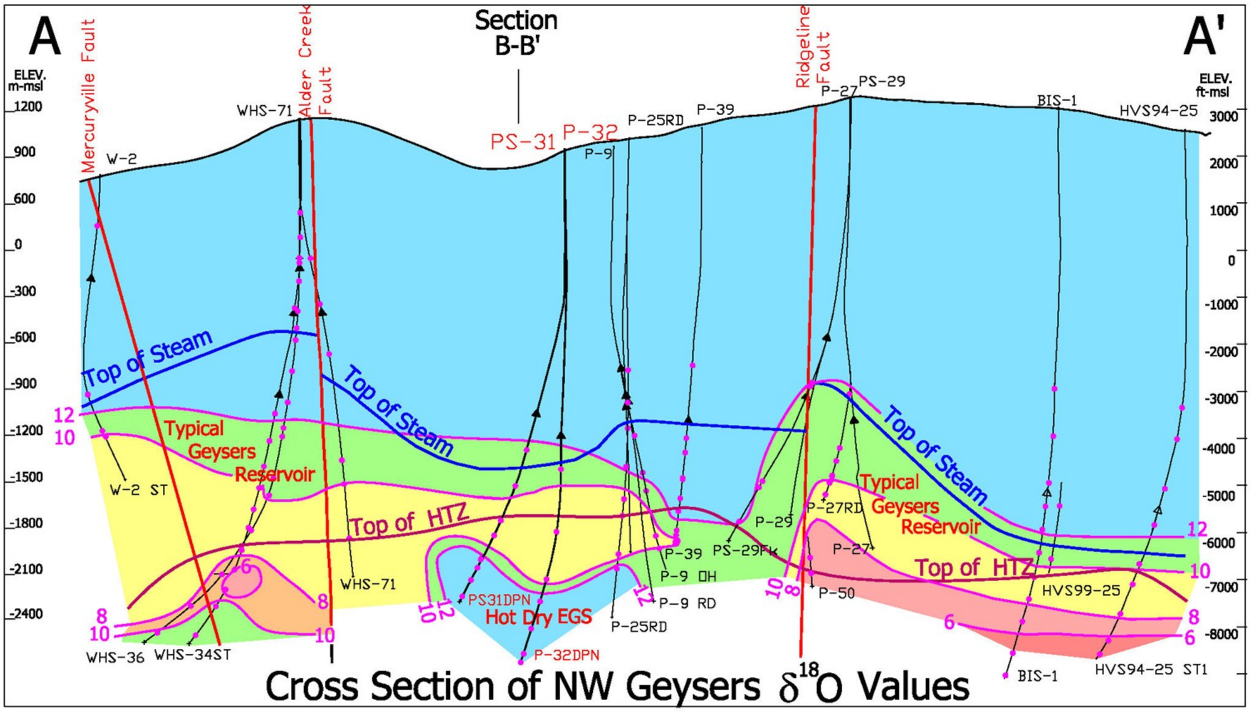

Figure 5: Southwest to Northeast Cross Section B-B' through the EGS Demonstration area.

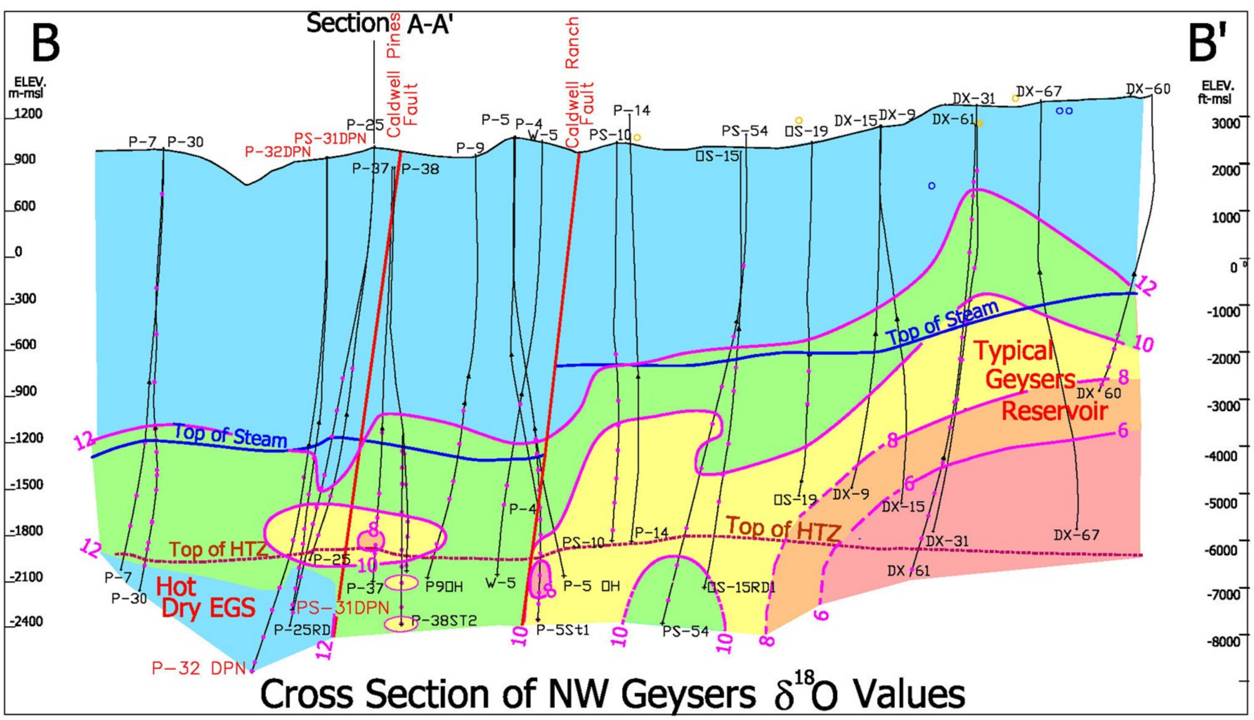

Figure 6: Northwest to Southeast Cross Section C-C' through the EGS Demonstration area.

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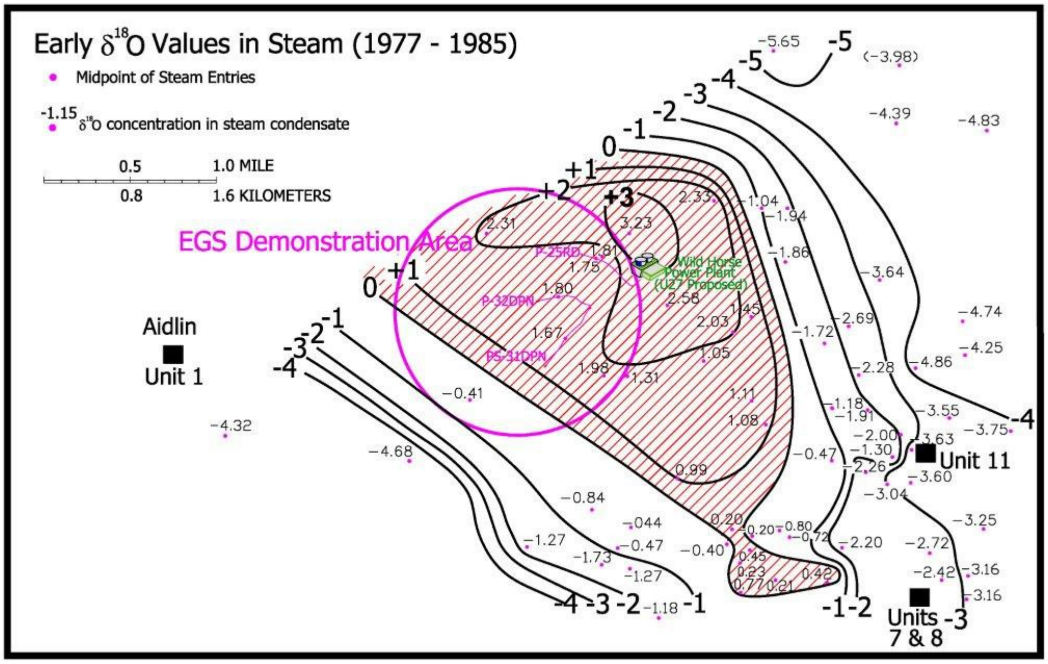

Figure 7: Early (1977-1985) _18O Isotope Values in Northwest Geysers Steam Condensate.

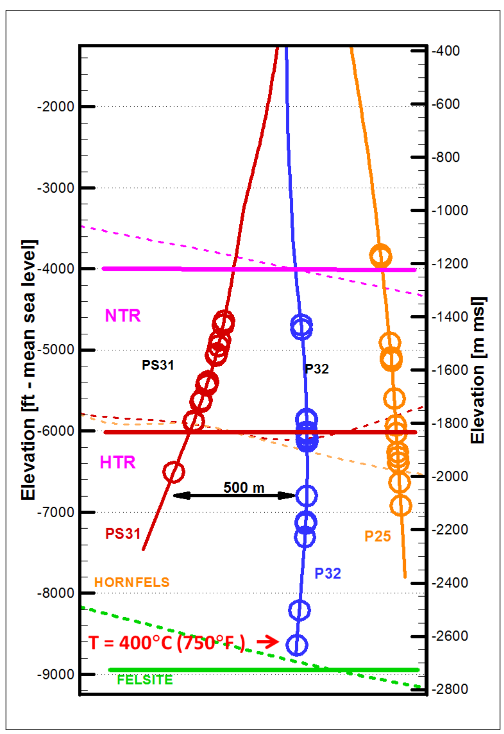

Figure 8: Cold water injected into P-32 (blue) is produced from PS-31 (red). Circles represent steam entries.

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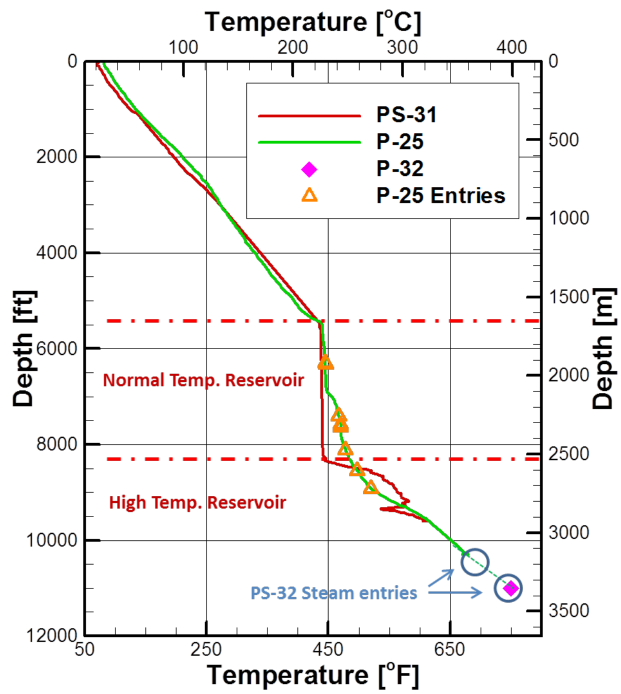

Figure 9: Static temperature profiles for P-25 (green line, temperature profile; orange triangles, location of P-25 steam entries) and PS-31 based on pressure-temperature logs. Maximum recorded temperature for P-32 indicated by magenta diamond and an extrapolated temperature profile in P-32 represented as a blue dashed line.

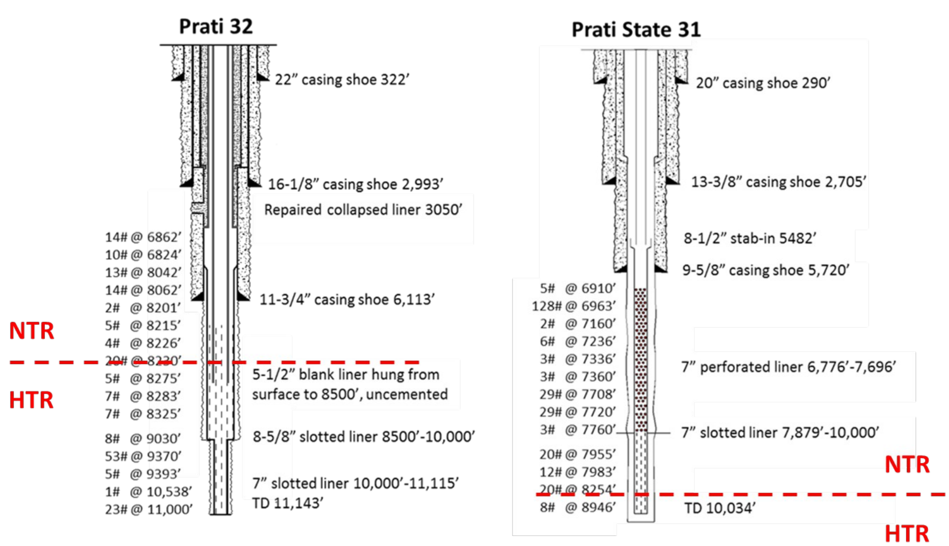

Figure 10: Left: P-32 completion schematic; Right: PS-31 completion schematic (not to scale). The relative force of the steam entries (psig, #) upon the pressures of the compressed air used in drilling wells and the measured depth at which these were encountered are listed to the left of the wellbore schematic above

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Figure 11: Average bit condition after 91.4 m (300 ft) of typical air drilling in the normal temperature Geysers reservoir (left) and Prati 32 final bit condition after 30.5 m (100 ft) of air drilling to a final depth of 3396 m (11143 ft) in the high temperature reservoir.

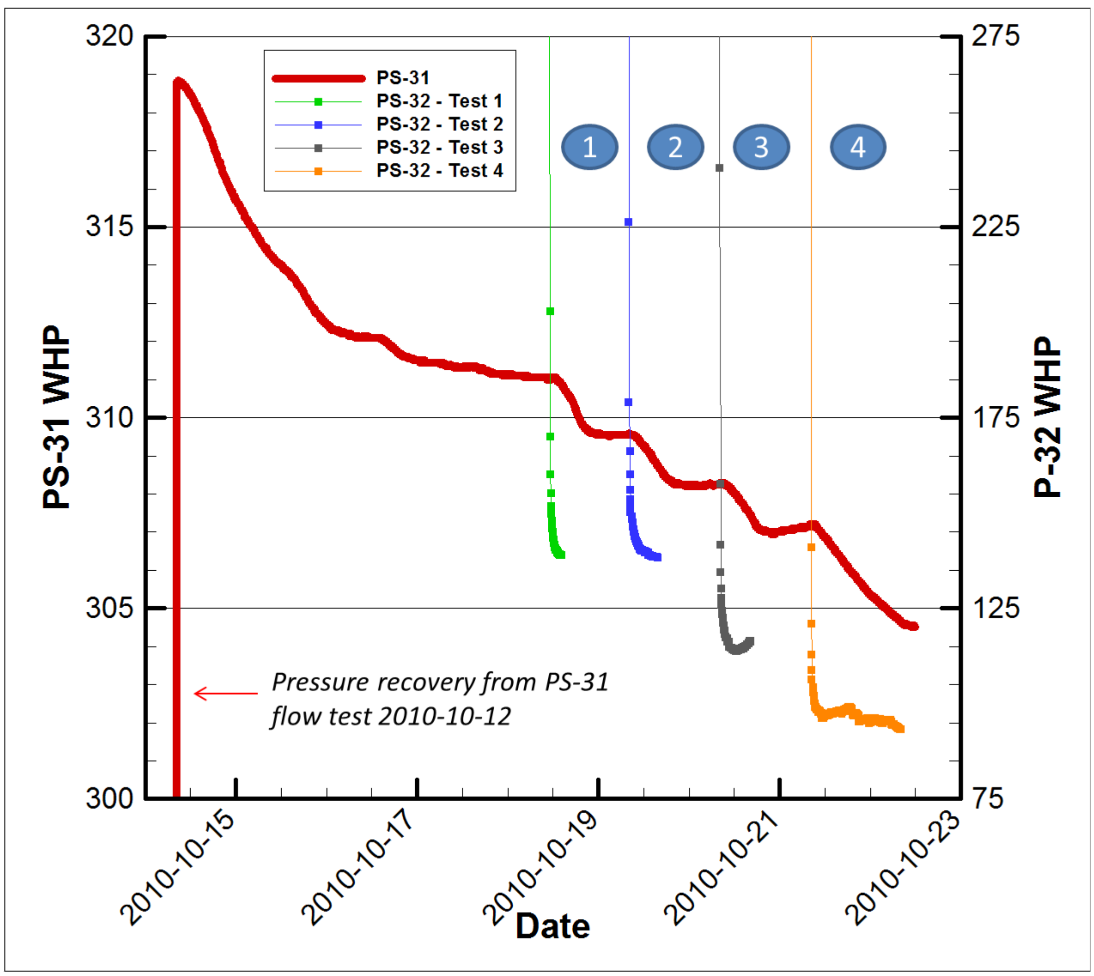

Figure 12: Wellhead pressure at PS-31 and pressure interference during isochronal flow tests at P-32 (2010-10-18 and 2010-10-22): WHP {psig}/ Flow Rate {KPH} at P-32 (1) 137.7/83.2, (2) 115.8/86.4, (3) 96.9/87.6, and (4) 92.8/85.0.

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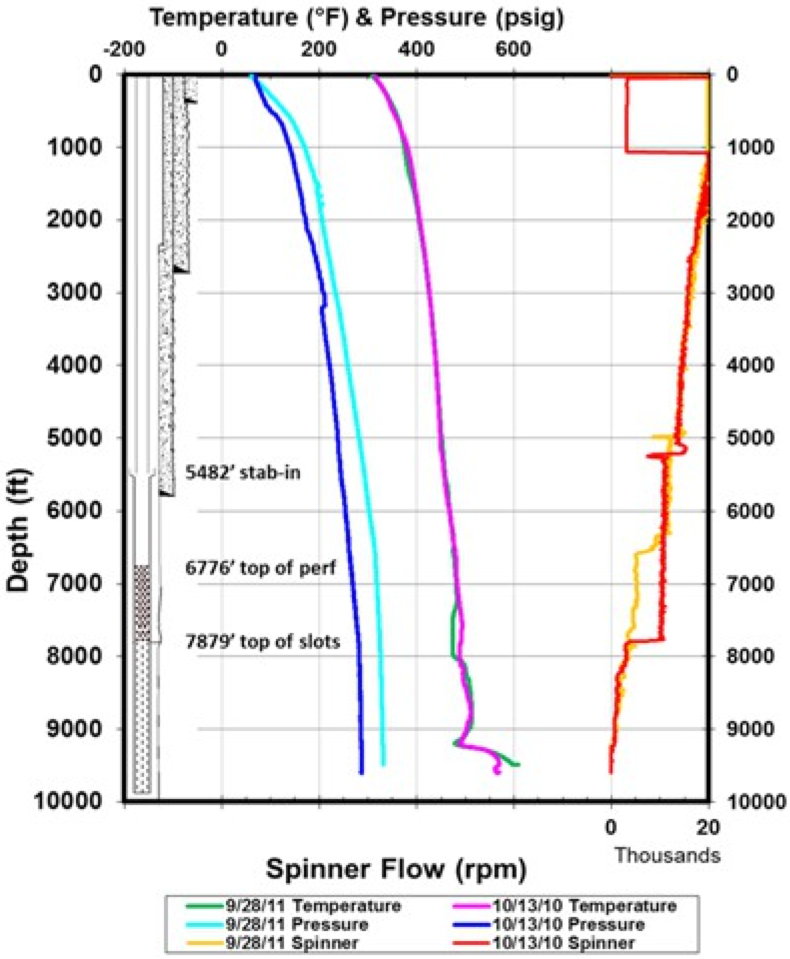

Figure 13: Flowing pressure-temperature-spinner (PTS) logs in PS-31(10/13/10 and 9/28/11)

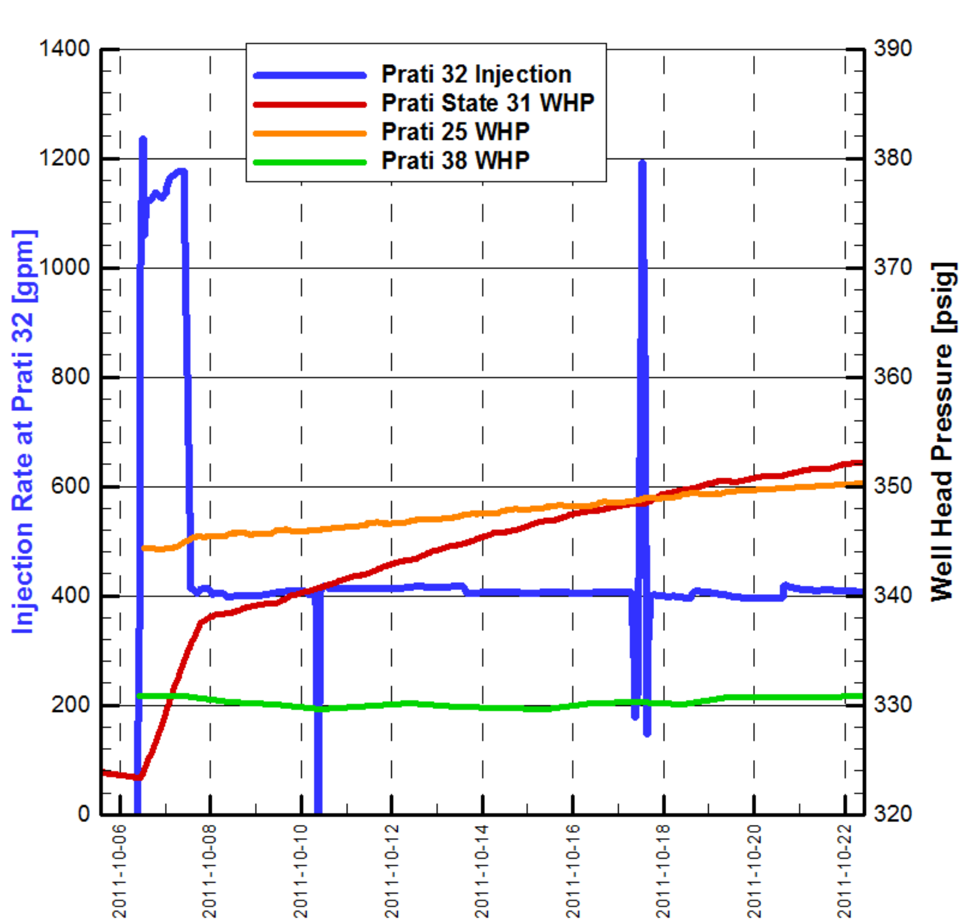

Figure 14: P-32 injection startup and well head pressures in P-25, PS-31 and P-38.

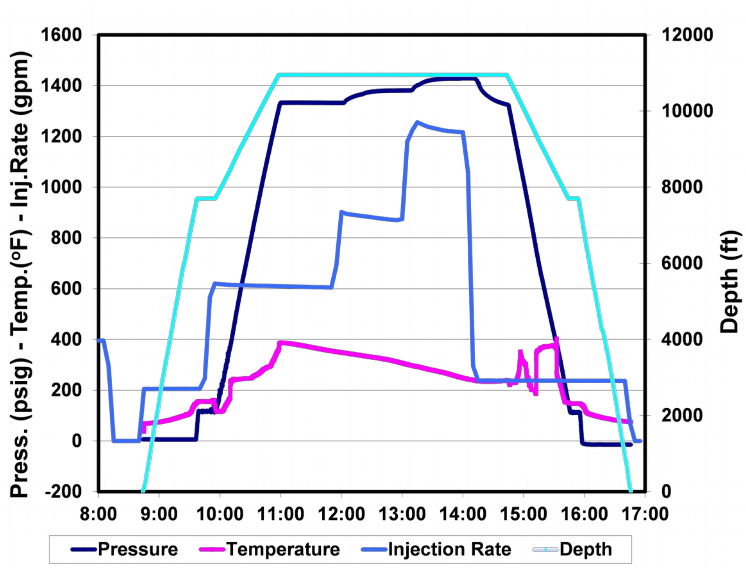

Figure 15: P-32 step-rate injectivity test on 11-15-11. PT tool hung at 10,950 ft during three injection rate steps (between 10:45 and 15:00). Light blue indicated PT tool depth as it traverses the well bore.

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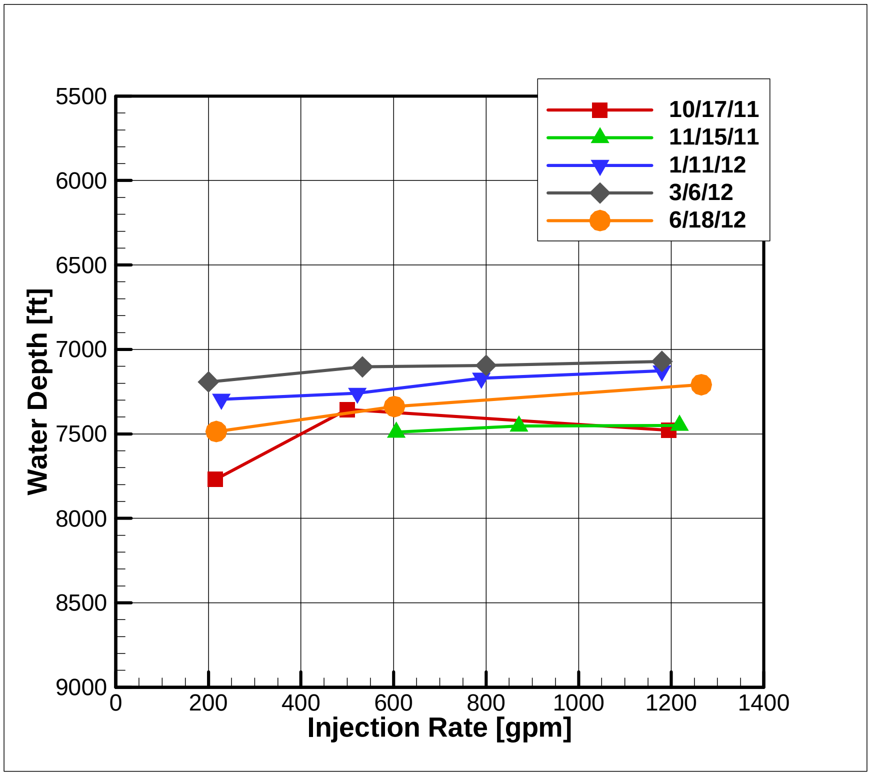

Figure 16: P-32 injectivity test. Lines represent depth of water table in the well measured from surface. Higher depth for a given rate indicates higher injectivity.

38

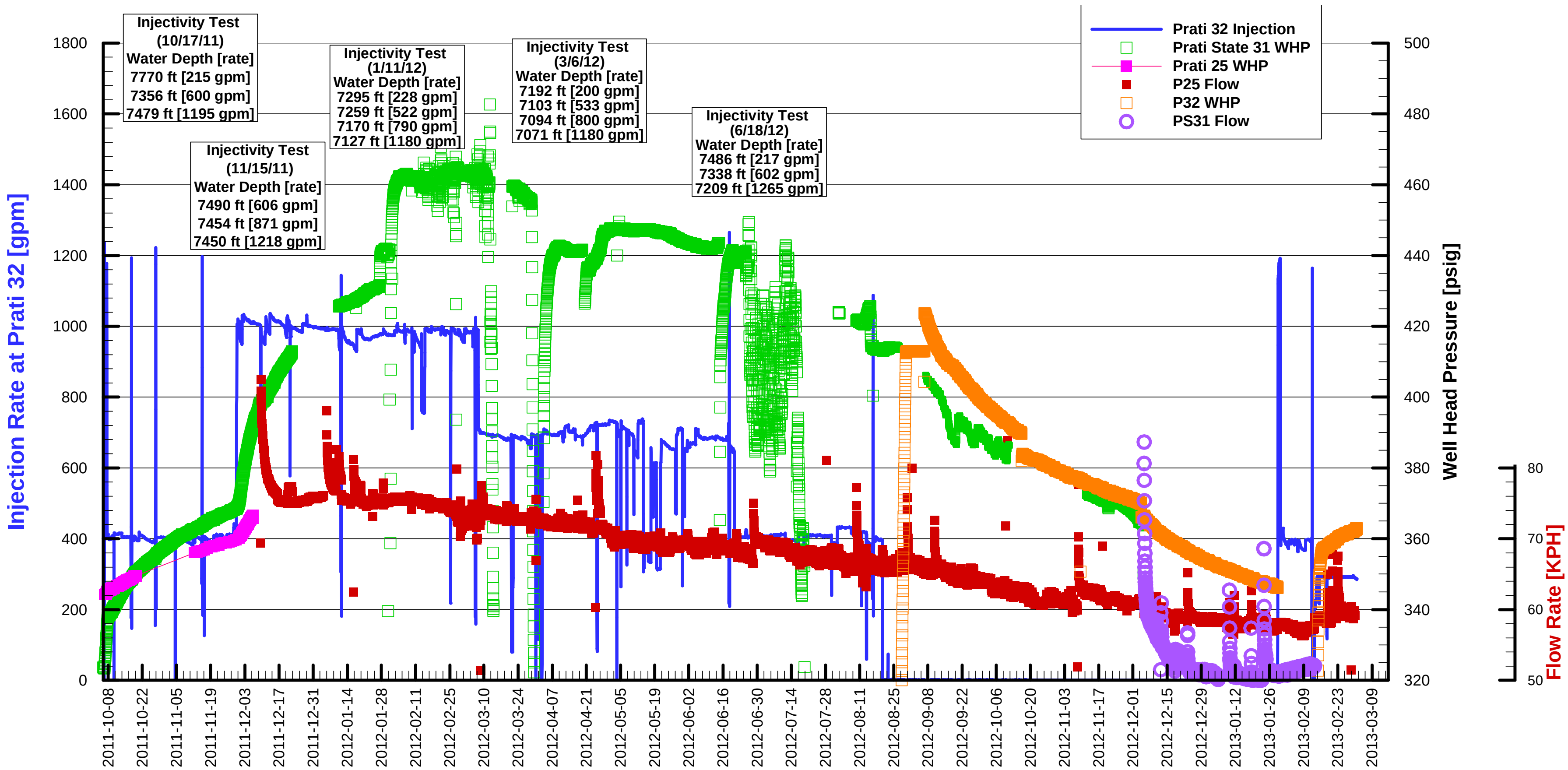

Figure 17: P-32 injection and well head pressure at PS31 and P25

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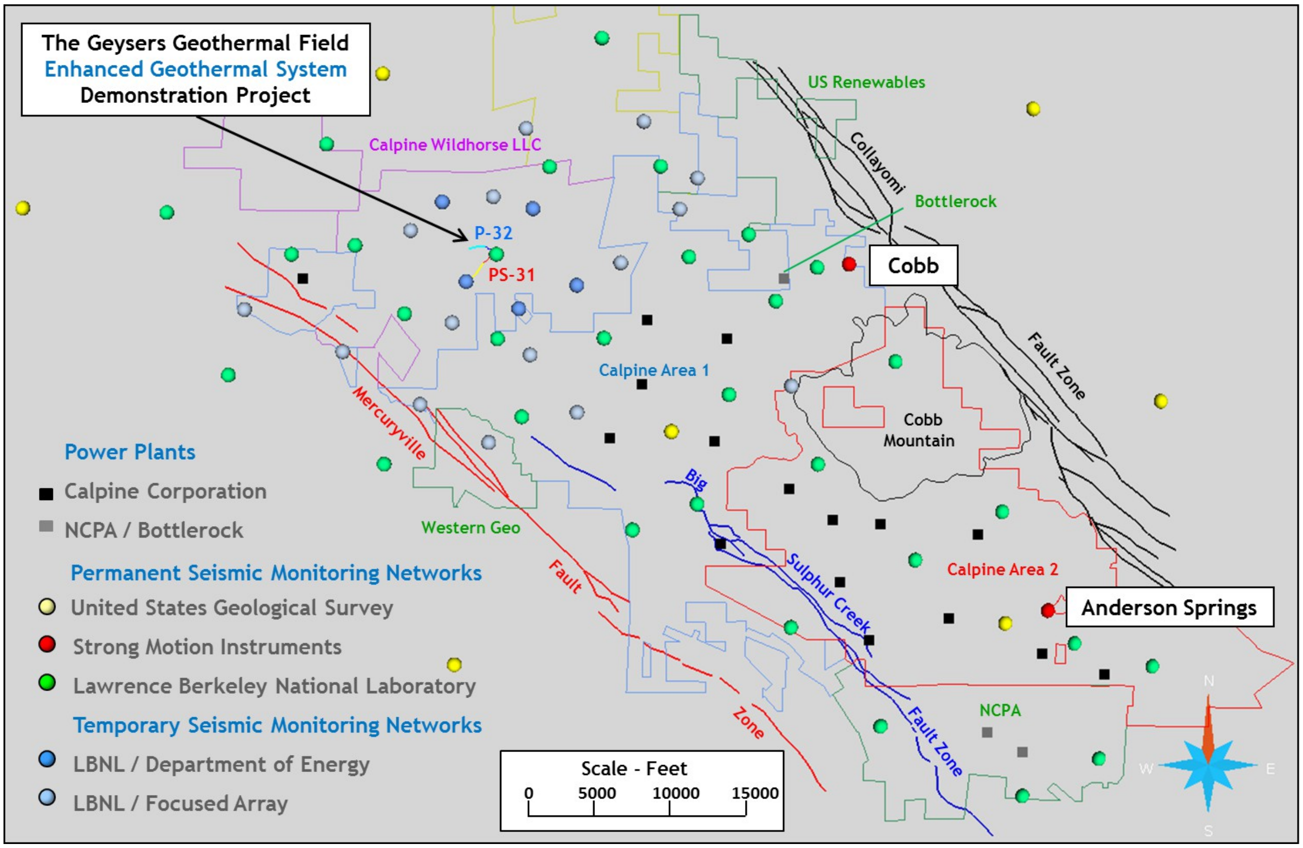

Figure 18: The Geysers Production Areas, Power Plant Locations, Primary Inactive Fault Zones, Permanent Seismic Monitoring Networks and Temporary Seismic Monitoring Networks.

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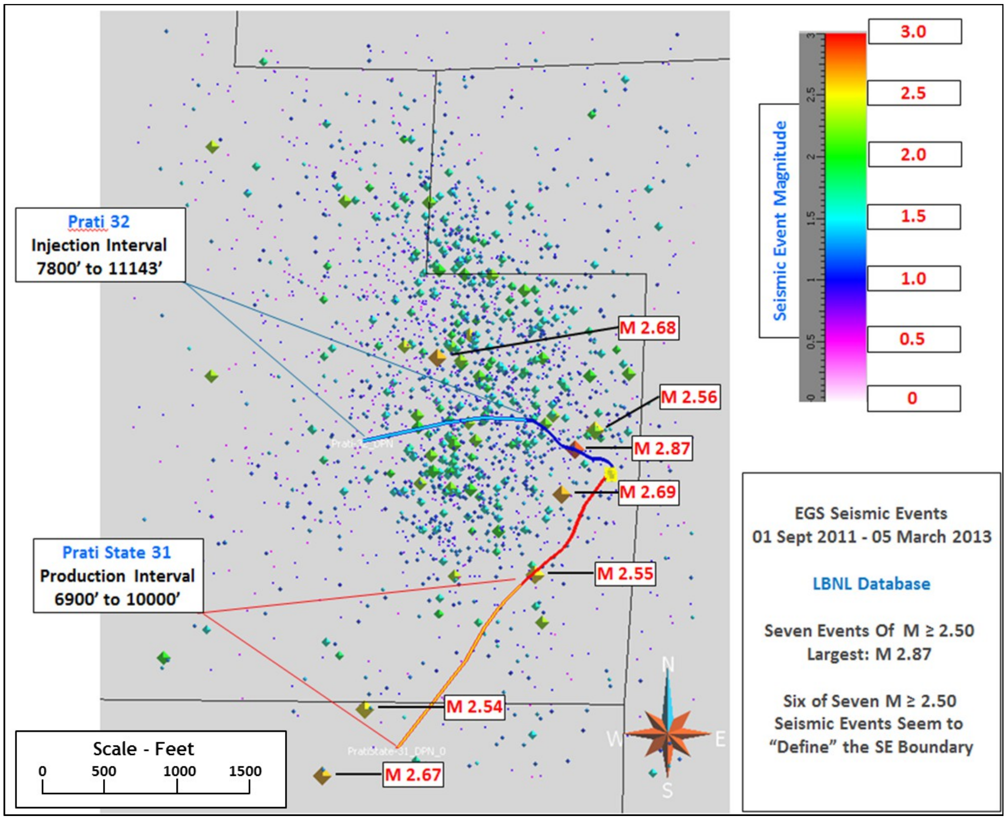

Figure 19: Map view of microseismic events from 01 September 2011 through 05 March 2013.The microseismic events are diamonds with color and size scaled to event magnitude. The area of detailed seismicity analysis is 3650 feet in the east-west dimension and 4860 feet in the north-south dimension and defined as: Longitude 122.8459° W to 122.8333° W (California II 402 Easting 1759041 to 1762691) Latitude 38.8336° N to 38.8471° N (California II 402 Northing 426108 to 430968).

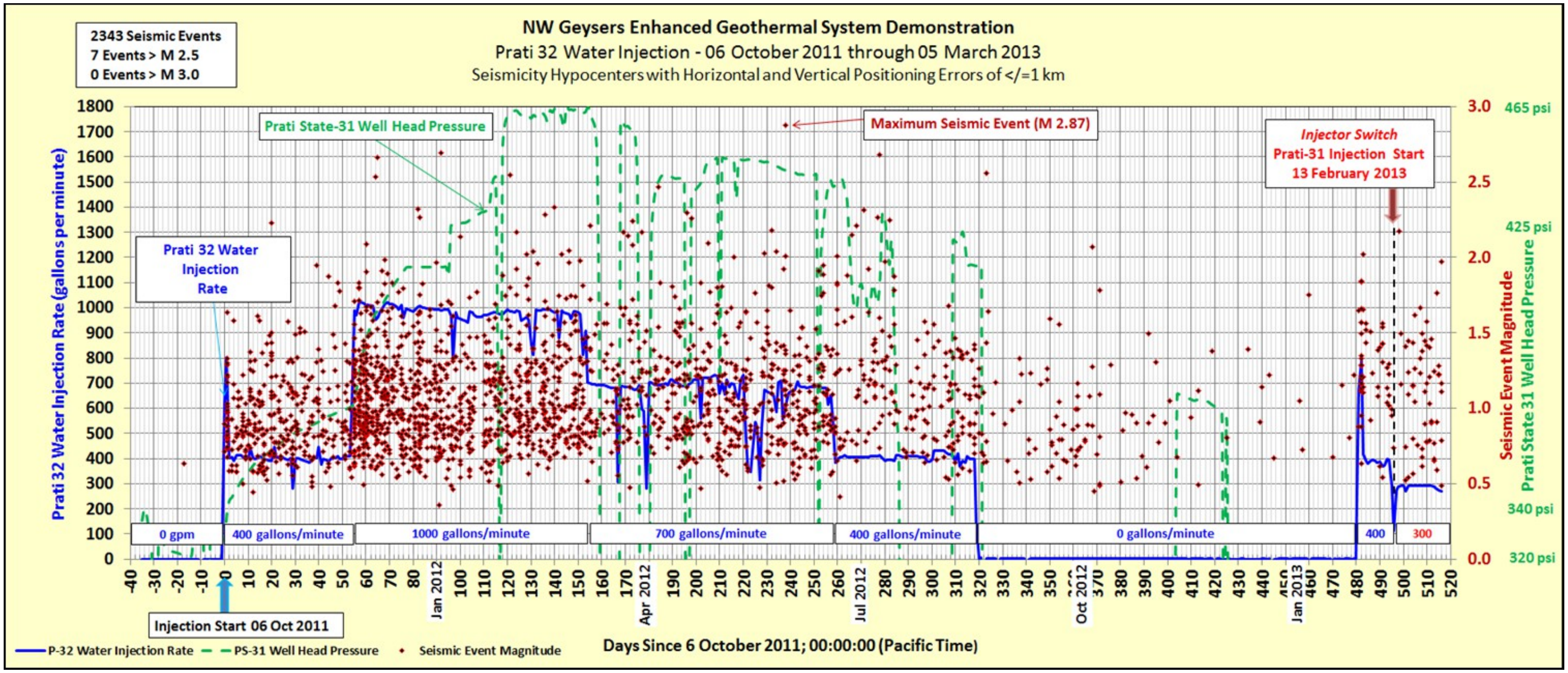

Figure 20: P-32 water injection (blue line and left axis), PS-31 well head pressure (green line and far right axis) and seismic event magnitude (diamonds and near right axis) for the period from 40 days prior to injection through 520 days after injection initiation.

42

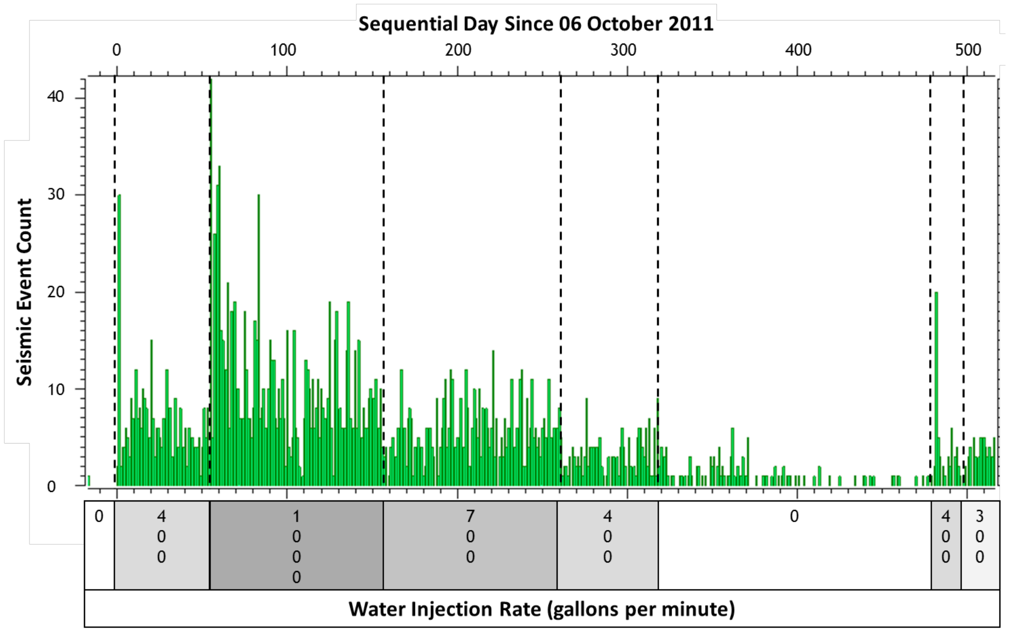

Figure 21: Water injection rate vs. seismic event count for the period from 40 days prior to start of injection on October 6, 2013 through 520 days after injection started.

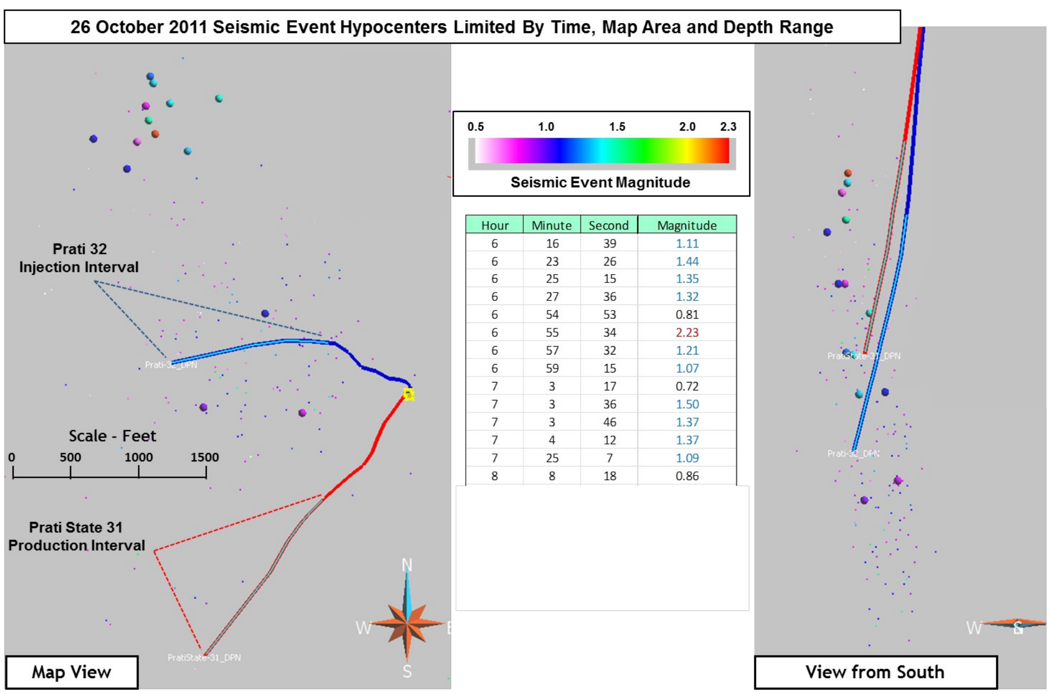

Figure 22: Map view (left) and cross sectional view from south (right) of the P-32 injector (blue), PS-31 producer (red) and the seismicity hypocenters associated with a period of approximately two hours on 26 October 2011. Details concerning the seismic event timings and magnitudes are in the center of the display. This temporally and spatially limited seismicity cluster is believed to indicate fracture reactivation within a previously unaffected volume.

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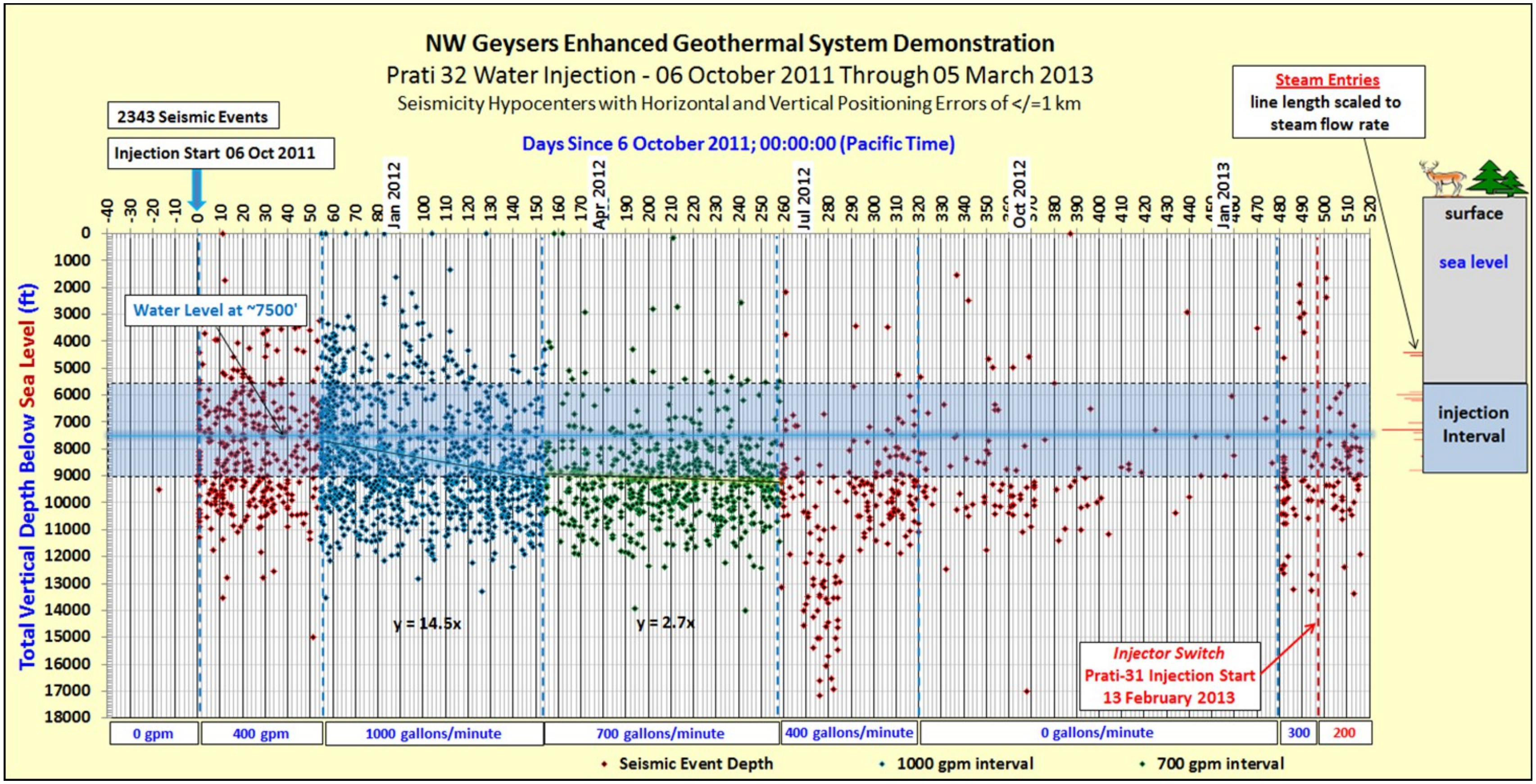

Figure 23: Seismic event depth (diamonds) for the period from 40 days prior to injection through 520 days after injection initiation. The linear least-squares fit is displayed for both the 1000 gpm injection interval (y =14.5 x) and the 700 gpm injection interval (y = 2.7 x).

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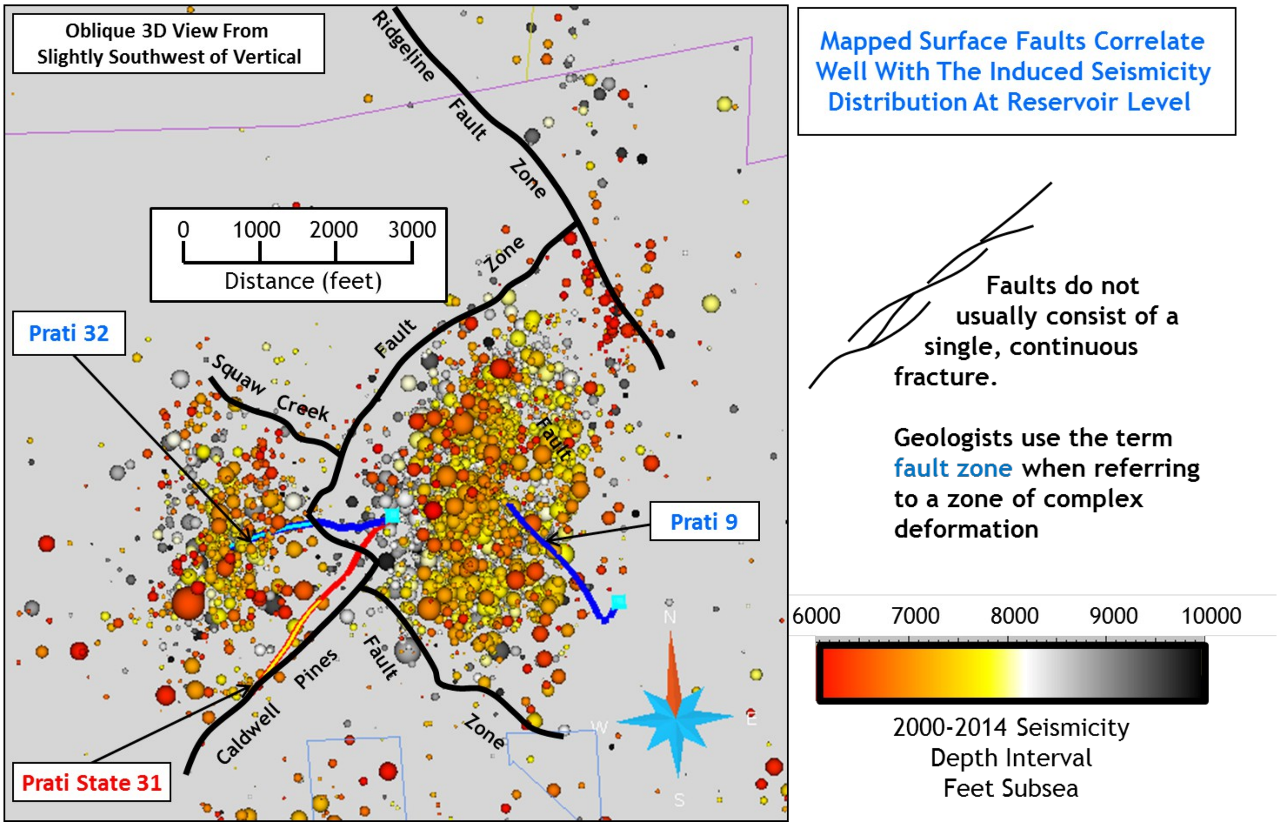

Figure 24: Map view (right) and zoomed oblique view (left) of seismicity in the Northwest Geysers and known surface fault zones (black solid and dashed lines). Recently noted linear seismicity boundaries to the southeast and northeast of the P-32 injection well appear to be confined to the northwest of the steeply northwest dipping Caldwell Pines Fault Zone and a steeply northeast dipping Squaw Creek Fault Zone.

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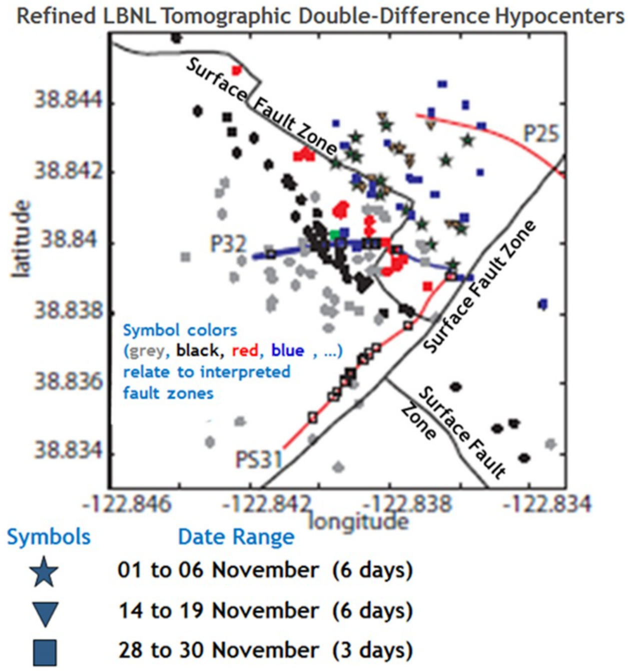

Figure 25: Map view of the relationship between previously mapped surface fault zones and subsurface fault zones interpreted from seismicity hypocenters. Figure modified from Jeanne et al. (2014b).

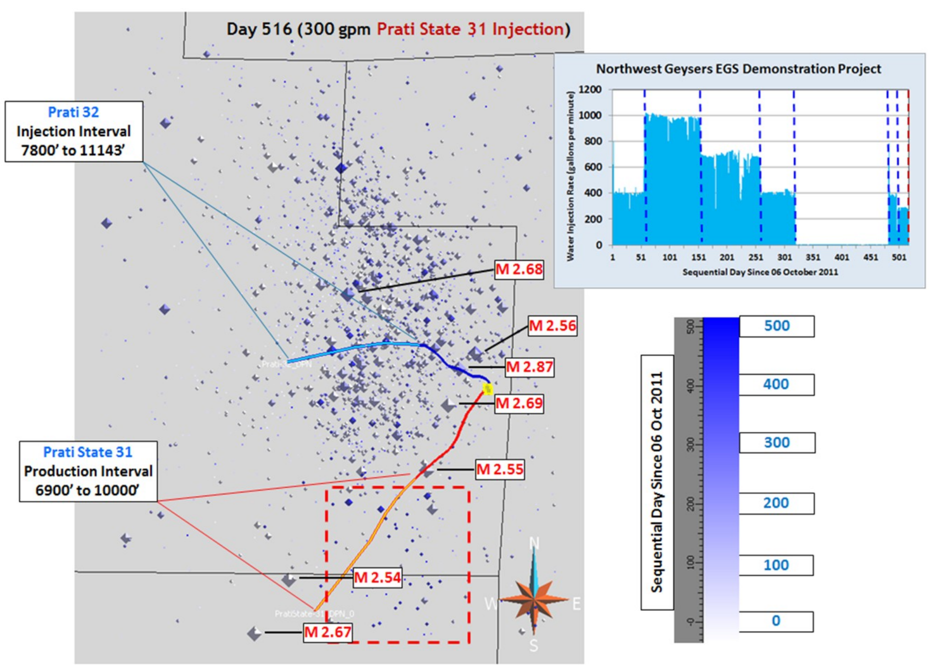

Figure 26: Map view of microseismic events from 01 September 2011 through 05 March 2013. The microseismic events are displayed as diamonds with their size scaled to event magnitude and color scaled to the sequential day since injection started (scale at lower right).The recent dark blue events within the red dashed box occurred after the transition from 400 gpm water injection at P-32 to 300 gpm water injection at PS-31.

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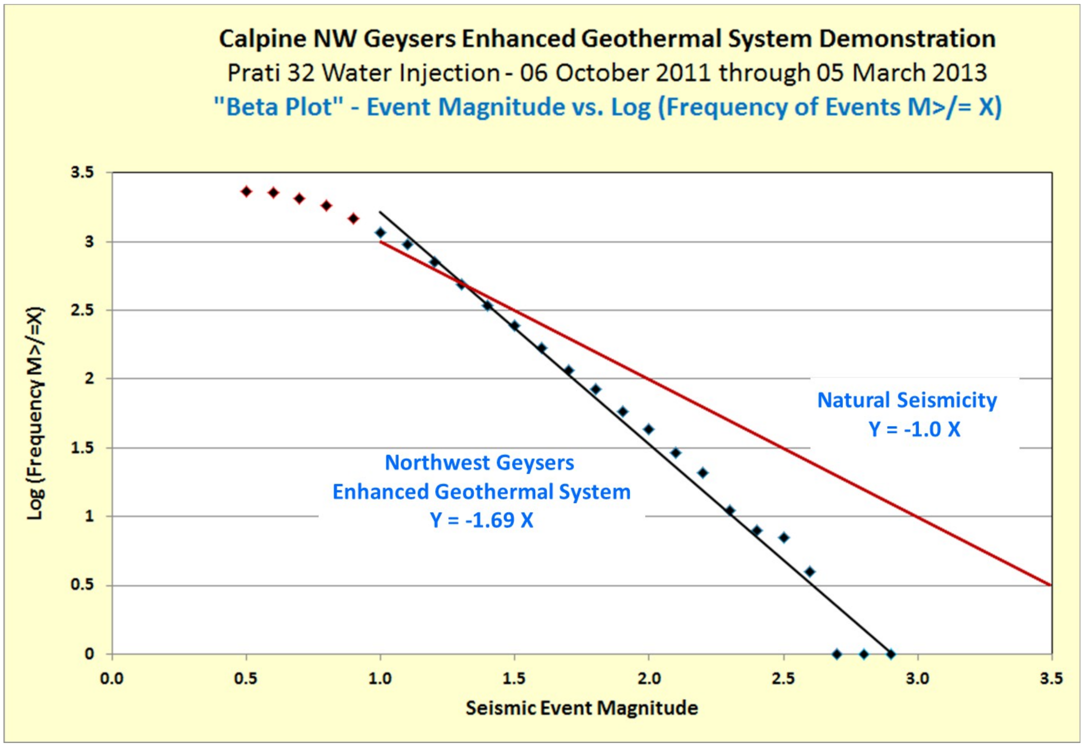

Figure 27: Gutenberg-Richter relationship between the magnitude x of a seismic event and the total number of seismic events with magnitudes higher than x. This generally expressed as log N (x) = a – b*x.

47

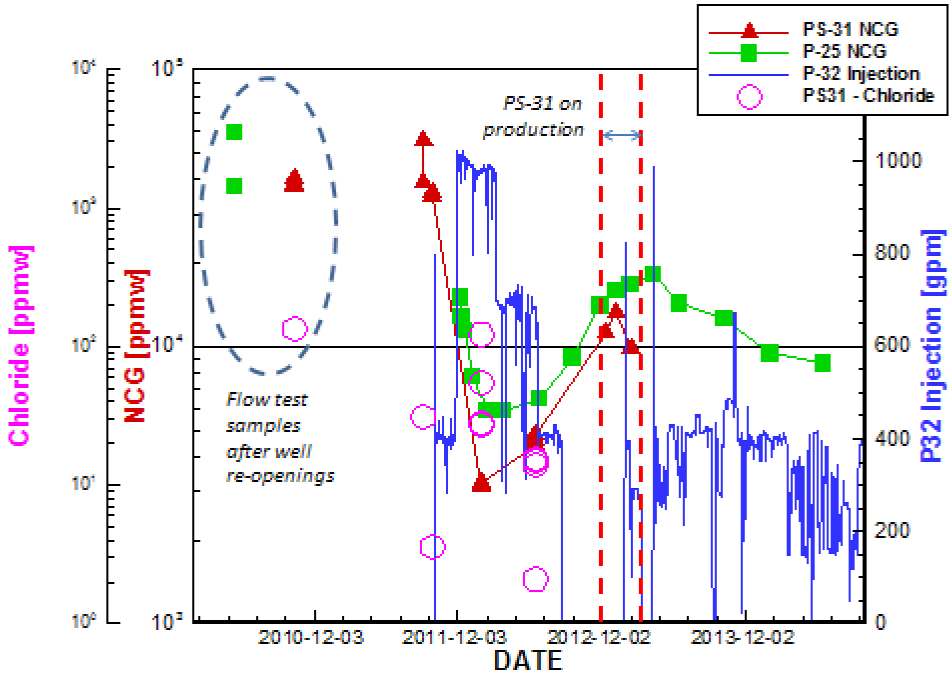

Figure 28: NCG and Chloride concentrations in PS-31 and P-25

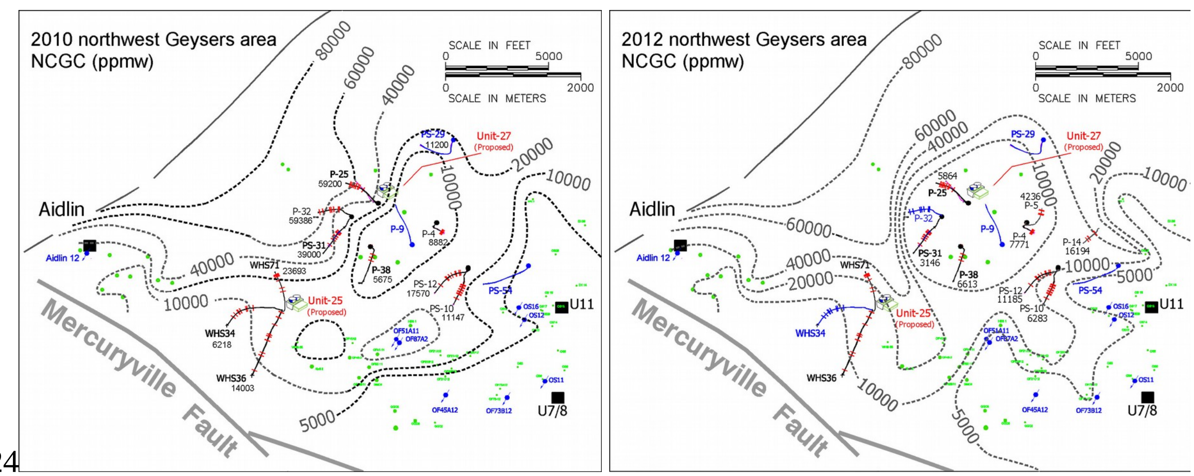

Figure 29: Northwest Geysers NCG concentrations before P-32 water injection (above) and 2 months after the start of P-32 water injection (below)

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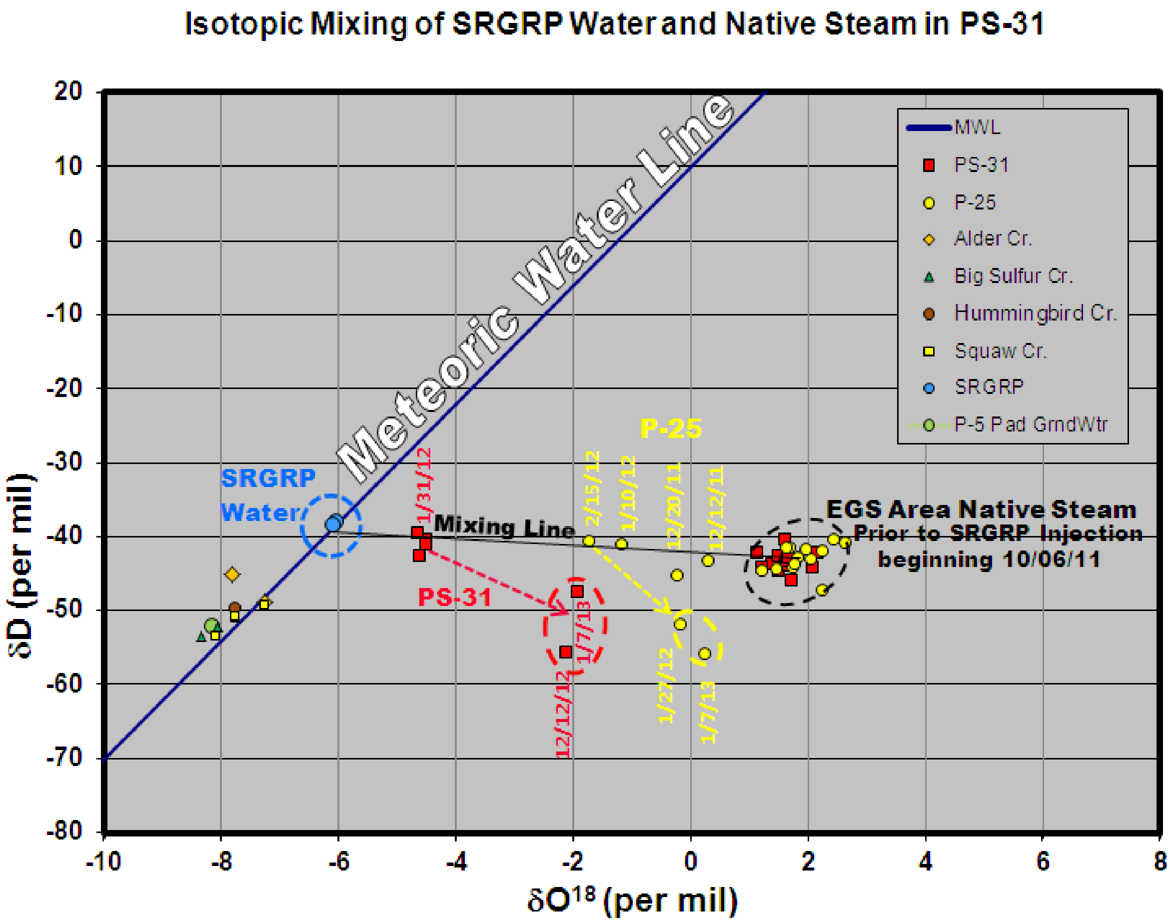
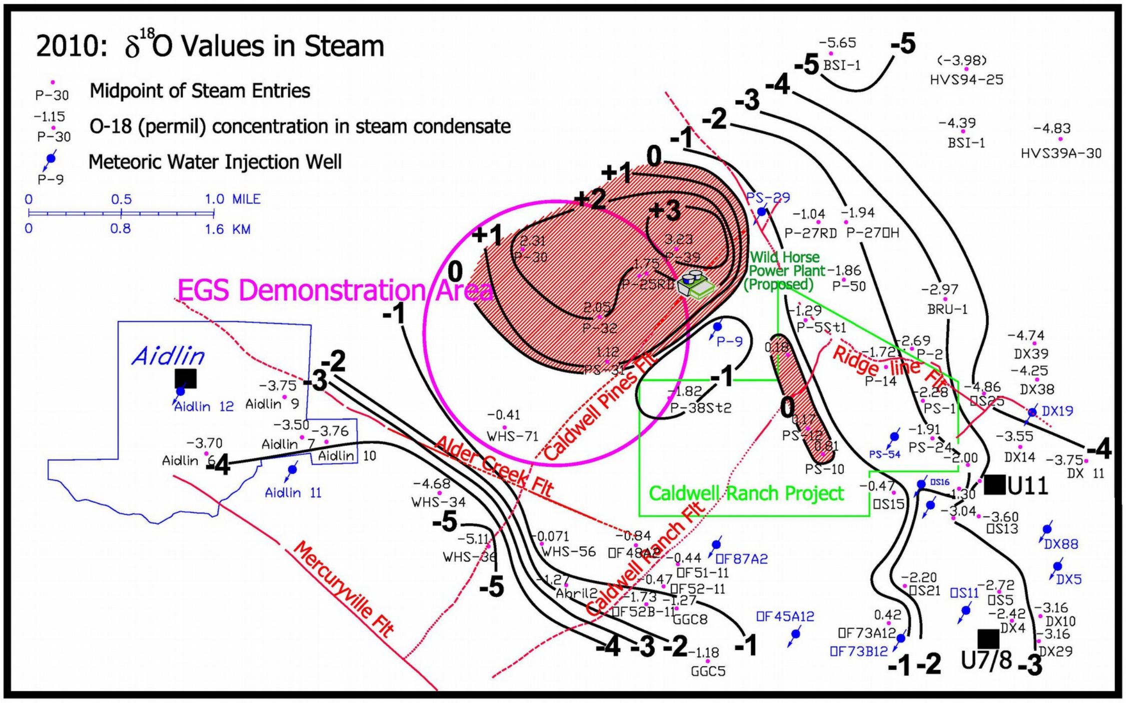


Figure 30: Changes to the isotopic composition of native steam by SRGRP water injection.



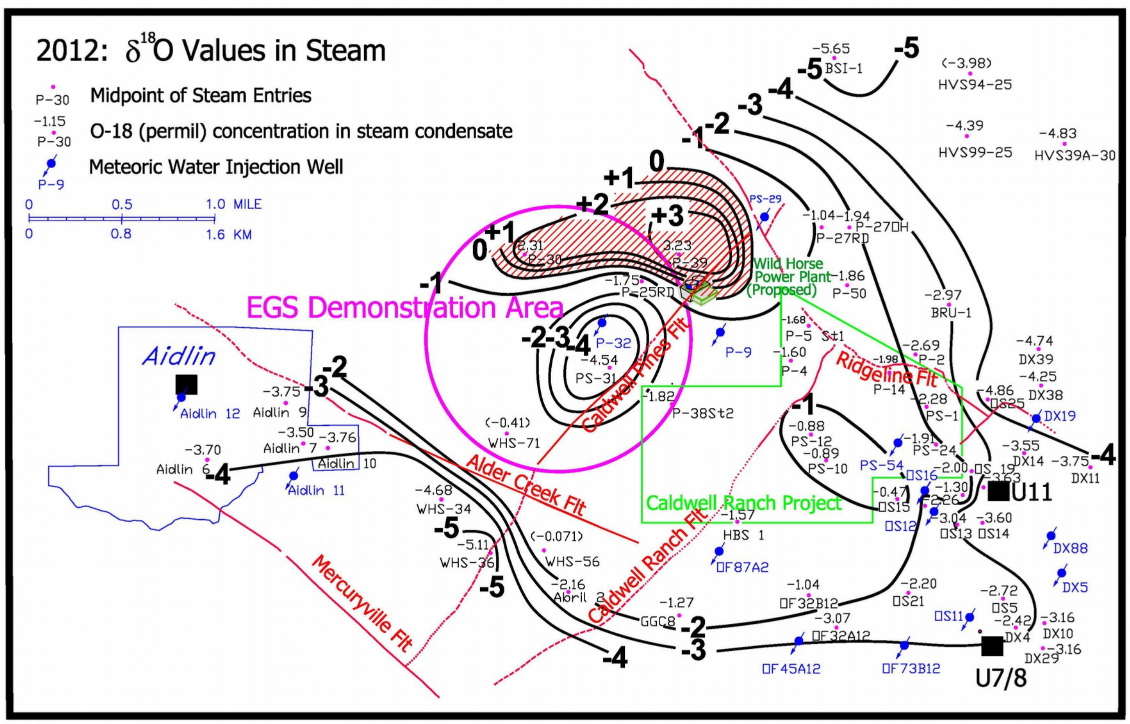


Figure 31: 2010-2011 δ^{18}O isotopic values in steam (top) and 2012 δ^{18}O isotopic values in steam (bottom)

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Table 1. PS-31 well testing flow and geochemistry results

PS-31	**KPH**	**WHP**	**SIWHP**	**NCG**	**H_2S**	**Cl**
Orifice	Testing	(klbs/hr)	(pisg)	wt%	ppmw	ppmw
10/13/2010	42.9	100	320	4.5	1386	135
9/7/2011	52.7	100		4.7	1299	31
9/29/2011	52	100		3.5	1077	3.6
1/31/2012				0.32	545	27-123
6/14/2012				0.46	628	0.67-15.3
Production						
12/12/2012				1.1	767	13.5
1/7/2013				1.3	808	23
2/13/2013				0.98		

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