New Insights Into the High-Temperature Reservoir, Northwest Geysers

Susan Juch Lutz¹, Mark Walters², Sarah Pistone², and Joseph N. Moore³

¹TerraTek, A Schlumberger Company, Salt Lake City UT
²Calpine Corporation, Middletown CA
³Energy and Geoscience Institute, University of Utah, Salt Lake City UT

SLutz@slb.com

Keywords
Enhanced geothermal system, petrology, X-ray diffraction mineralogy, magmatic-hydrothermal alteration, fluid inclusions, oxygen isotopes, core permeability, petrophysical properties, unconfined compressive strength, hot dry rock

ABSTRACT

As part of the Northwest Geysers Enhanced Geothermal System (EGS) Demonstration Project, Prati State 31 (PS-31) and Prati 32 (P-32) were reopened, deepened, and recompleted for direct injection and stimulation of a high-temperature reservoir (HTR) (up to 750 °F, 400 °C). Two wells nearby the EGS Demonstration Project, Prati 5 Sidetrack 1 (P5-St1) and Prati 38 Sidetrack 2 (P-38 St2), were also reopened, deepened, and recompleted as part of the Caldwell Ranch Exploration & Confirmation project. Rock samples were collected from the HTR in the Caldwell Ranch project area for further petrologic and petrophysical studies.

The P-5 St1 core (9940-9945 ft) represents one of the few windows into the hornfelsic metagraywacke HTR. Analysis of core samples indicates that the original illitic matrix of the laminated silty to sandy hornfelsic metagraywacke has been converted to biotite, actinolite, and calcium-rich plagioclase. High-temperature magmatic-hydrothermal veins cut the metagraywacke matrix and are composed of actinolite, biotite, clinopyroxene, quartz, albite, pyrrhotite, and tourmaline. Elemental analyses indicate that the vein albite has a pure sodic composition, and the rock appears to have undergone more extensive sodium metasomatism than in P-5 St1. P-38 St2 apparently has had greater volumes of saline hydrothermal brine, perhaps originating as connate water, moving through the rock matrix than in P-5 St1. Sodium metasomatism has caused extensive albite cementation of the rock matrix.

Basic core properties (density, porosity, and permeability) and scratch testing of the P-5 St1 core confirm the low matrix permeabilities and high rock strengths in the hornfelsic metagraywacke in the high temperature reservoir. Analyses of the P-5 St1 core samples indicate less than 1% porosity and 90 micropore gas permeability in unfractured samples. Scratch test results at ambient conditions indicate very high rock strengths, with unconfined compressive strength estimates of up to 56,000 psi (390 MPa) for the hornfelsic metagraywacke lithologies. Actual in-situ rock strengths and mechanical properties within the HTR are not known; and the rocks are sufficiently hot (400 °C) to behave in a ductile manner at these depths. However, a steam-bearing fracture near 11,000 feet was encountered while drilling P-32 and the injection of cool water into the HTR as part of the EGS Demonstration apparently has promoted brittle failure to depths 1 km below the bottom of the P-32 well.

Introduction

The intent of the Northwest Geysers Enhanced EGS Demonstration Project is to show that the permeability of the high-temperature reservoir (HTR, ~750 °F) that underlies The Geysers normal temperature reservoir (NTR, ~450 °F) can be stimulated by the injection of cool ambient-temperature water. This is being accomplished by injecting highly treated wastewater from the City of Santa Rosa into the HTR via Prati 32 (P-32, Figure 1). The wastewater is injected by gravity and under vacuum at low flow rates into the HTR to cause shear reactivation of existing fractures and thermal contraction of the very hot rock. The early responses of injection in P-32 indicate significant increases in well head pressures and 90% decreases in noncondensible gas concentrations in two offsetting wells, Prati State 31 (PS-31) and Prati 25 (P-25). Concurrent microseismic activity suggests preferential
water movement along a NNW/SSE trending, steeply-dipping zone of higher permeability at and below the P-32 injection zone to PS-31 and P-25. A greater pressure response between the P-32 injection well and the PS-31 well than the P-25 production well was observed, while no observable pressure response was measured in the neighboring P-38 St2 (P-38) production well. The differences in pressure response to injection suggest a northeast-trending permeability discontinuity between P-32 and P-38 St2 (Garcia et al., 2012).

The EGS Demonstration Area is part of a 10 square-mile area of the Northwest Geysers, between the Calpine Aidlin Power Plant and the Calpine Eagle Rock Power Plant, Unit 11. In this area, the HTR is at its shallowest depth, 5500 to 6000 ft below sea level. The rock in the HTR was originally metagraywacke and intercalated argillite but has been thermally metamorphosed to biotite hornfels (Figure 2). In PS-31, P-32, and P-25, the HTR is encountered below about 8000 ft (2.5 km). In P-32, the static temperature at a depth of 11,000 ft is 750°F (400 °C) and the flowing steam temperature is 657 °F (347 °C). The temperature logs in all three of these wells indicate a conductive temperature gradient of 10 °F/100 ft. Temperature logs and whole-rock oxygen 18 concentrations indicate that the hornfelsic metagraywacke in the HTR of these three wells is not flushed with meteoric water (Walters and Beall, 2002). Therefore the reservoir rock in the EGS Demonstration portion of the HTR is a non-hydrothermal, hot dry rock (HDR) reservoir. Based on the composition of the steam and high temperatures recorded in the HTR, much previous work has suggested that the EGS area is separated from the main NTR to the southeast and may be underlain by a very young igneous intrusion, which began cooling 5,000 to 10,000 years before present (Williams et al., 1993).

Despite efforts to collect core samples from both P-5 St1 and P-38 St2, only one 5 ft long whole core (9940-9945 ft) was successfully retrieved from P-5 St1 in the Caldwell Ranch area. In P-38 St2, selected cuttings samples were collected representing rock types and alteration mineralogy from 8250 ft to 9900 ft. The objectives of the petrologic study were to determine the lithologies, veins and types of alteration mineral assemblages of the HTR in the P-5 St1 core and the selected P-38 St2 well cuttings, and to compare the vein mineralogy and paragenesis to previous reports of secondary minerals, metamorphic grade and hornfelsic development in other wells from the northwest part of the Geysers. In conjunction with the X-ray diffraction (XRD), scanning electron microscopy (SEM), and petrographic work, core analyses were also conducted on selected plugs from the P-5 St-1 whole core to determine the density, porosity, permeability characteristic, porosity structure of the hornfelsic metagraywacke lithologies. Estimates of the rock’s unconfined compressive strengths were also determined.

**Rock Mechanics and Core Testing**

Mechanical and petrophysical property analyses were conducted on selected core samples collected from the P-5 St-1 core. The testing program consisted of:

- Continuous strength profiling of all rock types within the core segments using TSI™ scratch-testing apparatus;
- Basic petrophysical properties (i.e., density, porosity and permeability at ambient stress conditions);
- Pulse-decay permeability testing under a variety of confining conditions.
- Mercury injection at increasing pressures to determine porosity and pore throat radius aperture distributions.

![Northwest Geysers Caldwell Ranch and EGS Demonstration Project Areas](image-url)

*Figure 1. Location of the EGS Demonstration Area (outlined in magenta) and its proximity to the Caldwell Ranch Project (outlined in green). The Prati 5 (P-5), Prati 38 (P-38), and Prati 14 (P-14) wells in the Caldwell Ranch Project area were re-opened and re-completed as part of the demonstration project. Petrographic studies of hornfelsic metagraywacke were conducted on core taken from Prati 5 Sidetrack 1 (P-5 St1, 9940-9945 ft) and drill cuttings from Prati 38 Sidetrack 2 (P-38 St2, 8250-9900 ft). A deep core from the hornfelsic metagraywacke in Ottoboni Federal 27A-2 Sidetrack 1 (OF 27A-2 St1) is also referenced in this paper.*

The purpose of the testing was to provide the following:

- Semi-quantitative empirical information on variations in unconfined compressive strength with lithology and extent of veining, and an overall assessment of rock heterogeneity in the whole core interval using scratch testing.
- Strength and rock physics information for developing reservoir models for the material (e.g., Rutqvist, 2010). With adequate measurements of strength on core samples and with the availability of supplementary information such as mineralogy, clay content, porosity, and wellbore temperatures, predictions of in-situ strength may be possible. With such information, predictions of borehole stability and stress conditions can be performed.
The following tables list representative test results from the routine core analyses and uniaxial (unconfined) compression stress tests conducted on the P-5 St1 whole core samples. Table 1 lists physical property measurements and Table 2, next page, presents permeability relationships for selected samples from the P-5 St1 core. Table 3 represents a summary of the uniaxial compression tests as calculated from the TSIM™ scratch testing. Unconfined compressive strength profiles (UCS) for the metamorphic lithologies are shown in Figure 3.

Table 1. Routine Core Analysis Summary Prati 5 St1 Core Samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample Depth (feet)</th>
<th>Ambient Porosity (%)</th>
<th>Dry Bulk Density (g/cc)</th>
<th>Grain Density (g/cc)</th>
<th>Gas Permeability (md)</th>
<th>Net Overburden Stress (psi)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9939.93</td>
<td>0.74</td>
<td>2.735</td>
<td>2.756</td>
<td>0.661</td>
<td>400</td>
<td>Open Fracture</td>
</tr>
<tr>
<td>2</td>
<td>9939.96</td>
<td>0.68</td>
<td>2.721</td>
<td>2.740</td>
<td>0.000</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9940.04</td>
<td>0.61</td>
<td>2.726</td>
<td>2.742</td>
<td>0.001</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>9940.28</td>
<td>0.81</td>
<td>2.708</td>
<td>2.730</td>
<td>0.001</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>9940.75</td>
<td>0.72</td>
<td>2.774</td>
<td>2.794</td>
<td>0.087</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>9940.85</td>
<td>1.05</td>
<td>2.781</td>
<td>2.811</td>
<td>0.001</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>9941.45</td>
<td>1.76</td>
<td>2.692</td>
<td>2.740</td>
<td>2.155</td>
<td>400</td>
<td>Open Fracture</td>
</tr>
<tr>
<td>8</td>
<td>9941.50</td>
<td>0.78</td>
<td>2.724</td>
<td>2.745</td>
<td>0.018</td>
<td>400</td>
<td>Open Fracture</td>
</tr>
<tr>
<td>9</td>
<td>9941.75</td>
<td>0.81</td>
<td>2.712</td>
<td>2.734</td>
<td>0.001</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>9941.86</td>
<td>0.65</td>
<td>2.715</td>
<td>2.733</td>
<td>0.001</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>9942.34</td>
<td>0.43</td>
<td>2.740</td>
<td>2.752</td>
<td>0.001</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>9943.29</td>
<td>1.63</td>
<td>2.710</td>
<td>2.755</td>
<td>0.001</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

Core Analyses

Core analyses from the P-5 St1 core samples indicate matrix porosities typically less than 1% in unfractured samples (Table 1). Grain densities are moderately high (2.73-2.81 gm/cc³) because of the abundance of plagioclase feldspar (~2.65 gm/cc³, approximately 50 wt % of the rock according to the XRD analysis) combined with heavy iron-bearing metamorphic minerals such as actinolite (3.0-3.5 gm/cc³, ~5% by XRD) and biotite (2.81 gm/cc³, 10-18% by XRD). Pulse-decay permeability tests conducted on the core plugs indicate low permeabilities under confining conditions related to simple overburden pressures at approximately 10,000 ft. With no implied pore pressure, permeability values range from 40 nanodarcies up to 17 microdarcies. With 0.43 psi/ft pore pressure, permeability values are generally lower, with high values of only 6 microdarcies (Table 2).
Porosity and permeability testing of core samples from various wells in the northwest Geysers conducted in the 1990s indicate similar porosity and permeability values (<1.3% porosity and mostly <5 microporosity permeability) for all Franciscan meta-graywacke from the depths of 3900 ft to 6500 ft (CCPA, 1993). Nine samples from the HTR in Prati 29 (8445-8448 ft) indicate porosities of less than 1%, permeability of less than 6 microdarcies, and grain densities of 2.73 gm/cm³ (TerraTek, July 1993).

**Rock Mechanics Properties**

Estimates of unconfined compressive strength (UCS) from scratch-testing of the P-5 St1 core range from 15,000 psi in meta-argillite up to 56,000 psi in more silty or sandy metagraywacke lithologies (Table 3), and average 37,000-39,000 psi. In comparison, TSTM scratch-testing of standard segments of Berea sandstone indicate unconfined strength measurements in the range of 5,000 psi to 6,000 psi (Suarez-Rivera et al., 2003). In meta-volcaniclastic rock at the Brady’s geothermal field in Nevada, unconfined compressive strength (UCS) estimates range from approximately 4,000 psi to 30,000 psi, and average approximately 16,000 psi (111 MPa). Samples of chloritic meta-basalt at Brady’s have UCS estimates that range from approximately 6,000 psi to 42,500 psi, and average approximately 28,000 psi (194 MPa) (Lutz et al., 2011). Similar values (26,000-27,000 psi) were found for clay-rich meta-mudstones from the nearby Desert Peak geothermal field (Lutz et al., 2010a and 2010b). Clearly, the metagraywacke at The Geysers appears to be very strong at ambient temperatures and pressures in the laboratory environment, but rock behavior at in-situ confined conditions within the HTR at depths close to 10,000 ft and at temperatures of 400°C could be quite different.

**Matrix Porosity**

Mercury injection data from P-5 St1 core show that matrix porosity may be bimodal (Calpine, December 2011). Four core samples were used for mercury injection testing from depths near 9940 ft. Mercury was injected at increasing pressures up to 60,000 psi (414 MPa). The total mercury porosity and the percent of the total porosity for pore throat radius sizes are summarized in Table 4. There appears to be a distinct peak at 2-3 microns in Samples 2 and 4, whereas Sample 1 (sandy graywacke) is heavily weighted on the large pore throat radius sizes (40-125 microns) and Sample 3 (argillite) is weighted on the small pore throat radius sizes (0.005-0.1 microns). Since no intergranular pores appear to be present between metamorphosed sedimentary grains (based on a previous petrographic and confocal microscopic investigation; CCPA, 1993), the smallest pore throats (0.005-0.1 microns) are most likely microfracture apertures, intercrystalline micro pores, or dissolution vugs within plagioclase feldspars or quartz-calcite veins (see Figure 7).

**Lithology and Alteration Mineralogy of the HTR in the Prati 38 St2 Cuttings and Prati State 5 St1 Core**

P-38 St2 Sidetrack 2 Drill Cuttings

The drill cuttings samples from Sidetrack 2 of P-38 represent five depth intervals between 8250 ft and 9940 ft. The rocks in all five samples can be classified as biotite hornfels with variable amounts of hydrothermal biotite, actinolite, and clinoxyroxene. The presence of talc and serpentine minerals indicates localized serpentinite and shear zones in the metagraywacke. Minor phases include epidote, anatase, and apatite, and trace amounts of tourmaline, sphalerite, and pyrrhotite. Remnant calcite veins and cements are present in some sandy graywacke chips, even at the depth of 9900 ft. Original depositional textures for the poorly sorted graywacke are generally well preserved. Scanning electron microscopy indicates that the original argillic matrix of the graywacke has been converted to a microcrystalline and microporous mixture of quartz, biotite, and original magnesium-bearing chlorite to actinolite. Localized plagioclase or chlorite in the deeper samples at 9670 ft or 9900 ft. The abundance of talc and serpentine minerals indicates local shear zones in the metagraywacke. Minor phases include epidote, anatase, and apatite, and trace amounts of tourmaline, sphalerite, and pyrrhotite. Remnant calcite veins and cements are present in some sandy graywacke chips, even at the depth of 9900 ft. Original depositional textures for the poorly sorted graywacke are generally well preserved. Scanning electron microscopy indicates that the original argillic matrix of the graywacke has been converted to a microcrystalline and microporous mixture of quartz, biotite, and clinoxyroxene.
dance of albite (up to 40% of the whole rock composition) is an indicator of the pervasive sodium metasomatism of the rock constituents in the presence of saline hydrothermal brines. Potassic alteration appears secondary to sodic alteration in these rocks.

With depth, the rocks become more coarsely crystalline and less microporous. Differences in metamorphic grade between 8250 ft and 9940 ft consist of increased amounts of hornfelsic recrystallization and textural banding, subtle increases in the iron content of the metamorphic minerals (biotite and actinolite), higher amounts of albite, and a greater proportion of clinopyroxene to biotite in the deeper samples (Figure 4). The biotite changes from light greenish yellow-brown at 8250 ft and 8890 ft, to darker orange-brown at 9670 ft and 9900 ft. SEM-EDX elemental analyses confirm the higher iron contents in both the biotite and actinolite with depth, suggesting higher metamorphic temperatures. Clinopyroxene abundance increases below 9250 ft, and XRD indicates up to 5% pyroxene at 9670 ft. No granitic or felsite lithologies are recognized in the cuttings. All of the samples contain trace amounts of tourmaline. In the samples from 9670 ft and 9900 ft, the tourmaline occurs in coarsely crystalline chips with quartz, biotite, actinolite, and clinopyroxene.

**Clay Mineralogy and Zoning in P-38 St2**

In P-38 St2, X-ray diffraction analyses indicate the distribution of sheet silicate minerals with depth. Above 9250 ft, some muscovite and chlorite are present, but below this depth, the muscovite and illite has been converted to biotite, and the magnesium-bearing chlorite and talc has been converted to actinolite (Figure 4). Trace amounts of expandable clay are also present in the P-38 St-2 well cuttings. XRD patterns show mixed-layer illite-smectite (I/S) or smectitic clays with basal spacings of 11.2-11.8 angstroms that expand upon glycolation to 16.6 angstroms (Figure 5). The presence of a smectitic clay at these depths (>8250 ft) and temperatures (>400°C) is surprising, but similar clays have been described at The Geysers, albeit at much shallower depths (Hulen, 1995). The expandable clay could be a high-temperature iron-rich saponite, rather than I/S clay typically found at lower temperatures. Alternatively, the I/S clay could represent clays preserved by the poor permeability of these rocks.
**P-5 St1 Sidetrack 1 Whole Core Samples**

Approximately 5 feet of whole core (9940-9945 ft) from P-5 St1 represents a portion of the high-temperature but relatively impermeable reservoir in the northwest Geysers. The core consists of hornfelsic metagraywacke with various proportions of sandy or silty graywacke and argillite. A high-temperature magmatic-hydrothermal vein assemblage cuts the graywacke matrix and is composed of actinolite, biotite, clinopyroxene, quartz, albite, pyrrhotite, and tourmaline. The high temperature minerals are restricted to the veins and vugs, and do not occur in the wallrock.

In SEM, the argillite matrix can be seen as microporous with well-connected intercrystalline pores between plagioclase and biotite microcrystals in the matrix. However, other areas of the matrix are densely cemented with secondary plagioclase cement, especially adjacent to veins. The sandy and silty metagraywacke is also tightly cemented, and core analyses indicate less than 1% porosity and very limited permeability in most of the core samples.

**Alteration Mineralogy and Veining in Prati 5 St1**

The oldest mineral assemblage in the P-5 St1 core is recorded by the presence of distinctive orange-brown biotite within the metagraywacke matrix. This finely crystalline metamorphic biotite replaces the original potassium-bearing illite clays. Throughout the cored interval of P-5 St1 ST-1, the dominant wallrock alteration consists of authigenic plagioclase replacement and cementation that postdates the metamorphic biotite. XRD analyses indicate that plagioclase comprises 44-56% of the bulk composition. The SEM-EDX elemental analyses indicate two types of authigenic feldspar (Figure 7); one is a calcic plagioclase, extremely finely crystalline and present within the wallrock matrix and in diffuse selvages adjacent to veins, and the other is a coarsely crystalline vein mineral with a pure sodic composition (i.e., albite).

The most prevalent authigenic plagioclase is the first variety with an intermediate composition and usually with more calcium than sodium. Light-colored alteration zones are commonly observed as diffuse selvages on the veins, and these can be seen both in thin section and in the whole core samples; these alteration halos are composed of the calcic plagioclase (Figure 6). Previous alteration studies may have attributed these light-colored, ‘bleached’ vein selvages to minor silicification associated with the veins (Hulen, 1991), but here EDX analyses confirm that the authigenic phase is finely crystalline calcic plagioclase.

Within the veins, coarsely crystalline albite crystals display polysynthetic twinning. Elemental analyses indicate a pure sodium composition for the albite (Figure 7). The albite occurs in high-temperature magmatic-hydrothermal veins with actino-

**Fluid Inclusions**

Fluid inclusions are common in quartz crystals from actinolite and biotite-bearing veins encountered at 9941.75 ft in the P-5 St1 core. Both liquid- and vapor-rich inclusions are present but not always in the same assemblage. Fluid inclusion assemblages containing only vapor-rich inclusions are common and define healed fractures indicating that boiling has occurred in the system, but not necessarily at the site of trapping. Most of the vapor- or liquid-rich inclusions appear to be secondary in origin.

Many of the liquid-rich inclusions contain one or more solid phases, including halite and sylvite. The presence of halite crystals

*Figure 6. Thin section images displaying the light-colored, ‘bleached’ selvages on veins (upper left image in plane light), and dark cryptocrystalline character of the authigenic plagioclase (pl) in the selvages (upper right image in crossed polarized light), Prati 5 St1 core samples 9940-9945 ft. Lower images show finely crystalline plagioclase selvages (dark in crossed polarized light) and coarsely crystalline veins (outlined in the lower right image) composed of quartz (qtz), biotite (bio), and albite (alb). The veins cut finely crystalline metamorphic biotite in the metagraywacke matrix.*
at room temperatures implies salinities of more than 26 wt % NaCl. Our petrographic observations suggest that there is considerable variation in the number and type of solid phases present in individual fluid inclusion populations. This implies that the solids are accidentally trapped minerals that were precipitating from the hydrothermal fluids at the time of inclusion formation. More detailed thermometric evaluation of the fluid inclusions is currently underway.

**Whole-Rock $^{18}$O Analyses**

The $\delta^{18}$O concentration in the whole-rock within the HTR and below the NTR of the EGS Demonstration Area is unexchanged by meteoric water and has the same range of $\delta^{18}$O concentrations (+12 to +15 permil) as the cap rock of the overlying NTR (Figure 8a). Calpine’s analysis of whole-rock $^{18}$O analyses made by Southern Methodist University in the EGS Demonstration Area together with a conductive temperature gradient (10°F/100 ft) meets the definition of a hot dry rock (HDR) reservoir and is not part of a pre-existing hydrothermal system. In contrast to hornfelsic metagraywacke of the HTR in the EGS Demonstration Area, hornfelsic metagraywacke of the Caldwell Ranch Area (wells P-5 and P-38) is exchanged by meteoric water to values of +9.5 to +10.5 permil $\delta^{18}$O (Figure 8b). Elsewhere in the Caldwell Ranch area and adjacent areas to the south, southeast and southwest, the hornfelsic metagraywacke is part of a hydrothermal system which has been flushed by meteoric water (Moore and Gunderson, 1995; Walters and Moore, 1996; and Walters and Beall, 2002).

**Figures 8a and 8b.** The $\delta^{18}$O concentrations in the HTR of the EGS Demonstration Area are unexchanged with meteoric water just as the overlying cap rock (Figure 8a, left). In contrast, the $\delta^{18}$O concentrations in the metagraywacke throughout the Northwest Geysers as represented by the “Typical Well” are progressively exchanged with depth in both the NTR and HTR. Figure 8b (right) shows that the metagraywacke in Prati 5 St1 and Prati 38 St2 is progressively exchanged with depth by meteoric water in both the NTR and HTR, although the $\delta^{18}$O permil whole-rock concentrations in the NTR are not as depleted as in the “Typical Well.”
As mentioned in the introduction, independent reservoir analyses and differences in pressure response to injection in P-32 at PS-31 and P-25 compared to P-38 St2 suggests a northeast-trending permeability discontinuity in the reservoir between P-32 and P-38 St2 (Garcia et al., 2012). This permeability discontinuity may be a northeast-trending fault or shear zone that separates and compartmentalizes the hydrothermally-altered, hornfelsic metagraywacke HTR in the Caldwell Ranch Area from the HDR hornfelsic metagraywacke in EGS Demonstration Area. There are no cores from the EGS Demonstration Area but a previous petrographic study of drill cuttings samples (Sternfeld, 1989) shows that calcite is absent from the hornfelsic metagraywacke of the HTR and the predominant secondary minerals are tourmaline, biotite, and amphibole.

Modeling Implications

The petrologic and petrophysical information collected in this study will be used in the future to refine Calpine’s 3-D geologic model of the Geysers and to apply an updated reservoir model to reservoir simulation efforts. The top of hornfels surface has been previously defined (Figure 9) and the new data reported here are now available to assign rock properties. Currently, a surface for the top of hornfels is defined in the model (Figure 9), which has a defined matrix and fracture porosity that are nearly constant. One update may be to apply a geostatistical approach to account for the variability of pore throat sizes measured during the mercury injection tests (see Summary of Rock and Mechanical Properties). In addition, interpretations of the mercury injection and petrographic analysis indicate that some of the measured pore throats may in fact be apertures of microfractures in the rock. These measurements can be taken into consideration when evaluating fracture specifications in the reservoir model.

Discussion and Conclusions

The oldest wallrock alteration appears to be the fine metamorphic biotite that replaces original illite in the graywacke matrix. Coarsely crystalline actinolite occurs as crosscutting veins and in clumps within the wallrock, postdating the older biotite. In the P-5 St1 core, it appears that there was only one episode of high-temperature veining which produced the actinolite-biotite-clinopyroxene-quartz-albite-pyrrhotite-tourmaline assemblage.

Notes on the interpreted paragenesis of veins and vug-filling minerals from the OF27A-2 core (10,373-10,382 ft) and the L’Esperance-2 core (11,051 ft) by Hulen (1991 and 1995) suggest the presence of two types and periods of biotite mineralization, with hydrothermal biotite in veins after the metamorphic biotite. This paragenesis generally seems appropriate for the P-5 St1 core, where we also see the two types of biotite. However, Hulen also reports that the younger potassic veins have potassium feldspar with the vein biotite, which is not observed in the P-5 St1 core samples.

In the P-38 St2 cuttings (8250-9940 ft), high-temperature secondary minerals (albite, biotite, actinolite, clinopyroxene, tourmaline) appear to be related to contact metamorphism and the minerals are subtly zoned by depth and proximity to a presumed underlying igneous intrusive. The overall alteration mineralogy appears to be similar to the magmatic-hydrothermal veins in P-5 St1 at 9940 ft, but the big difference between these two wells is in the intensity of the alteration and the degree of hornfelsic recrystallization. Especially in the deeper cutting samples, the metagraywacke in P-38 St2 is extensively recrystallized with hornfelsic banding of quartz and biotite layers in the matrix, and large areas of the matrix are replaced or mineralized with the high-temperature minerals. In P-5, the high temperature minerals are generally restricted to the veins, and the matrix is less recrystallized. As shown in Figure 8b, the whole-rock permil values in both the P-5 St1 and P-38 St2 wells are depleted in δ18O concentrations in the NTR and HTR relative to the cap rock, however deep in the P-5 St2 HTR the whole-rock values are more depleted in δ18O concentrations than deep in the P-38 St2 at similar depths.

The high temperature minerals that
only occur as veins in the P-5 St1 core occur throughout the
matrix in rocks from similar depths in well P-38 St2. In contrast
to the P-5 St1 calcic plagioclase cement, the secondary
plagioclase in the matrix of the P-38 St2 metagraywacke is
dominantly sodic. P-5 St1 has more calcic plagioclase and P-38
St2 has more calc-silicates and sodium feldspar; P-5 St1 has
more calcic alteration and P-38 St2 has more sodic alteration.
These observations taken together suggest that well P-38 St2 is
located closer to a magmatic heat source and/or has had greater
volumes of saline hydrothermal brine moving through the rocks
perhaps due to higher initial permeabilities.

Vapor- and liquid-rich inclusions containing up to several
solid phases were trapped in the veins at depths of ~9,940 ft in
Prati 5. Similar fluid inclusion populations were observed in
tourmaline-bearing veins in OF27A-2 St1, GDCF-15D, DV-2
and in quartz + clinopyroxene + biotite veins in L’Esperance-2.
Both L’Esperance-2 and OF27A-2 ST1 were completed in the
HTR in the northwest Geysers (Moore and Gunderson, 1995). These
fluids had salinities up to 44 wt % NaCl and homogeniza-
tion temperatures as high as 385°C. If these inclusions formed
under lithostatic pressures, the trapping temperatures could have
been as high as ~440°C. The high salinities were interpreted to
result from boiling and it was suggested then that the waters were
magmatic in origin based on their salinities, fluid inclusion gas
compositions, and the presence of tourmaline (Moore et al.,
2001; Hulen et al., 1997). Tourmaline commonly forms near intrusive
contacts in response to the introduction of boron-bearing fluids.
In contrast to these saline waters, fluid inclusions from shallow
depths in P-5 St1 record salinities of 0.9 to 2.7 wt % NaCl equiv.
and homogenization temperatures of 188-221°C (Moore and
Gunderson, 1995). These waters were interpreted as mixtures of
meteoric and connate waters. Based on fluid inclusion micro-
thermometric analyses of other well samples, the connate water
component was interpreted to contain approximately 5 wt % NaCl.
The composition of discharged gases from wells in the northwest
Geysers also indicates that connate fluids are the dominant source
for fluids in this part of The Geysers geothermal field (Lowenstein
and Janik, 2003).

Investigations of porphyry copper systems have led to the
conclusion that sodium metasomatism reflects the heating of
sodium-rich connate waters (e.g. Dilles and Einaudi, 1992). Thus
it is possible that the fluids responsible for albite deposition at The
Geysers also originated as connate waters similar to those trapped
in the fluid inclusions in the shallow propylitically-altered rocks.
Irrespective of the fluids’ origins, the presence of tourmaline in the
deep biotite hornfels implies the addition of a magmatic
component to the system. The ‘water’ may have been the con-
nate fluids already present in the rocks; this water was heated to
boiling by the young intrusion that also supplied magmatic gases
to the evolving hydrothermal system.

Our petrologic observations indicate that the saline fluids
moved from the veins (then fractures) into the metagraywacke
wallrock. Replacement of calcium in original metamorphic
plagioclase by sodium along the vein margins has created the
bleached selvages with a diffuse alteration fronts into the wallrock.
Pervasive sodium metasomatism of the rock matrix has occurred
where the saline fluids completely penetrated the wallrock. The
rocks, especially in P-38 St2, are now composed of 40% sodic
albite. The albite cements the rocks and they are negligibly porous
and dense with high rock strength.

Because of the extensive albition, the rocks are no longer
clay-rich. Experiments conducted by Lockner et al. (1982) were
performed on clay-rich meta-graywacke and argillite rocks and
the mechanical characteristics of these rocks may not apply to the
albitized rocks in the HTR. TerraTek’s estimates of unconfined
compressive strength from the scratch testing were performed under
dry ambient conditions in a laboratory setting, and also are
not likely to represent true reservoir conditions at 400°C and
lithostatic pressures at 10,000 ft depth. In their native state,
the rocks in the HTR are sufficiently hot to behave in a ductile man-
ner at these depths (Fournier, 1999). However, a steam-bearing
fracture near 11,000 feet was encountered while drilling P-32,
and the injection of cool water into the HTR as part of the EGS
Demonstration apparently has promoted brittle failure to depths
1 km below the bottom of the P-32 well, as recorded by the mi-
croearthquake monitoring array.

Acknowledgements

DOE funded the core and petrologic analysis for the P-5 St1
whole core and P-38 St2 cuttings through the Caldwell Ranch
Project grant, DE-EE0004042-002. The results of these petro-
logic analyses are also directly related to the geologic model of
the NW Geysers EGS Demonstration Project, DOE grant DE-
FC3608GO18201.

References

CCPA, July 1993, Core Analysis Program, unpublished document by Terra-
tek, Salt Lake City, UT.

Calpine, December 2011, Petrologic Evaluation of Whole Core Samples from
Well Prati 5 St1, Geysers Geothermal Field, CA unpublished document by TerraTek (TR11-503605), Salt Lake City, UT.

Dilles, J.H. and Einaudi, M.T., 1992, Wallrock alteration and hydrothermal
flow paths about the Ann Mason porphyry copper deposit, Nevada-a

from Plastic into Brittle Rock in the Magmatic-Epithermal Environment:
Economic Geology, v. 94, n. 8, p. 1193-1211.

Garcia, J., Walters, M., Beall, J., Hartline, C., Pingol, A., Pistone, S., and
Wright, M., 2012, Overview of the Northwest Geysers EGS Demon-
stration Project: Proceedings, Thirty-Seventh Workshop on Geothermal
Reservoir Engineering, Stanford University, January 30-February 1,
2012, p.693-703.

Hulen, J.B., 1991, Petrographic Summaries for Cores from 15 Geothermal
Wells in The Geysers Steam Field, California: Earth Science Laboratory,

Hulen, J.B., 1995, Geysers felsite study- selected lithologic and mineralogic
maps and cross sections: Earth Science Laboratory, University of Utah
Research Institute, Report for Unocal Geothermal, Brian Koenig, March

Hulen, J.B., Heizler, M.T., Stimac, J.A., Moore, J.N., and Quick, J.C., 1997,
New constraints on the timing of magmatism, volcanism, and the onset
of vapor-dominated conditions at The Geysers steam field, California:
Proceedings, Twenty-second Workshop on Geothermal Reservoir Engi-
neering, Stanford University, p. 75-82.


