PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Establishing the Frontier Observatory for Research in Geothermal Energy (FORGE) on the Newberry Volcano, Oregon

Alain Bonneville[1], Trenton T. Cladouhos[2], Adam Schultz[3]

[1]Pacific Northwest National Laboratory, 902 Battelle Blvd, PO Box 999, Richland, WA 99352

[2]AltaRock Energy Inc., 4010 Stone Way N, Suite 400, Seattle, WA 98103

[3]Oregon State University, 104 CEOAS Administration Building, Corvallis, OR 97331-5503

alain.bonneville@pnnl.gov; tcladouhos@altarockenergy.com; adam.schultz@oregonstate.edu;

Keywords: Newberry, FORGE, EGS

ABSTRACT

The proposed Newberry Volcano FORGE site is in central Oregon on the northwest flank of the largest volcano in the Cascades volcanic arc. Beneath Newberry Volcano is one of the largest geothermal heat reservoirs in the western United States, extensively studied for the last 40 years. The large, shallow (200 °C at less than 2 km depth), conductive thermal anomaly has already been well-characterized by extensive drilling and geophysical surveys. Four deep (greater than 3,000 m) boreholes completed on the leasehold currently managed by AltaRock have conductive thermal gradients with bottom hole temperatures above 320°C. Three large geothermal pads and two deep geothermal wells exist on the leasehold as well as eight, 200-290 m deep monitoring boreholes that have been used for seismic monitoring and sampling of shallow groundwater. All these investments have built the scientific foundation that establishes the site's high EGS potential, demonstrates a record of addressing potential risks (induced seismicity, wildlife, groundwater, etc.), and has developed true support and engagement with the local and regional communities. The high temperatures at relatively shallow depths at the site will allow a greater variety of drilling methods to be tested and a greater share of DOE funds to be reserved for non-drilling activities.

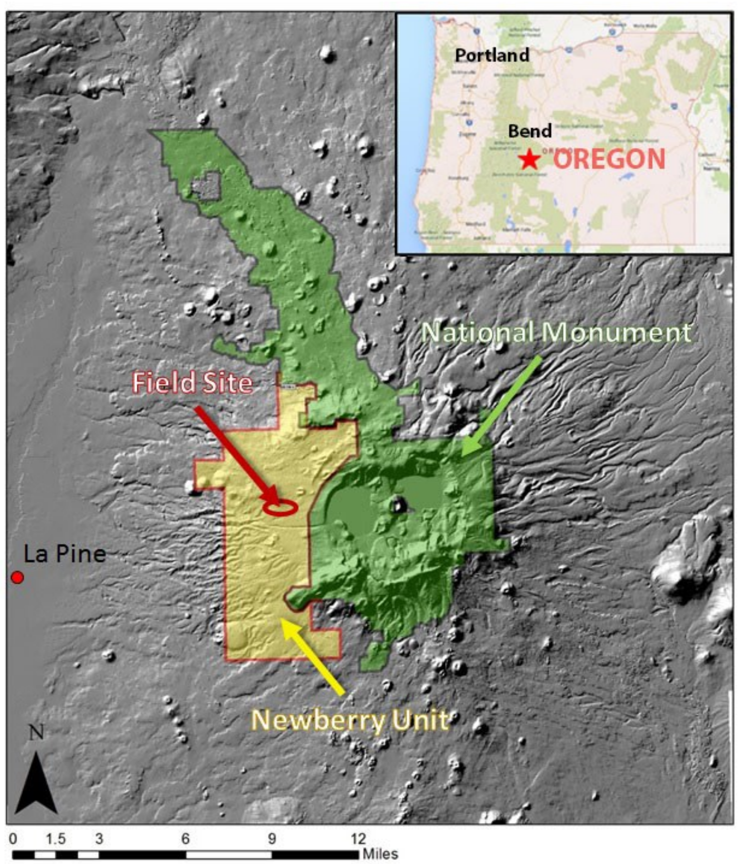

Figure 1. Location Map for the Proposed FORGE Location at Newberry Volcano, Showing Newberry National Volcanic Monument and the Geothermal Leases (Newberry Unit) administered by the BLM with Davenport Newberry Holdings, LLC designated as the Unit operator for the purposes of exploration, development and operations.

1. INTRODUCTION

NEWGEN - for Newberry Geothermal Energy - is the consortium built to design, implement and manage FORGE at Newberry volcano. It is a public-private consortium that brings a breadth and depth of scientific knowledge, technical and industrial expertise and community resources to make the project successful and lead to further commercial applications that will be widely deployable across the EGS industry. We envision Newberry FORGE becoming an international research center on Enhanced Geothermal Systems (EGS) where the research teams selected in Phase 3 will find the infrastructure required for them to succeed. NEWGEN will provide test wells and all the support in material, personnel and logistics, core sample processing, cyber-infrastructure and management structures necessary for the efficient operation and equitable distribution of FORGE resources, as well as the archival preservation and dissemination of the knowledge gained at the NEWGEN FORGE.

Newberry Volcano has already been demonstrated to be extremely favorable for EGS technologies and the development of EGS reservoirs. Four deep, high-temperature production wells have been drilled in the area, along with a number of temperature gradient and core holes. The target formation has an average bulk permeability of 2.6 10-16 m^2 and presents temperatures in the range 175-225 °C between 1,750 m and 2,250 m depth. This fulfills all the criteria required for an ideal FORGE site.

We will present in this paper the main characteristics of the site and a rough sketch of our vision for FORGE.

2. THE NEWGEN SITE

The proposed project area is located 37 km south of Bend, Oregon, the county seat of Deschutes County, and 16 km from La Pine, the nearest town (Figure 1). The project site is on land leased from the Bureau of Land Management (BLM), with the surface controlled by the US Forest Service (FS). The leased land lies adjacent to the Newberry National Volcano Monument (NNVM), which was created in 1990 to preserve the volcanic features inside the Newberry Volcano caldera, while providing for geothermal development and other uses on adjacent lands. Land that had been leased for geothermal development inside the caldera was exchanged for land outside the NNVM boundaries, with the proviso that the presence of the NNVM would not preclude development of projects suitable to the site outside the NNVM.

The Newberry Volcano geothermal lease area, which is owned by Davenport Newberry Holdings (DNH) and controlled by NEWGEN partner AltaRock Energy, Inc. (AltaRock) represents about 11,000 acres. These leases have recently been unitized to allow them to be managed as one body, which simplifies operations and makes all of the lease areas eligible candidates for FORGE activities.

2.1 Existing wells

Two full-sized geothermal exploration wells (NWG55-29 and NWG46-16) exist on separate well pads. These wells were completed to depths below the 225 °C maximum target temperature specified for FORGE. There are currently eight seismic monitoring boreholes completed to depths up to 289 m to reduce surface noise and improve sensitivity. These boreholes can be furthered deepened using rotary or core rigs to gather new data. Two of the monitoring boreholes have also been used to sample and monitor shallow groundwater. All of these wells and boreholes, and currently operating seismic equipment, can be made available to support FORGE activities (e.g., monitoring, tracer testing, tool testing). The location of these wells and boreholes on US National Forest land is approved under a Special Use Permit, which will be renewed and revised for FORGE activities.

Graded gravel forest roads provide vehicle access to all three well pads and each of the monitoring station locations

Figure 2. Well Pad 17, one of the 3 pads available for FORGE activities.

2.1 Regional Geology

Newberry Volcano is situated near the juncture of several geologic provinces in central Oregon: the Cascade Range and volcanic arc to the west, the Columbia River Basalt Plateau to the northeast, and the Basin and Range to the southeast. The Cascade Arc created by the subduction of the Juan de Fuca plate under the North American plate is a long-lived feature with a magmatic history including several prominent eruptive periods, the Western Cascades from 35-17 Ma, the early High Cascades from 7.4 to 4.0 Ma, and the late High Cascades from 3.9 Ma to present (Priest, 1990). Modern volcanic features include large stratovolcanoes, such as Mount Hood at 3,429 m, Mount Jefferson at 3,199 m, Mount Bachelor at 2,764 m, and the Three Sisters at 3,062-3,159 m, as well as many smaller domes and mafic vents. The Columbia River Basalt Group is one of the largest flood basalt plateaus on Earth, extending between the Cascade Range and the Rocky Mountains, and covering about 160,000 km^2 of the Pacific Northwest (Tolan et al., 1989).

2.2 Geology of the NEWGEN site

The sections below describe geologic features specific to the western flank of Newberry Volcano based on conditions measured at the numerous temperature coreholes (TCH) and geothermal exploration wells completed since the 1970s.

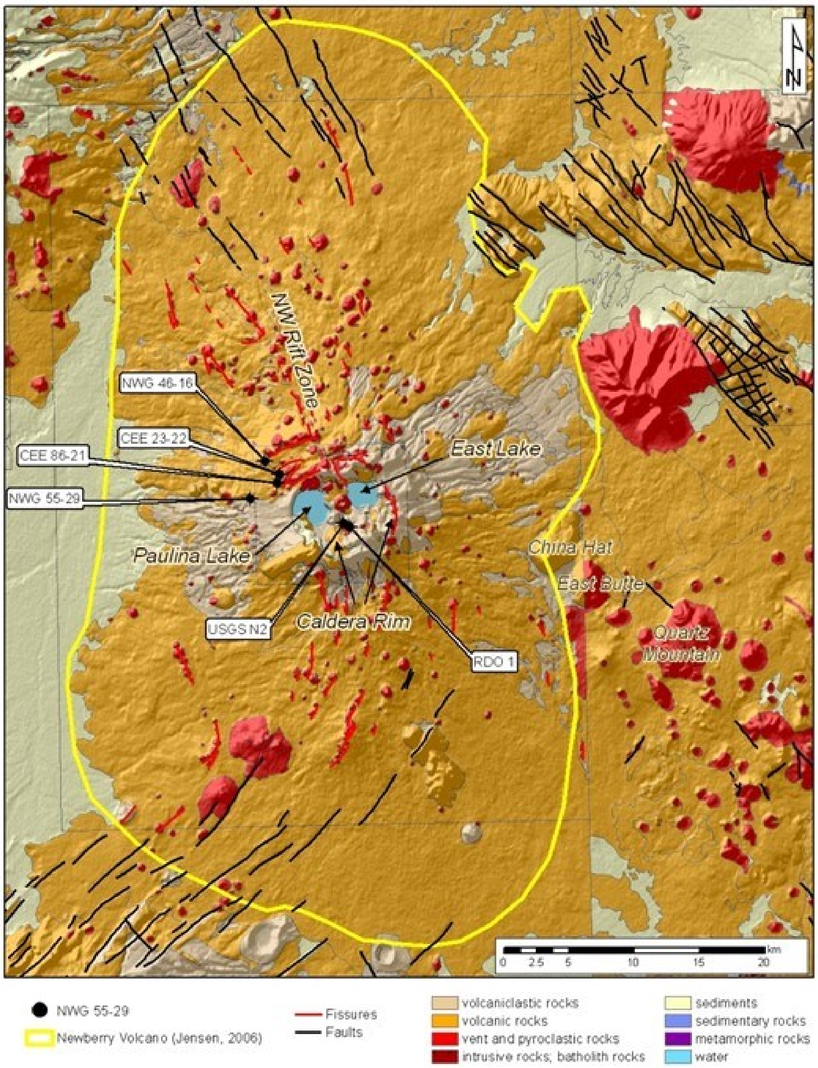

Figure 1. Outline of the Newberry Volcano Massif (in Yellow), Showing Caldera, Rim, Extent of Flows, and Locations of Some Geothermal Exploration Wells

2.2.1 Geomorphology

Newberry Volcano is a broad eruptive center active for approximately the last 600,000 years that rises 2,408 m on the southeastern side of the Deschutes Basin (MacLeod et al., 1982; Jensen, 2006). The volcano is an elliptical shaped massif approximately 50 km by 30 km with some lava flows reaching more than 64 km north of the caldera (Figure 3). The lower flanks are composed of ash and lahar deposits, basaltic lava, cinder cones, and minor silicic domes. Several basalt flows sourced from rifts in the NW flank of the edifice are younger than 7,000 years, coeval with the regionally extensive Mazama ash. The more steeply sloped upper flanks of the volcano are composed predominantly of overlapping silicic domes and subordinate basaltic rock. The central caldera is about 8 km by 5 km and is a nested composite of craters and vents. The central caldera contains two lakes, Paulina Lake on the west at an elevation of 1,930 m and

East Lake on the east at an elevation of 1,941 m. Paulina Lake is drained by the west-flowing Paulina Creek, the only perennial surface water found on the flanks of the edifice. Paulina Creek is a losing stream for most of its reach due to a water table 600 ft below the surface. Within the caldera are resurgent obsidian flows, cinder cones, and maars, with the most recent eruption, which produced the Big Obsidian flow and ash fall occurring between 1.6 ka and 1.3 ka. The elevation of the rim of the caldera ranges from 2,133-2,408 m, except along the breached western side, where the elevation is 1,929 m. Due to the porous nature of the surface material on the flanks of Newberry, little modern fluvial erosion or deposition occurs, except at Paulina Creek or after heavy rainfall or melt events (Donnelly-Nolan and Jensen, 2009). Soil development is fairly limited in the 1-3 m of ~7 ka Mazama ash that blankets the edifice.

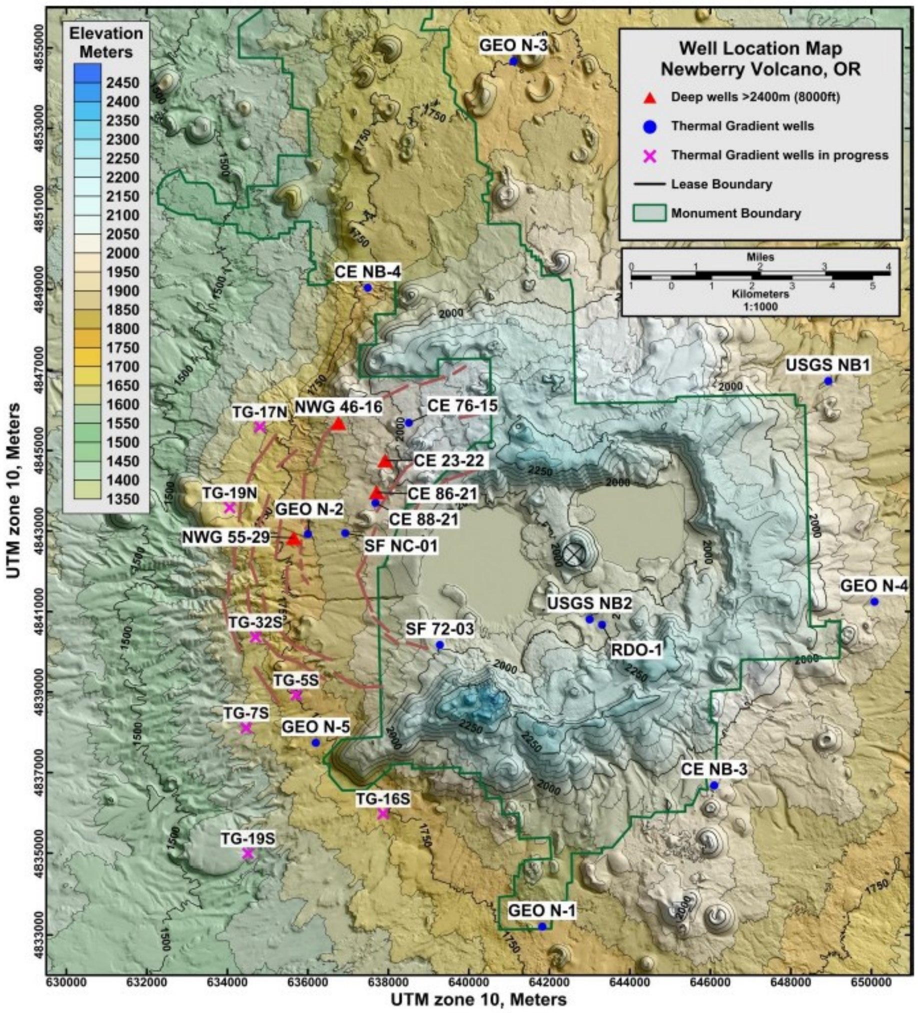

Figure 4. Location of temperature coreholes and geothermal exploration wells at Newberry Volcano (figure from Frone, 2014).

2.2.2. Surface Geology

Newberry volcanic rocks are built upon the regionally extensive Pliocene Deschutes Formation (>7-4 Ma), which includes basalt flows, andesite flows, debris flows, ash-flow tuffs, ignimbrites, rhyolite and rhyodacite, and eroded and reworked basaltic and andesitic volcanic sediments (Figure 2.4; Smith, 1986; Sherrod et al., 2004). Beneath the Deschutes Formation, older volcanic, sedimentary, and tuffaceous rocks of the John Day, Mescal, and Clarno formations are either encountered or inferred.

2.2.3 Thermal Setting and Exploration Wells

Public domain equilibrated temperature-depth profiles are available for some of the temperature coreholes and geothermal exploration wells (Figure 4 and Figure 5). Two coreholes and two relatively shallow geothermal exploratory wells were drilled in the caldera. The shallow exploratory wells were drilled by the USGS (N-2) and Sandia National Laboratory (RDO-1). A maximum temperature of 265°C was measured in USGS N-2 at its total depth of 932 m. A maximum temperature of 160°C at a total depth of 411 m was encountered in RDO-1. Temperatures encountered in RDO-1 were significantly higher than those at comparable depths in USGS N-2. Four deep exploratory wells have been drilled on the northwestern flank of the volcano (Figure 4), two by CalEnergy (CEE 86-21 and CEE 23-22) and two by DNH (NWG 55-29 and NWG 46-16). The temperature profile for NWG 55-29 (Figure 5) indicates a conductive regime from an elevation of about +1,700 m to a total depth at -1,300 m. While the temperature profiles for the other three wells remain confidential, Spielman and Finger (1998) reported that the two CalEnergy wells encountered temperatures in excess of

315°C below a depth of 2,740 m. They concluded, based on the two CEE wells and two temperature coreholes, that while adequate temperatures are present, the permeability in the area investigated was too low for a commercial geothermal resource.

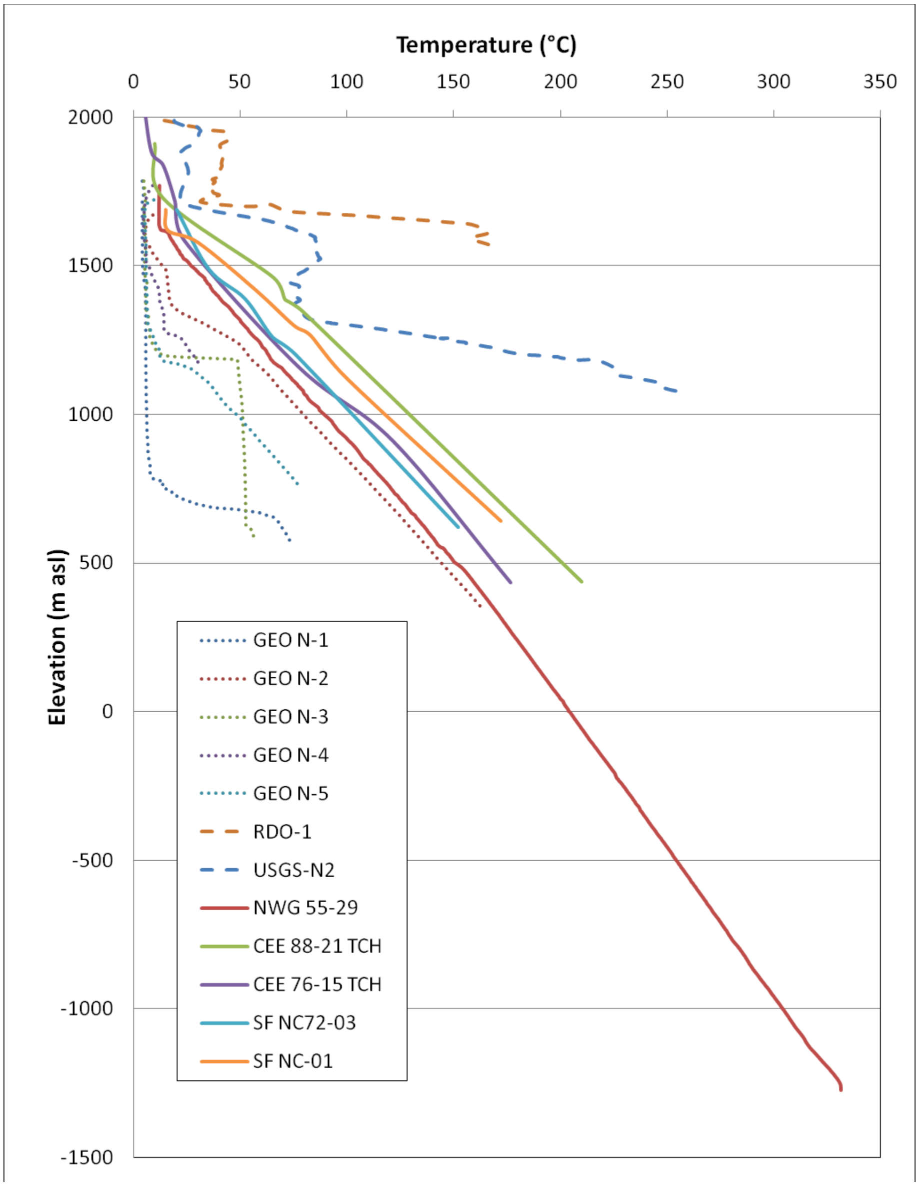

Figure 5. Equilibrated Temperatures of Coreholes and Exploration Wells at Newberry Volcano. Elevation in meters is relative to mean sea level.

2.2.4 Stratigraphy

Analyses of surface rock samples show a wide range of igneous rock compositions, dominated by a bimodal concentration of basaltic andesite and rhyodacite. Hundreds of volcanic vents and fissures are located on and adjacent to the volcano, some of which pre-date Newberry. Data from MacLeod et al. (1982), and from deeper temperature coreholes, suggest that the early eruptive history of the edifice was dominated by mafic lava. Over time, the magmatic character changed to the current bimodal basaltic andesite and rhyodacite. The Newberry flows are deposited on older volcanic and clastic sequences, most of which do not outcrop locally. The geologic formations are presented in details in the Newberry EGS Demonstration site characterization report (AltaRock, 2009). The most important ones for the range of depths considered for FORGE are:

- Pliocene Deschutes Formation (>7-4 Ma) – The upper portion is composed of olivine basalt flows, andesite flows, basaltic ash, debris flows, eroded and reworked basaltic and andesitic volcanic sediments, and debris flows dating from about 6 Ma to 4 Ma (Smith, 1986). These are underlain by ash-flow tuffs, ignimbrites, rhyolites and rhyodacites, and black-pumice dacite pyroclastics, dating to about 7.4 Ma (Smith, 1986).

- Oligocene John Day Formation (37-19 Ma) – The John Day Formation is composed of silicic, intermediate, and basaltic volcanic lava flows, rhyolite ash-flow tuff, and dacite to rhyodacite tuffs and alluvial deposits, dated at 19 Ma to 37 Ma (Robinson et al., 1984).

Stratigraphic correlation in an area with millions of years of volcanic activity emanating from multiple eruptive centers is problematic. Inter-well correlations were determined by AltaRock (2009) and used to generate cross sections across the project area: a west-east line (Figure 6). However, for the purposes of geothermal resource evaluation and drilling considerations, formation identification is of only marginal interest; the composition of the rocks is more important with respect to the tendency to fracture and conduct heat. Debris flows, cemented tuffs, and volcaniclastic sediments typically have a clay matrix, are poorly consolidated as deposited, and undergo plastic deformation when stressed. Lava flows, welded tuffs, and intrusive rock tend to be brittle, and will mechanically fail (fracture) when stressed. Rock intruded by magma has the potential to be recrystallized by high heat and become more brittle, as well as be fractured by the pressure and mechanical movement of the intruding magma. Post-intrusive cooling fractures can occur in both the crystallizing magma and adjacent rock. Even in the absence of detailed geologic correlations, the combination of brittle rock, regional tectonic strain and faulting, intrusive-related fracturing, and high temperatures present an attractive combination for EGS development.

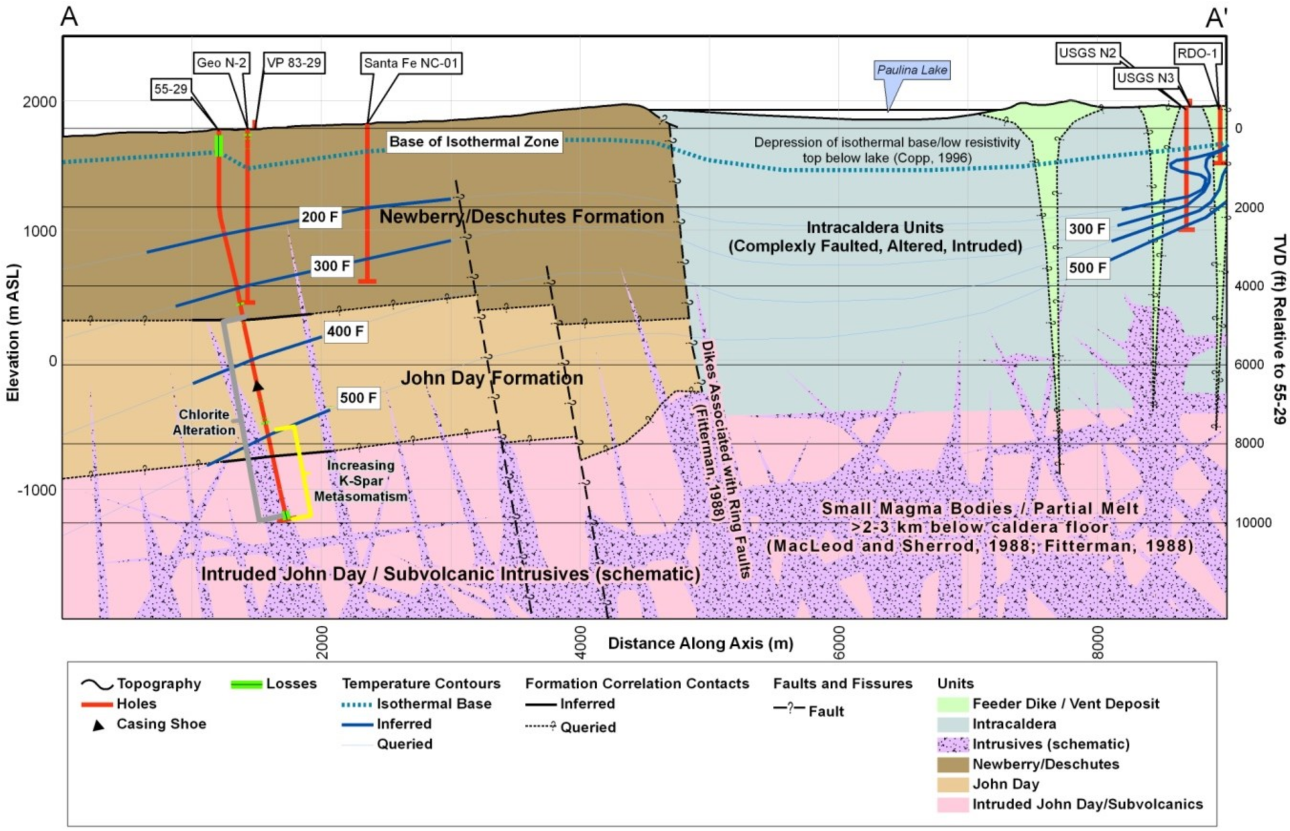

Figure 6. West-East Cross-Section Showing Formation Correlations and Speculative Isotherms

2.2.5 Porosity and Permeability

At depths between 200 m and 330 m beneath the NWG 55-29 pad, increased smectite and green clay alteration forms an impermeable base in the host rock, and at greater depths (approximately 1,500 m), the altered tuffs of the John Day Formation result in extremely low permeability. The results of historical injection tests for wells located on the western flank of Newberry Volcano in the vicinity of the FORGE site reveal injectivity several orders of magnitude lower than the lowest permeabilities found in typical hydrothermal fields, as required for the FORGE project location. Attempts to flow these exploration wells were completely unsuccessful – injected water boiled, flowed out of the borehole, and the wells then ran dry.

Results of the injection tests for CEE 23-22, CEE 86-21, CEE 76-15 TCH, and NWG 55-29 reveal injectivity several orders of magnitude lower than the lowest permeability geothermal producers. Spielman and Finger (1998) note that injectivity in geothermal wells typically range from a high of 1,000 kph/psi, to a low of 1 kph/psi for low-permeability wells. The injectivities for wells 23-22 and 86-15 were 0.024-0.026 kph/psi and 0.022 kph/psi, respectively. Injectivity for CEE 76-15 TCH and NWG 55-29 are even lower, at 0.0015-0.0031 kph/psi and 0.007-0.014 kph/psi, respectively. Bulk permeability for CEE 23-22 was determined to be 2.6 10-16 m^2. By comparison, permeability in geothermal fields such as Coso and the Salton Sea ranges from 2.5 10-14 to 3. 10-13 m^2 (Spielman and Finger, 1998).

Based on the results of the four exploration wells drilled on the northwestern flanks of the volcano in 1995, Spielman and Finger (1998) concluded that while the area had an adequate temperature, it did not have the permeability necessary to host a viable hydrothermal resource. The authors note that the injectivity measured in two CEE wells closely resembles those found at 'hot dry rock' (HDR) projects worldwide. In Japan, HDR wells had an average injectivity of 0.002 kph/psi (Kaieda et al., 1990), the Tirniauz HDR well in Russia had an injectivity of 0.04 kph/psi (Kruger, 1992), and the Soultz-sous-Forêts (Soultz) well in France had an injectivity of 0.1 kph/psi (Jung, 1992). Spielman and Finger (1998) specifically note that the low permeability and high temperatures "qualify this area for a hot dry rock project."

3. GEOLOGIC MODEL

A comprehensive geologic model using all the geophysical and geological information is being built and is presented in a companion paper by Mark-Moser et al. (2016).

4. SEISMICITY

4.1 Natural Seismicity

Historic earthquake data demonstrates that Newberry Volcano is essentially aseismic (Wong et al., 2010). No earthquakes greater than ML 5.0 are known to have occurred within 100 km before 1980. Since the expansion of the Pacific Northwest Seismic Network (PNSN) into Oregon in 1980, only six ML ≥ 3.0 earthquakes were detected within 100 km, most in a single 1999 swarm located 98 km to the southeast. The regional seismic network at Newberry Volcano has improved greatly since 2009. In 2009, the only station was NCO, a single-component, short-period seismometer on the east flank and only four microearthquakes (M 1.3-2.2) were detected in Newberry in the prior 25 years (PNSN, 2015). In 2011, the USGS installed six three-component broadband seismometers and one three-component short-period sensor (PNSN, 2015). Four of the borehole stations in the AltaRock Newberry MSA (NN32, NN19, NN17, and NN21) as well as the strong motion sensor (NNVM) were also added to the PNSN network. The seismic coverage of Newberry Volcano is now comprehensive, with events smaller than M 0.0 being locatable. Since 2011 there were about 100 natural seismic events ($-1<M<2.3$) located in the Newberry edifice (PNSN, 2016). The increase in the number of earthquakes outside of the EGS stimulation zone (>1 km from well 55-29) located at Newberry Volcano since 2012 does not indicate increased seismicity due to natural causes or EGS activities. Instead, it is a consequence of the much improved seismic network.

4.2 EGS Induced Seismicity

The first induced seismicity at the site occurred during the 2012 well stimulation of NWG 55-29 as part of the Newberry EGS demonstration, an American Recovery and Reinvestment Act funded project awarded to AltaRock by the DOE.

During the 2012 stimulation, the well head pressure (WHP) reached 167 bar (2450 psi), 40,000 m^3 (11 million gallons) of water were injected, and over 175 microearthquakes with magnitudes between M 0.0 and M 2.3 were located (Cladouhos et al., 2013) illuminating an EGS reservoir with a bimodal distribution of depths. While the horizontal extent of the microseismic cloud was impressive - events were located almost 1 km from the well - about 90% of the events were above the casing shoe - suggesting that injected fluid had leaked out of the casing to stimulate relatively shallow and cool rock. Well surveys in 2013 determined that shallow seismicity in 2012 and early 2013 was due to a failure in the steel well casing.

The casing was repaired in September 2014, and injection of water to create a deeper, hotter EGS zone occurred between September and November of 2014. Stimulation began September 23 and the first locatable microseismic event occurred on September 25 during a significant increase in flow rate stepping up to 180 bar (2,580 psi). Significant microseismicity began on September 30, when WHP was consistently held above 196 bar (2,800 psi); over 30 events per day were located. The microseismicity rate dropped to less than 15 events per day by the third week, even at pressures above 196 bar (2,800 psi.) The largest event had a moment magnitude of 2.3, and 400 events were preliminarily located, 15 of which had a moment magnitude greater than 1.0 (Cladouhos et al., 2015). Preliminary microseismic locations indicate an EGS reservoir with a 400 m radius and a vertical extent of over 1,500 m (Cladouhos et al., 2016).

4.3 Assessment of Induced Seismicity and Seismic Risks

An Induced Seismicity and Seismic Hazards and Risk Analysis was performed for the Newberry EGS Demonstration, which concluded there is no difference in hazards between baseline conditions and EGS induced seismicity. However, potentially larger EGS earthquakes of M 3.0 and higher, should they occur, might be felt within 10 km of the project site (e.g., La Pine and Sunriver), but not at damaging levels of ground motions (>0.1 g). For natural earthquakes, a peak ground acceleration (PGA) of 0.1 g is perceived by humans as strong shaking with only a light potential for damage (Wald et al., 1999); it has been observed that perceived shaking and damage due to EGS induced seismicity is typically lower (Majer et al., 2007). Thus, the effects of induced seismicity at Newberry are expected to be at worst a nuisance rather than a hazard to local residents because of the small size of the events.

5. FORGE IMPLEMENTATION

The NEWGEN FORGE team will develop rigorous and reproducible methodologies to improve the economics of EGS. FORGE-developed technologies will not only enable development of greenfield EGS projects in the long term, but also provide short term commercial benefits to existing geothermal operations. They will both facilitate rehabilitation of underperforming geothermal wells and lower the risk of expanding existing geothermal fields. These near term applications must be considered during FORGE operations and research in order to promote adoption and tuning of EGS technologies by the geothermal industry.

In phase 3 of FORGE (2019 and beyond) R&D projects will be selected after competitive requests for proposal. Solicitations will be focused on the development of subsurface technologies, auxiliary-well activities, well characterization and multi-well stimulation technologies, inter-well connectivity, fluid path imaging and dynamic control of flow path physical and geochemical conditions, and long-term reservoir sustainability techniques. The research platform that NEWGEN will offer at the Newberry Volcano to the R&D teams performing in phase 3 will include:

- Two full-sized geothermal wells. Well design will be based on subsurface characterization efforts carried out during Phases 1 and 2, and will be optimized for the in situ state of stress. The wells will be capable of testing a wide variety of reservoir creation technologies.
- New drilling technologies. Drilling costs are one of the biggest impediments to developing geothermal power projects. Both alternative drilling techniques and well completion designs (e.g., vertical, horizontal, and variable orientations) with the goals of maximizing stimulation success and reducing cost will be evaluated.
- Innovative completion design, techniques and materials.
- Continuous monitoring of seismicity and of long-term geofluid flow. This will be conducted using both current and state-of-the-art technologies. Currently used methods will be evaluated for optimization and retrofit as needed. For example, surface/downhole electrical resistivity tomography and reactive tracers could be combined for improved fracture network characterization and monitoring of fluid flow.
- Auxiliary Boreholes to test new monitoring tools.

The geothermal community at large will benefit of real-time sharing of characterization and monitoring data and annual dissemination of data, physical samples, and results from drilling operations and R&D projects. A significant effort will also be accomplished in terms of communication and outreach locally and nationally, including development of new curricular materials to support post-secondary education and training suitable for the emerging EGS industry.

ACKNOWLEDGEMENTS

The Newberry FORGE project is supported by the Department of Energy under Award Number DE-EE 0007158.

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