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Super Hot EGS and the Newberry Deep Drilling Project

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ABSTRACT

A productive geothermal well drilled into super-hot rock (SHR) with a temperature above 400°C will produce super-critical fluid. At a flow rate of 60 kg/s, a SHR well could produce 50 MWe compared to 5-7 MWe for the same flow at 200°C. Even though these deeper, super-hot wells will cost more, the high energy density means power produced by engineered geothermal systems (EGS) can meet the market ($46 MW-hr) by directly tapping the heat source. We propose a proof of concept where hot rock is close to the surface (~5 km), and the cost of drilling and EGS stimulation will be lowest. A suitable, ready-to-go SHR site is on Newberry Volcano, Oregon, one of the largest geothermal heat reservoirs in the USA, extensively studied for the last 40 years. Millions of dollars have already been invested in the site by private geothermal developers and the US Department of Energy (DOE), resulting in a ready-to-use facility with the necessary infrastructure, environmental permits, land commitments, and monitoring plans. The Newberry Deep Drilling Project (NDDP) will be located at an idle geothermal exploration well, NWG 46-16, drilled in 2008, 3500 m deep and 320°C at bottom, which will be deepened another 1000 to 1300 m to reach 500 °C. The original well was drilled with few lost circulation zones and the temperature profile indicates conductive heat flow. Compared to other SHR projects world-wide, this well would return more materials (cuttings, core and fluids) with more predictable drilling conditions, thus providing a suite of data near and across the brittle-ductile transition in silica-rich rocks. After drilling, a hydraulic well stimulation will both change the pore pressure in fractures and cool the fracture walls resulting in permeability enhancement through both thermal fracturing, and hydro-shearing. The first step for the NDDP was an International Continental Drilling Program (ICDP) sponsored workshop held at the OSU-Cascades campus in Bend from Sept. 10-14, 2017. The workshop concluded by setting ambitious goals for NDDP: 1) test EGS above the critical point of water, 2) collect samples of rocks within the brittle-ductile transition, 3) investigate volcanic hazards, 4) study magmatic geomechanics, 5) calibrate geophysical imaging techniques, and 6) test technology for drilling, well completion, and geophysical monitoring in a very high temperature environment. The second step, completed January 15, 2018, was submitting a proposal to ICDP for 46-16 deepening. The next steps will be to continue building a team with project, technology, and investment partners to make NDDP a reality.

1. INTRODUCTION

Recovery of just 2% of the thermal energy stored in hot rock 3 to 10 km below the continental US would be sufficient to meet the US energy consumption for over 2000 years (Tester et al., 2006). Much of that thermal energy is stored in rock at 200°C and below; hence, in the last decade, most enhanced geothermal systems (EGS) R&D and deployment has focused on the <200°C resource. Indeed, in the EU, EGS and deep geothermal heat systems using resources below 200°C are enjoying economic success (Genter et al., 2016; Weber et al., 2016; Boissavy et al., 2016). However, this success requires a combination of significant pre-engineered formation permeability, nearby thermal-heat users, and large feed-in tariffs for the electricity generated. The lack of economically viable greenfield EGS projects outside of the EU illustrates that the goal of economic *EGS anywhere* may not be achievable unless power production per well can be significantly improved. There are three ways to increase power production per well: increase flow rate, increase flow temperature, or both.

The DOE's Frontier Observatory for Research in Geothermal Energy (FORGE) is focused on increasing flow rate through more successful creation of permeability pathways in low permeability rocks ($k<10^{-16}$ m^2) like crystalline basement and granites using the analogy to long-horizontal reach wells and multi-stage stimulations that have been successful in the O&G industries. A 175-225°C temperature range for the target formations was chosen for FORGE (DOE, 2014) because it has been considered easier to adapt oil and gas technologies to these lower temperatures. The incremental approach might lead to a technical success; however, large-scale global economic success will be far harder due to the sheer number of wells that would need to be drilled. The most optimistic estimates are that each EGS well producing 200°C water will generate 5 MW of electricity (i.e. Li et al., 2016). To generate 100 MW of electricity delivered to the grid, at least 42 wells would need to be drilled (Figure 1, left). Even if there is a breakthrough in drilling costs, the costs of materials needed to complete the drilled wells alone (250 miles of steel pipe and a half million cubic feet of concrete) would make the costs of electricity from 200°C EGS uncompetitive in the current and future electricity markets.

Increasing the flow temperature of EGS wells has a greater potential payoff and supercritical geothermal production represents the geothermal energy moonshot; a step-change in energy per well. A geothermal well which produces fluids at 400°C, above water's supercritical point of 375°C, would generate 10 times the amount of electricity compared to a 200°C well - due to five times the energy content of the fluid and two times the conversion efficiency (Figure 2). Compared to a 200°C well in the same area, a SHR well will need to be drilled about twice as deep; however, the extra drilling depth will be worth the additional cost. Creating or enhancing permeability in SHR (that is creating an EGS) will involve different geomechanics than creating an EGS in 175-225°C rock, but SHR EGS won't necessarily be more difficult. For one, the influence of thermal stresses will be far greater (Asanuma et al., 2015; Watanabe et al., 2017; Jeanne et al, 2015), which may make SHR EGS creation easier than EGS in colder rock.

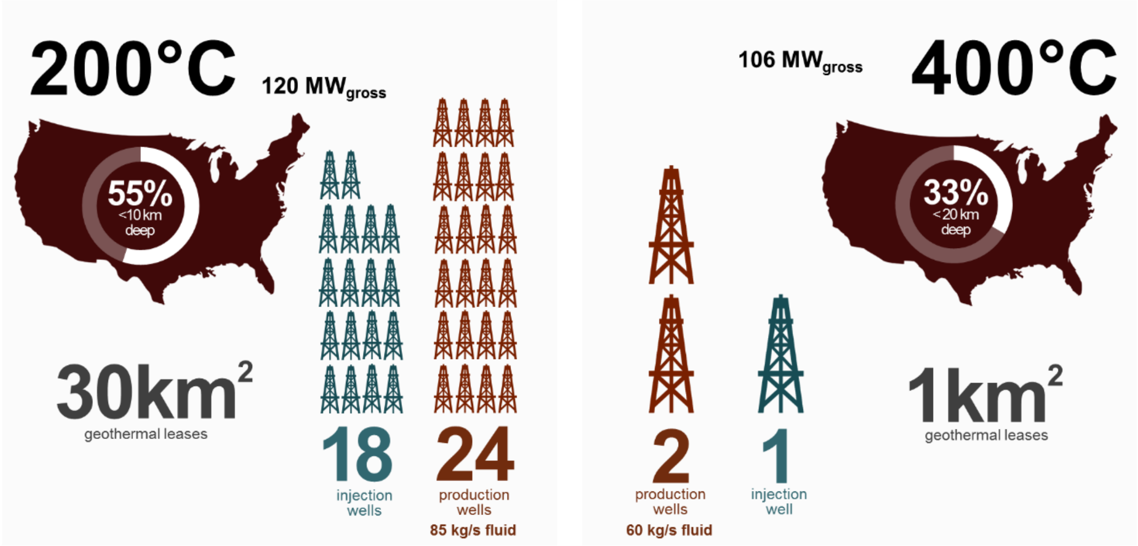


Figure 1. Hypothetical 100 MW utility-scale power plant. 200 °C and 400 °C. In 55% of continental US, 200 °C can be reached by 10 km depth, while of continental US and in 33% of the continental US 400 °C can be reached by 20 km depth.

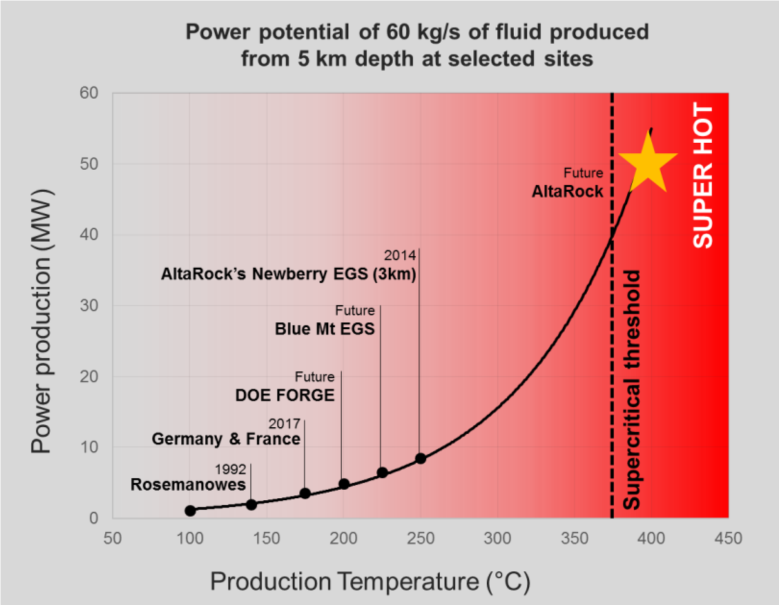


Figure 2. Power production per well by production temperature

To demonstrate the economic advantage of SHR EGS, we calculated levelized cost of energy (LCOE), using the same methods as GETEM (2016), but we did not use GETEM itself, which we found does not translate to supercritical temperatures. We modeled a 100 MW utility-scale power plant using the flow from two 53 MW producers with reinjection to a third well (Figure 1, right). We start with a generous cost estimated for each 5 km deep well: $10.6MM to drill, $10.8MM to case with specialty alloys (i.e. Titanium alloys) that will survive supercritical fluids, $5.6MM in other ancillary drilling costs, and $2MM to stimulate and create an EGS reservoir (Table 1). Next, we estimate the power plant costs, including the power units (superheated steam turbines, $1750/kW), ancillary equipment ($500/kW) and 10 miles of transmission line ($400k/mile). The total capital costs calculate to $330MM, which we assume is financed with a 20-year loan at 5% interest rate, resulting in total interest cost of $199MM. An initial net power production of 100 MW, $6.5MM in annual O&M, a production decline rate of 2%, and a discount rate of 6%, gives a LCOE of $46/MW-hr (4.6 cents/kW-hr).

Table 1: LCOE calculation inputs

Well Field Costs	Cost/unit	units	Total: 3 wells
Drilling	$10,589,600	/well	$31,768,800
Casing	$10,808,300	/well	$32,424,900
Stimulation	$2,000,000	/well	$6,000,000
Other drilling	$5,620,100	/well	$16,860,300
Total Well Cost	$29,018,000	/well	$87,054,000

Power Plant Costs	Cost/unit	units	Total – 106 MW
Power generation units	1760	$/kw	$187,531,000
Ancillary equipment	500	$/kw	$51,300,000
Transmission line	400,000	$/mile	$4,000,000
Total plant & transmission			$242,546,060
O&M	6,500,000	$/yr	

Total to finance = $329,600,060

Financial rates	
Discount rate	6%
Loan term	20 years
Interest on debt	5%

Resource and power plant factors	
Capacity factor	95%
Production decline rate – flow and temperature (annual)	2%

At $46 per MW-hour, renewable, baseload super-hot EGS is a cost-competitive power source compared to all sources of electricity. Recent LCOE calculations by EIA (2017) for plants entering service in 2022, give advanced nuclear at $99/MW-hr, natural gas combined cycle at $56.5/MW-hr, onshore wind at $63.7/MW-hr, and solar PV (weighted for availability) at $85/MW-hr. The DOE Geothermal Technology Office set a goal to reduce the LCOE to $60 per MW-hour by 2020 for conventional geothermal, and by 2030 for enhanced geothermal (DOE, 2017). Thus, SHR EGS is a clear pathway to meet the DOE's cost goals for geothermal electricity.

While the USA has been focused on lower temperatures, the international geothermal community understands the economic value of producing supercritical fluid. The international race to develop technologies to extract energy from SHR is happening now. The most geothermally savvy countries in the world, Iceland, Italy, Japan and New Zealand, are all currently pursuing SHR projects (Dobson et al., 2017). No doubt there will be technical challenges to produce SHR wells, but as shown by the LCOE estimates above, overcoming these challenges can result in competitive electricity costs.

2. NEWBERRY VOLCANO

Newberry Volcano in Central Oregon, an active volcano that contains one of the largest geothermal heat reservoirs in the western United States, has been extensively studied for the last 40 years (Fitterman, 1988; Fitterman et al., 1988; MacLeod et al., 1988; Sammel et al., 1988; Macleod et al, 1995; Bargar and Keith, 1999; Waibel et al., 2015). The detailed characterization of this continental volcanic system reveals that it is an excellent choice for drilling a well to reach temperatures greater than 450˚C at relatively shallow depths (< 5000 m).

2.1 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 Plateau to the northeast, and the Basin and Range to the southeast (McCaffery et al., 2013; Cladouhos et al., 2011a). The Cascade Arc 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; Hildreth, 2007).

Newberry Volcano (Figure 3) 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; Donnelly Nolan et al. 2011). The current central caldera formed about 75,000 years ago. 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 (Jensen et al. 2009; Donnelly Nolan et al. 2011). 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, postdating the regionally extensive Mazama ash (7,700 years old) from Crater Lake (McKay et al. 2009). 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. Within the caldera are resurgent obsidian flows, cinder cones, and maars, with the most recent eruptions 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). Infrequent, widely distributed boulders with exotic lithologies interpreted to be glacial erratics (Donnelly-Nolan and Jensen, 2009) may indicate the presence of a glacier at the summit prior to the cataclysmic eruption at ~80 ka. Soil development is fairly limited in the 1-3 m of ~7.7 ka Mazama ash that blankets the edifice.

Two structural patterns dominate the Newberry Volcano area. The first are the volcanic and caldera-related structures of the volcano itself, including arcuate vents and ring fractures in its central portion. Four caldera ring fractures have been mapped on the NW flank of the Newberry Volcano (Sherrod et al., 2004). The second group of regional structural features is the northwest- and northeast-trending faults (e.g., the Walker Rim, Brothers, and Tumalo fault zones) that are found across and beyond the Newberry massif and are likely transitional between the Cascade Arc Central Graben and the Basin and Range extension.

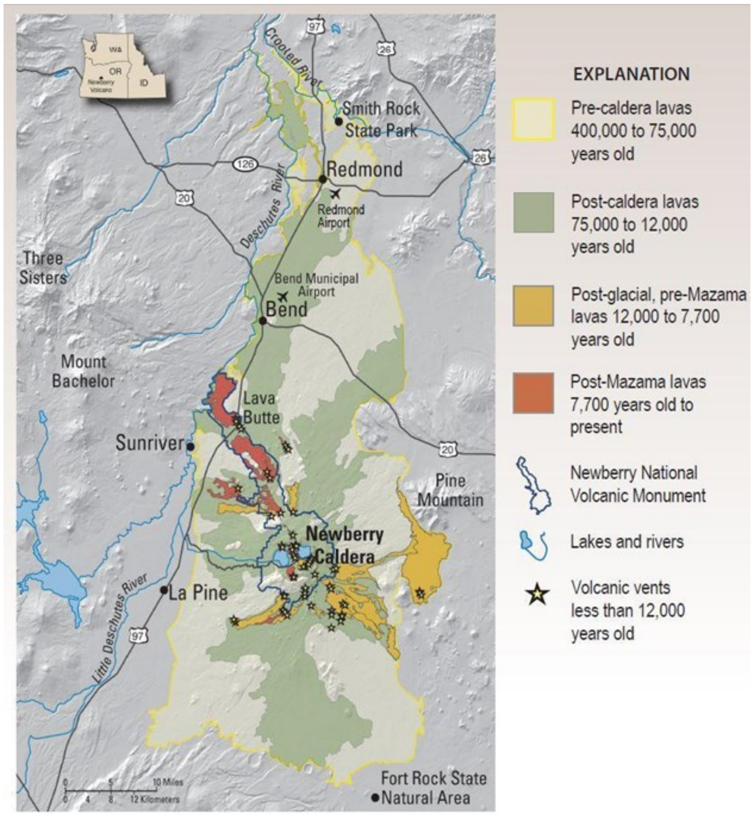


Figure 3: Lava flows and young volcanic vents at Newberry Volcano. The USGS continues to study and monitor the area (from Donnelly Nolan et al. 2011).

2.2 Thermal Setting

The large conductive thermal anomaly (320°C at 3000 m depth) on the flanks of Newberry has been well-characterized by extensive drilling and geophysical surveys. Four deep exploratory wells have been drilled on the northwestern flank of the volcano, two by CalEnergy (CEE 86-21 and CEE 23-22) and two by Davenport Newberry Holdings (NWG 55-29 and NWG 46-16). The temperature profile for NWG 55-29 (Figure 4) indicates a conductive regime from an elevation of about +1,700 m to a total depth at -1300 m. An equilibrated temperature profile to TD was never measured in NWG 46-16. Linear projections of the temperature profile determined on the shallower conductive portion of the profile give bottom hole temperature (BHT) from 350°C (Figure 4) to 375°C (Frone, 2015) using a gradient of 112°C/km. Spielman and Finger (1998) reported that the two CalEnergy wells encountered temperatures above 315°C below 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 (i.e. natural hydrothermal) resource. Temperature gradient holes in the caldera and geothermal hot springs along the shores and floors of the caldera lakes, indicate that there is a hydrothermal resource in the caldera, protected within the Newberry Volcano National Monument.

Extensive geophysical investigations, temperature surveys and fluid injectivity tests to the geothermal wells confirms that the thermal anomaly is mostly conductive. A possible exception is that outgassing of magmatic CO_2 at one of the deep wells, NWG 46-16, suggests some degree of connectivity exists between deeper magma bodies, possibly those mapped through seismic tomograms beneath the caldera (Beachly et al., 2012), and the otherwise impermeable west flank geothermal leasehold area.

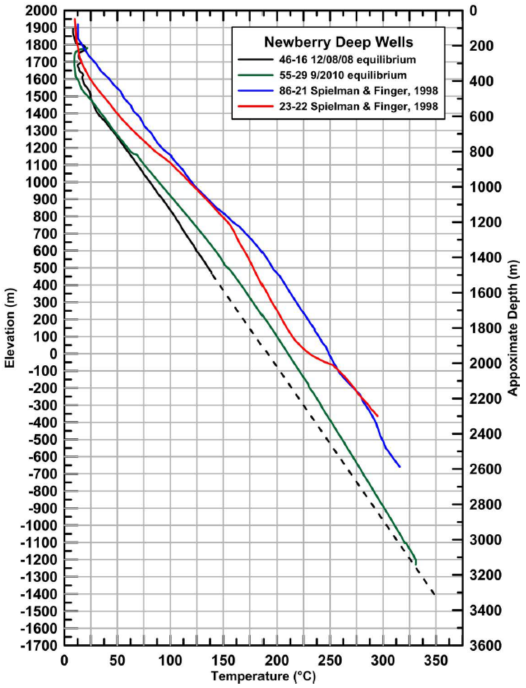


Figure 4. Equilibrated temperatures of exploration wells at Newberry Volcano from Frone (2015). Depth scale on right side is approximate due to site topography, with a zero-depth reference at the highest well, 23-22. 55-29 and 46-16 well locations shown in Figure 5.

2.3 Geothermal Assets

AltaRock Energy holds over 48 km^2 (11,887 acres) of the Bureau of Land Management (BLM) geothermal leases on the west flank of Newberry (Figure 5). The leased area includes two deep geothermal wells, three large drilling pads, two water wells, and other infrastructure. AltaRock has permits in hand to drill an additional geothermal well. Workovers or deepening of either existing well can be approved through a sundry notice to the US Federal Bureau of Land Management.

The first geothermal exploration well drilled by AltaRock's predecessor and now subsidiary Davenport Newberry Holdings (DNH) was NWG 55-29. This well was the site of AltaRock's DOE-Funded Newberry EGS Demonstration from 2010 to 2015 (Davatzes and Hickman, 2011; Cladouhos et al, 2011a, 2011b, 2015, 2016; Sonnenthal et al., 2012, 2015). For that project, NWG 55-29 was completed with a 7-inch liner to the bottom of the well. While 55-29 can be used for monitoring and further EGS tests, this well is not a good candidate for deepening to greater temperatures due to the liner.

The second well Davenport drilled at Newberry was NWG 46-16. The well was sited to drill through a west-northwest striking linear gravity boundary (Al Waibel, personal communication, 2017). The well pad was located on the northern side of the boundary, and the well was directionally drilled southward, toward the gravity boundary. NWG 46-16 was spudded in August 2008 and completed at a TD of 3536 m on 19 October 2008. The well is completed with 13.375-inch surface casing to 1444 m, 12.25-inch open hole to 2100 m, and 10.625-inch open hole to TD. The open hole and large casing completion, make this well ideal for deepening.

Research at Newberry has strong support from all the local communities eager for a better understanding of volcanic hazards and the economic boost that geothermal energy would bring to the area. This project will be the first scientific leg of an ambitious program that aims to test the concept of SHR EGS, a concept promoted by NEWGEN, a public-private collaboration between AltaRock Energy Inc., Oregon State University (OSU), Pacific Northwest National Laboratory (PNNL) and Statoil.

2.4 Geophysical data and 3D Conceptual Geologic Model

As part of a geothermal exploration program, Davenport Newberry Holdings collected an extensive geophysical data set at Newberry, adding to more than three decades of previous data at the volcano (reported in a Journal of Geophysical Research special issue in 1988). In 2012, Oregon State University, in partnership with the US Dept. of Energy National Energy Technology Laboratory and Zonge International began the project *Novel Use of 4D Monitoring Techniques to Improve Reservoir Longevity and Productivity in Enhanced Geothermal Systems*. This project was an extensive program of geophysical monitoring of subsurface conditions within AltaRock's geothermal leasehold that produced a geophysical baseline model from the compendium of pre-stimulation data, including many hundreds of (micro)gravity and magnetotelluric stations, microseismicity, seismic velocity tomography, ground deformation monitoring using satellite InSAR and ground-based interferometric radar, and aeromagnetics (Schulz et al., 2014).

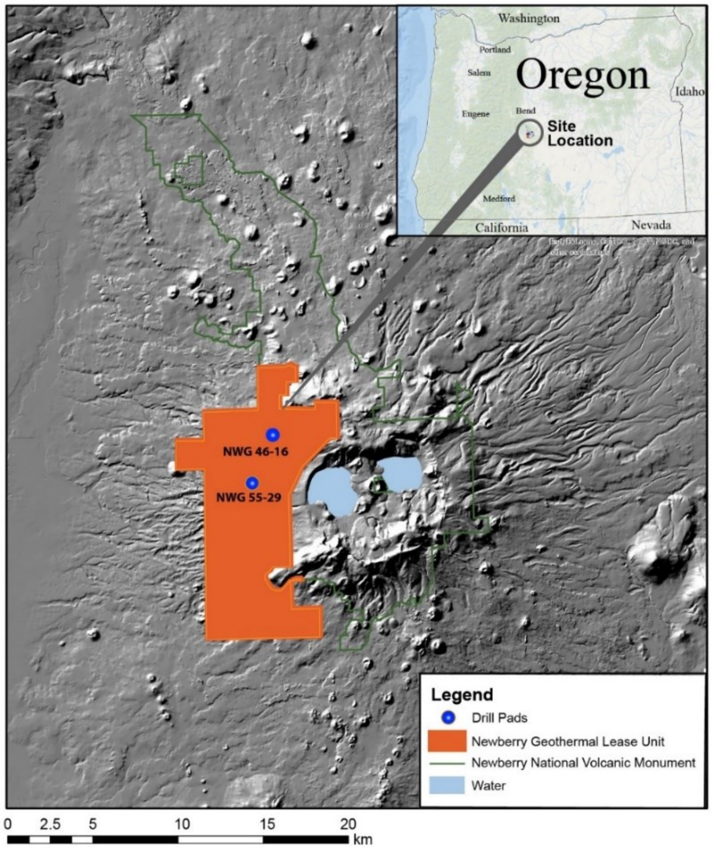


Figure 5. Location map for the proposed NDDP site, showing the Newberry National Volcanic Monument and geothermal leases. Blue dots with identification numbers correspond to the two existing deep wells, NWG 46-16 being the intended target for deepening.

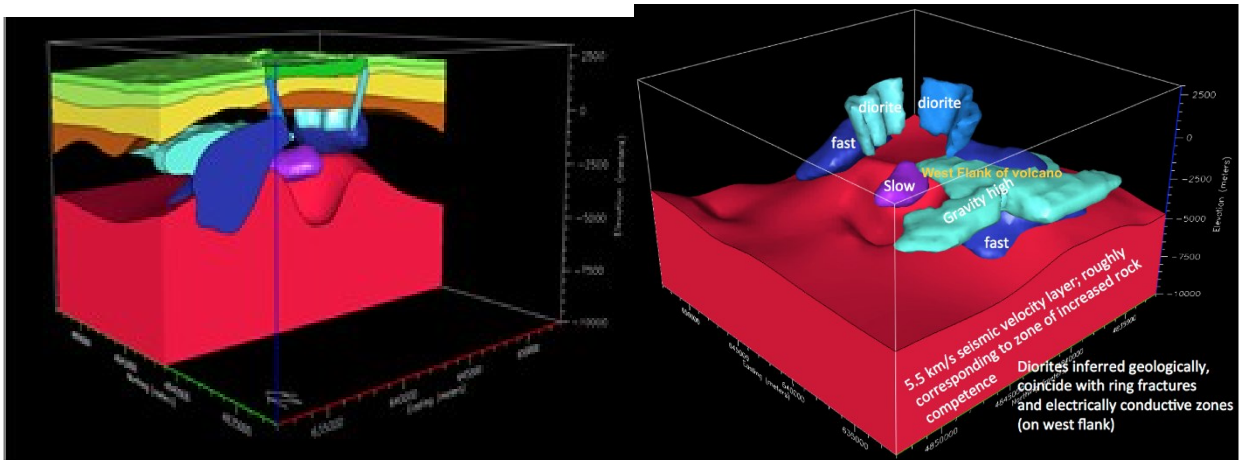


Figure 6. (left) Geophysically-inferred intrusive bodies beneath Newberry volcano, viewed from the northwest (nearest to viewer) to the southeast, showing ring dykes along periphery of caldera (labeled "diorite"), seismically fast zones (dark blue zones; inferred mafics), a slow zone representing the sub-caldera magma chamber (purple/lavender), and formations interbedded with dykes and sills and potentially a deeper plutonic body seismically fast, consistent with interbedded granites, all at depths greater than 3000 m below surface level. These features, and particularly the deeper plutonic body would be important deep drilling targets. (right) Representative geophysical data layers displayed in EarthVision viewed from northwest looking toward southeast showing north-to-south cross-section with zones of inferred increased chlorite concentration/potential epidote alteration removed to reveal intrusive bodies. The deep intrusive bodies and/or zones of interbedded dyke intrusion beneath the drill site are the blue/cyan objects on the left side.

Geophysical and geological data was synthesized in a robust conceptual geologic model built in 2016 during Phase 1 of the US DOE FORGE program (NEWGEN, 2016; Mark-Moser et al., 2017; Bonneville et al., 2017). A three-dimensional model (Figure 6), developed using the EarthVision™ software environment, provides a unified framework that identifies formations and their properties and constrains their spatial extent. In the conceptual model, the temperature profile within the target reservoir units is constrained by borehole equilibrium temperature measurements from deep wells, backed by thermal conductivity measurements of rock cores and cuttings, diffusive heat flow models, and coupled thermal-hydrological- mechanical-chemical (THMC) models that make use of constraints on porosity and permeability obtained from measured well data, bulk permeability data, and injectivity test data (Sonnenthal et al., 2012, 2015). Multiple terabytes of high-quality geologic, geophysical, geomechanical, and geochemical data from the site are now publicly available on the US DOE Geothermal Data Repository (NEWGEN, 2016).

3. NEWBERRY DEEP DRILLING PROJECT

After completion of AltaRock's Newberry EGS Demonstration (Cladouhos et al, 2015, 2016) and NEWGEN's FORGE Phase 1 (NEWGEN, 2016), the NEWGEN team evaluated the strengths of the Newberry site, relative to other geothermal test sites. We determined that the shallow heat anomaly (320°C at 3000 m), plus infrastructure, environmental permits, land commitments, and monitoring plans are the sites greatest strengths. Hence NEWGEN organized an International Continental Drilling Program (ICDP) sponsored workshop held at the OSU-Cascades campus in Bend from Sept. 10-14, 2017 to evaluate the suitability of the site for Super Hot EGS and drilling. Important scientific questions related to breakthroughs in geothermal energy, drilling at extreme temperatures, seismology, and volcanology were discussed by more than 40 engineers and scientists. The unanimous conclusion of the workshop participants was that an ICDP proposal at Newberry should proceed. Several important scientific goals which fit into the overarching research goals of ICDP (Horsfield et al., 2014) can be pursued at NDDP; in particular, those concerning heat and mass transfer in the crust from the points of view of natural hazards and geothermal energy including: EGS (supercritical and beyond-brittle), volcanic hazards, mechanisms of magmatic intrusions, geomechanics close to a magmatic system, calibration of geophysical imaging techniques and drilling in a high temperature environment.

We propose to deepen geothermal well NWG 46-16 from 3534 m to up to 4877 m MD (4813 m TVD) at the northwestern flank of Newberry Volcano (Figure 5). This activity will extend current knowledge from the existing ~3000 m boreholes at the sites, into and through the brittle-ductile transition (to projected temperatures >450°C), and potentially approaching regions of partial melt. Geothermal, volcanic, geophysical, and engineering information gained at the Newberry site will be widely applicable across the Cascade volcanic arc, as well as other magmatically active areas throughout the Pacific Rim and beyond.

3.1 Motivations and Goals of Drilling

Going deeper than existing wellbores at Newberry, for the first time into the brittle-ductile transition, will test the efficiency of thermally-induced fracturing and reservoir creation during the drilling stage. The drilling fluid temperature should remain below 200°C to cool drill bits and logging equipment, which will induce a thermal shock while drilling into hot rocks with temperature above 400°C. In addition, a hydraulic well stimulation will both change the pore pressure in fractures and cool the fracture walls. The extent of thermal fracturing and the associated changes in the permeability of the formation remains a big unknown in this kind of thermally activated EGS, and its knowledge and modelling constitute important factors of development for supercritical steam (>374°C, >22 MPa) geothermal energy. Unlike wells drilled in many conventional geothermal resources, Newberry wells were drilled with full returns; that is, all cuttings were returned to the surface for analysis. Thus, we expect to successfully collect samples from the deeper hole - unlike the IDDP-2 hole, which was recently drilled blind with low core recovery (Friðleifsson et al., 2017).

Drilling at Newberry will bring additional information, to a very promising field of research initiated by the Deep Drilling project in Iceland with IDDP-1 on Krafla in 2009 (Pálsson et al., 2014; Friðleifsson et al., 2014a), followed by IDDP-2 on the Reykjanes ridge (Friðleifsson et al., 2014b, Friðleifsson et al., 2017) in 2016 and ENEL's DESCRAMBLE project in Lardarello in 2017, in the future Krafla Magma Drilling Project (Eichelberger, Personal Communication, 2017), and the future Japan Beyond-Brittle project (Asanuma et al., 2015; Muraoka et al., 2014). Dobson et al. (2016) summarizes all these international high-enthalpy geothermal projects. NDDP will be the first such project set in a continental volcanic setting. While drilling through silicic rocks will have its own challenges, the information and conclusions drawn from NDDP will be easily extrapolated to non-volcanic continental crust settings.

3.2 Technical Gaps, Pre-drilling Planning and Equipment Qualification and Decisions

NDDP will be on the cutting edge of drilling, stimulation, and characterization technologies. Therefore, during the planning phase the team will need to evaluate products, vendors, and technologies to ensure that they meet the specifications required to drill NGW 46-16D and achieve the project's goals. Further, a well-documented decision process will be established, so that future projects can replicate our successes and learn from our inevitable failures. Best practice documents will be drafted to capture all lessons learned.

To achieve the scientific and drilling objectives, NDDP will prepare and execute a drilling program, considering the feasibility and technology gaps related to:

- Ultra-high temperature and pressure casing and couplings as well as cement designs capable of withstanding the geochemistry of super-critical fluids and thermal cycling,
- Drilling bits, muds and methods suitable at super-hot temperatures,
- Coring and stress measurements in a previously-drilled hole and during drilling,
- Open hole packers needed for stress measurements at super-hot temperatures,

- Rock mass mechanics derived from drilling monitoring,
- A suite of geophysical logs (including sonic velocity, imaging) for super-hot temperatures,
- Super-hot downhole energy sources or seismic instruments for vertical seismic profiling (VSP) and velocity calibration,
- Super-hot downhole ERT transmitter/receiver electrodes incorporated into electrically isolated well casing collars,
- Reservoir creation methods (hydraulic, thermal, chemical, gas, energetic source) suitable for semi-ductile rocks,
- Reservoir sustainability challenges including long-term geochemistry and permeability maintenance
- Syn- and post-drilling ground and borehole-based geophysical monitoring.

In cases where technology development is needed, NDDP will work with technologists, and other international high-enthalpy geothermal projects to identify and implement new solutions.

3.3 Site Selection and Well 46-16D (D for deepened)

The goals of NDDP are to 1) test EGS above the critical point of water, 2) collect samples of rocks within the brittle-ductile transition, 3) investigate volcanic hazards, 4) study magmatic geomechanics, 5) calibrate geophysical imaging techniques, and 6) test technology for drilling, well completion, and geophysical monitoring in a very high temperature environment. The geologic, geophysical, and thermal setting of AltaRock's geothermal leases on Newberry and geothermal well NWG 46-16, are well-suited to meeting these ambitious goals.

As already described above, the Newberry site has extensive geophysical data sets and a robust 3D conceptual model. Due to the existing geothermal leases and completion of the NEPA process for a major geothermal project, workovers or deepening of existing wells can be approved through a Sundry notice to the US Federal Bureau of Land Management.

The shallower conductive temperature profile in NWG 46-16 projects to a bottom hole temperature of 350-374°C at 3,494 m TVD (3,536 m MD). If NWG 46-16D continues with a deviation from vertical of 10° (Figure 7) and the gradient remains the same, 450°C will be reached at 4180 m TVD (4,232 m MD), and 500°C at 4,621 m TVD (4,680 m MD). If a more conservative value of BHT of 340°C is chosen, then 500°C will be reached deeper at about 4877 m. We can conclude that even if we use conservative estimates for the predicted temperature profile, the NDDP temperatures goals can be reached with 1000 to 1310 m of additional drilling relatively easily. Thus, compared to the drilling costs listed in Table 1 for a new well, deepening 46-16 will be much less.

During the drilling of NWG 46-16, there were no significant lost-circulation zones deeper than 300 m and cuttings were fully recovered. Therefore, in NWG 46-16D we can expect high recovery rates of cuttings and core at temperatures at which the rocks are transitioning from brittle to ductile mechanical behavior.

NWG 46-16 is situated outside the Newberry National Volcanic Monument and the current caldera. The recent volcanic activity at Newberry is not limited to the caldera. Ring dykes, cinder cones, and lava flows are abundant outside the caldera, and these extrusives must be connected to a young magma chamber. Therefore, there is a possibility that feeder sills or dykes will be intersected in NWG 46-16D. Further, the center of the Newberry or pre-Newberry volcanoes has likely migrated across the NWG 46-16 location. Therefore, information on volcanic hazards and magmatic geomechanics is very likely to be obtained when NWG 46-16D intersects intrusive rocks.

In 2008, NWG 46-16 was targeted at the edge of a gravity anomaly with a southward trajectory designed to intersect a hypothesized intrusive body at depth (Al Waibel, pers. comm., 2017). Although the original hole did not reach a significant lithological or density change, the geophysical (MT and gravity) data and models presented above indicated that NWG 46-16D would likely intersect a higher density pluton. Therefore, NWG 46-16D provides an opportunity to test the geophysical inference that a pluton will be reached with further drilling.

As noted above, the bottom hole temperature of NWG 46-16 was estimated to be between 340°C and 374°C. All additional drilling and geophysical monitoring in NWG 46-16D will be conducted at technologically challenging temperatures of 340-500°C. Therefore, NWG 46-16D offers the opportunity to test the super-hot drilling tools, without the costs of conventional drilling to reach these temperatures.

4.4 Drilling/Sampling/Completion Strategy

NWG 46-16, drilled in 2008, has a TD of 3536 m at a projected equilibrated temperature between 340°C and 374°C. There is 13.375-inch casing set to 1446 m followed by a long open hole to TD (Figure 7). There is a blockage at 1525 m that formed during a flow-test in October 2008, and then was easily re-opened by a drill bit and well-conditioning. A wireline tool could not pass this depth in December 2008. From 2100 m to 3536 m, the hole needs to be reamed from 10.625-inch to 12.25-inch to allow for 9.625-inch casing to be run as the production string. Then, the well will be deepened to about 3750 m so that the open hole interval below is all above the critical point of water (374°C). The well will be cased back to the surface using materials capable of withstanding the potentially corrosive flow of supercritical steam from below, should that exist. Finally, the well can be deepened to 4621-4877 m, where Newberry intrusives are likely to be intersected.

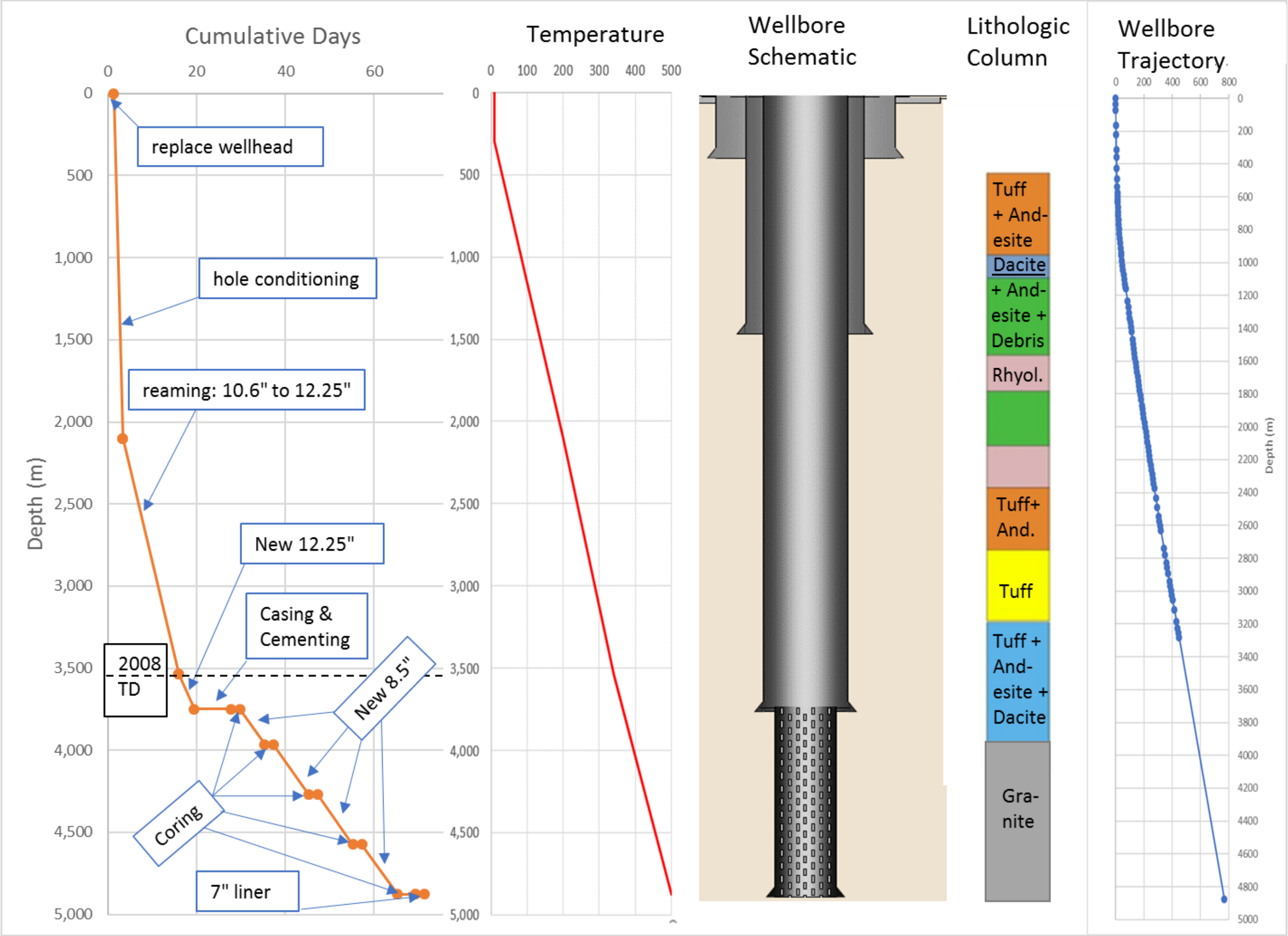


Figure 7. Summary of drilling plan for 46-16D. From left, 1) projected rig time and drilling activities - orange circles delineate drilling intervals and drill string trips, 2) projected temperature, 3) planned well bore schematic, 4) lithology with projected granite below 4 km depth, and 5) well bore trajectory, actual and planned. All depths except #5 are MD.

To drill 46-16D, we have proposed the following drilling program (Figure 7), note that all depths are MD:

1. Prior to arrival of the main rig, the 13.375-inch casing will be evaluated to confirm mechanical integrity.
2. Optionally, a coiled tubing rig or workover rig will be used to clean-out the blockage at 1525 m.
3. A new well head and master valve, suitable for superheated steam temperatures and pressures will be installed.
4. A flow test will be performed to characterize the CO2 flux observed during 2013 testing. During this flow test, gas, water and microbiological sampling will be performed.
5. A rig will be moved in and rigged up. Drill-string with 12.25-inch bit will be run into the hole and through the blockage. The hole will be conditioned with mud to re-support the formation at the bridge. If necessary, a temporary liner across the zone may be installed. During this stage, the 12.25-inch bit will tag the top of the 10.25-inch interval at 2100 m.
6. From 2100 to 3536 m, a reaming bottom-hole assembly will be used to increase the hole size to 12.25-inch to TD of 46-16.
7. If the hole is stable, the hole will be further deepened using 12.25-inch bits to at least 3750 m, the depth at which a temperature of 374°C is expected (scenario with BHT at 340°C). This activity will isolate the open hole interval above the critical point of water. Hole instability may require casing before this depth.
8. The well will be cased with 9.625-inch casing tied back to the surface. The detailed procedures, and casing and grouting materials for this very challenging step will be developed and independently reviewed during the pre-drilling planning and qualification phase of the project.
9. The cement shoe will be drilled out and a leak-off test performed.
10. The first core will be collected just below the casing shoe after drilling out cement.
11. The hole will be deepened with 8.5-inch bits to an expected depth of 4877 m and temperature of 500 °C (scenario with 46-16 BHT at 340°C). Continue drilling at azimuth (210°) and deviation from vertical (10°). There is no expectation that directional corrections will be needed. Based on geophysical models, 46-16D is expected to intersect granitic rocks between the current TD and 4000 m.
12. Logging (LWD and wireline), coring, and stress measurements to be conducted as described below.
13. Install 7-inch perforated liner in open hole interval, 3650 to 4877 m.

A detailed plan with contingencies will be developed during the pre-drilling planning and qualification phase of the project. Casing point depth and total depth are subject to change based on further data analysis and technological review.

4.5 Coring and Sample Analysis

Cores will be collected starting at the current TD of NWG 46-16. Initial field analysis of core material will allow determination of the onset of ductility. Lab characterization and testing of core will provide critical information on most of the goals of the NDDP. Fluid inclusions in core samples will provide uncontaminated samples of in situ, native fluids for both geochemical and microbiological analysis.

The anticipated core tool will cut a 6-inch hole and collect a 4-inch core with a 10 m core barrel length. If paired with a bit change, we estimate that each core will add two days of rig time. The upper goal would be to collect a core at every bit change (provided each bit lasts 160 m or more) for a total of about ten cores. The minimum goal would be five cores. In addition, the coring program will be flexible, to allow for spot coring if cuttings or drilling behavior indicates that a distinct lithology has been intersected.

4.6 In Situ Stress Measurements

Measuring stress magnitudes above 300°C will be extremely challenging; success will depend on whether very high temperature removable packer technology is available to hydraulically isolate a short (<5 m) interval of formation and then safely remove the packer, allowing drilling to continue. Here, we have proposed two different options, one which assumes such a packer will be available in time and another which assumes it will not.

If removable high temperature packer available - The minimum principal stress magnitude will be measured using the standard extended leak-off test (aka mini-frac or XLOT) at three different depths. If removable high temperature packer not available – the stress magnitude testing will only be attempted at TD, where a zone-isolating packer will be permanently installed and, after use, left in the hole by installing a breakable link in the drill string just above the packer. If the rock type at TD is granitic (silica-rich) as expected, then the rock mass should behave ductily at tectonic strain rates. Comparing the fracture closure pressure to the pressure generated as the well creeps shut would provide a novel measurement and significantly advance understanding of brittle/ductile geomechanics and the feasibility of an EGS above the critical point of water.

5. PROJECT FUNDING

NEWGEN has developed an extensive, multi-pronged plan for obtaining funding from a variety of interested parties. ICDP approval of this proposal would be leveraged to gain support from other parties. For the purposes of management and investment, the project will be separated into three categories: Technology, Science and Development.

Technology - New technology will be needed to bring currently best available technology for high temperature drilling, casing and cementing and well stimulation from both geothermal and oil and gas to the point where it can be successfully utilized in production and injection for SHR EGS. A new business entity will be created to develop and hold intellectual property (IP). This entity will be owned by investors who may come from industry, venture capital or other investment participants. Patentable innovations will result from this effort and will be held by participant investors in the technology company,

Science – Advances made at IDDP-1 and IDDP-2 as well as other wells drilled at above supercritical temperatures will make it possible to drill 46-16D, to 500 °C. This effort will use best available methods to ensure a well that can be used to study and better understand the brittle-ductile transition zone as well as the eruptive history and mechanisms of Newberry Volcano with application to other subduction zone volcanos. The well will also serve as the basis for experimental stimulation in the brittle-ductile transition zone for future supercritical EGS development. Scientific drilling, testing and monitoring as well as future stimulation tests will be funded through industry, government and philanthropic grant funding. The NEWGEN Consortium led by PNNL will manage science related activities for 46-16D to supercritical temperatures. Industry, philanthropic and non-US government entities can participate through purchase of a *Stadium Seat* gaining participation in project meetings and full access to project data prior to publication.

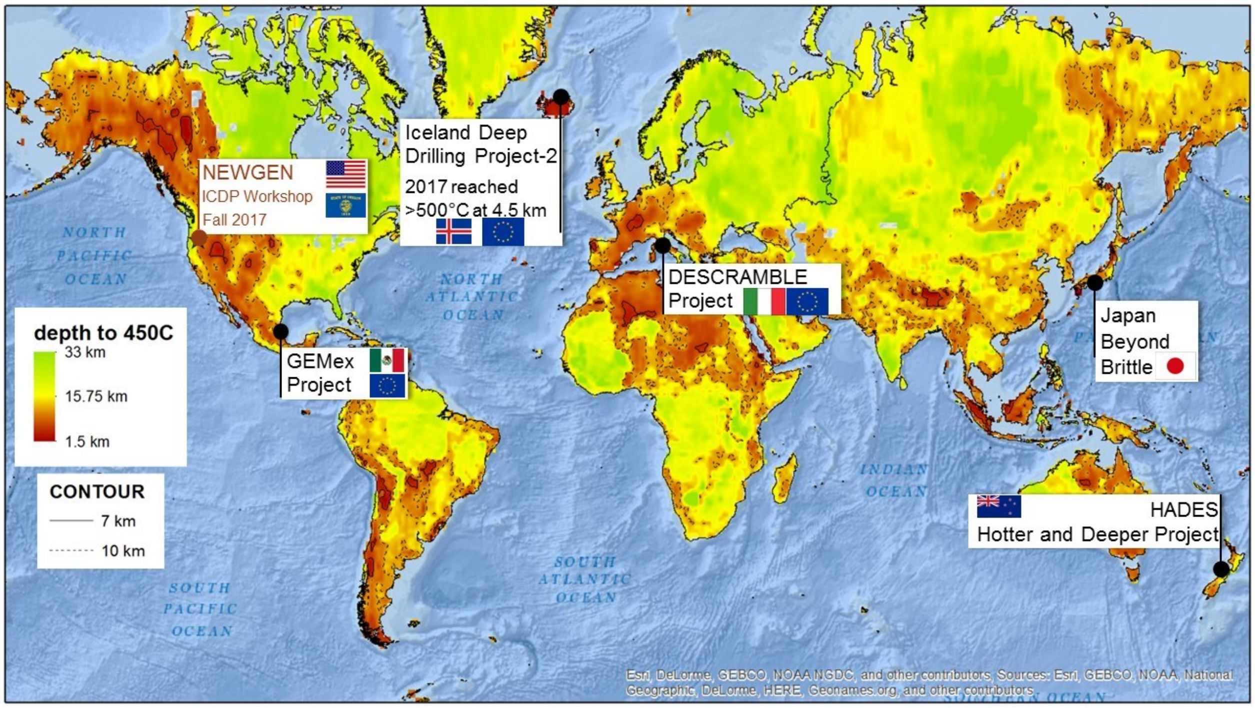
Development – The long-term goal of NEWGEN is the production of geothermal electricity at Newberry Volcano. While 46-16D is the basis for the scientific aspects of the proposed project, if properly completed the deepened well can continue its useful life as the injector for an EGS power project development. Development would include drilling, stimulation and circulation testing of at least one production well and possibly two. Each well can produce as much as 25-50 MW from flow rates of supercritical water per well of 30-60 kg/s. The construction of a power plant would be financed based on the results of the circulation testing of the wells.

6. CONCLUSIONS

The technology and scientific goals of NDDP are to 1) test EGS above the critical point of water, 2) collect samples of rocks within the brittle-ductile transition, 3) investigate volcanic hazards, 4) study magmatic geomechanics, 5) calibrate geophysical imaging techniques, and 6) test technology for drilling, well completion, and geophysical monitoring in a high temperature environment. The geologic, geophysical, and thermal setting of AltaRock's geothermal leases on Newberry and geothermal well NWG 46-16 , in particular, are well-suited to meeting these ambitious goals. NWG 46-16D also supports the development goal of NEWGEN to produce electricity at Newberry, as with successful SHR EGS creation it can become the injector for the geothermal subsurface system, recharging one or two production wells.

Testing and developing the technology platform needed to produce SHR EGS will be worth the effort as this is the clearest route to making geothermal electricity cost competitive. The NEWGEN consortium has already held an ICDP workshop, set ambitious goals, and written an ICDP proposal. The next steps are to implement the project funding plan to attract additional investors and partners ready to contribute to this exciting challenge.

NDDP and the other supercritical geothermal system projects in areas with shallow heat are the first step to making SHR EGS a viable, global resource. Eventually, advanced drilling methods such as energy drilling and casing-while-drilling, could allow wells to be economically drilled to 10-20 km, expanding SHR EGS power to much of the world's population (Figure 8).



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 8. World map with color contours showing depths to 450 °C. Solid contour shows where 450 °C can be reached at 7 km depth or less and the dashed line where 450 °C can be reached at 10 km or less. Note the many populated areas in the world within transmission distance (~300 km) of hot spots on the map (western North and South America, western and central Europe, northern Africa, southeastern Asia, and Japan). Also shown is the current supercritical geothermal projects worldwide (Dobson et al., 2017).

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