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Preliminary Geothermal Resource Assessment of the St. Helens Seismic Zone Using the Results from the Geothermal Play-Fairway Analysis of Washington State Prospects

Michael W. Swyer[1], Matthew E. Uddenberg[1], Trenton T. Cladouhos[1], Alexander N. Steely[2], Corina Forson[2] and Nicholas C. Davatzes[3]

[1]AltaRock Energy Inc., 4010 Stone Way North, Suite 400, Seattle, WA 98105

[2]Washington Geological Survey, Department of Natural Resources, 1111 Washington St., Olympia, WA 98504

[3]Earth and Environmental Science, Temple University, Beury Hall, 1901 N. 13th Street, Philadelphia, PA 19122

mswyer@altarockenergy.com

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ABSTRACT

The northern St. Helens Seismic Zone was one of the areas of interest during Phase 2 of the Washington State Play-Fairway analysis. The area is assessed for geothermal resource potential using the volumetric reserve estimation method developed by the US Geological Survey. Multiple hypotheses for reservoir volume are proposed and analyzed based on interpretation of data gathered during Phase 2 within a geothermal lease. The data utilized in the analysis includes new geologic mapping, ground-based gravity survey, magnetotelluric survey, and passive seismic survey. The hypotheses will be tested, and the resource model will be updated after temperature gradient holes are drilled in the area during Phase 3 at sites selected from Phase 2. The analysis also makes use of the prior geologic knowledge of the area, including the increased seismic and geodetic monitoring following the eruption of Mount St. Helens on May 18th, 1980, existing geologic mapping and models developed from seismic and geodetic data, and past geothermal prospecting efforts by the Washington Division of Geology and Earth Resources. The analysis uses reservoir temperature from geochemistry and a single temperature gradient hole for a low value, and a temperature required for steam flash as a high value. Subsurface temperatures, and heat flows are expected to be better constrained after Phase 3 drilling. The preliminary results suggest power generation potential ranging from 65 MWe to 1.5 GWe within the lease area.

1. INTRODUCTION

The St. Helens Seismic Zone (SHSZ) north and south of Mount St. Helens was one of three geothermal prospects in Washington State selected for geothermal Play-Fairway Analysis (PFA) by the Washington Geological Survey, a division of the Washington State Department of Natural Resources with funding from the US Department of Energy. The purpose of PFA is to minimize risk associated with geothermal resource development through geothermal favorability models that can be used to site exploratory drilling targets.

Phase 1 of the PFA included a desktop study of publicly available data to assess the geothermal heat potential and fracture permeability of each prospect area (Norman et al., 2015). To assess permeability potential from localized crustal deformation, this phase included geomechanical modeling of faults and volcanic centers with geometries from previous geologic and geophysical studies, and boundary conditions derived from geodetic strain data. The heat and permeability layers were combined and weighted based on consensus-based hierarchy for the various layers in the favorability models.

In Phase 2, geological and geophysical data were collected in the most favorable areas identified in Phase 1. The favorability maps were refined to a higher resolution for siting temperature gradient (TG) holes to be drilled in Phase 3 (Forson et al., 2017). Presented here is a preliminary site-specific geothermal resource assessment of one of those areas using the data gathered during Phase 2 in the northern SHSZ on a geothermal lease (Figure 1). Data gathered during Phase 2 of the PFA includes 1:24,000-scale geologic mapping with interpretation and field checking of existing LIDAR, magnetotelluric (MT) survey, ground-based gravity survey, ground based magnetic and aeromagnetic surveys, and passive seismic survey. This data was used to qualitatively identify and calculate the volume of a potential geothermal reservoir within the lease, as well as potential feed zones for deeply circulating and upwelling geothermal fluids also acting as a fluid storage volume. This analysis was done using the volumetric reserve estimation method developed by the U.S. Geological Survey (Muffler, 1978) and mainly considers multiple hypotheses for potential reservoir volumes and feed zones. The reservoir temperature was assumed to be high enough for commercial grade electricity production and will be better understood after the Phase 3 drilling campaign. Other parameters were assumed for typical operating conditions, efficiencies, and economic life of a binary power plant and geothermal resource.

2. BACKGROUND

Mount St. Helens is the most active volcano in the Cascade arc and is uniquely positioned as the westernmost volcano of the Cascade Range in southwest Washington. This may be due to lateral migration of magma from under Mount Adams 50 km to the east that is stalled and flows upward near a cold (700°C) serpentinite wedge resulting from the Juan de Fuca plate decoupling from the overriding mantle wedge (Hansen et al., 2016). In months leading up to and in years following the eruption on May 18th, 1980, additional seismic monitoring equipment was deployed on and around the volcano, giving it the best seismic monitoring of any volcano in the US with millions of earthquakes detected and cataloged by the Pacific Northwest Seismic Network (PNSN). The area also has the highest density of Global Positioning System (GPS) benchmarks in the Pacific Northwest placed by the National Science Foundation Earthscope's Plate Boundary Observatory (PBO) and Central Washington University's Pacific Northwest Geodetic Array (PANGA). The GPS benchmarks monitor crustal strain-rates in the region, and Mount St. Helens has the highest rate of crustal strain in the Pacific Northwest. These datasets have helped to characterize the structure and motion of the SHSZ as a north-northwest trending near-vertical fault zone that runs

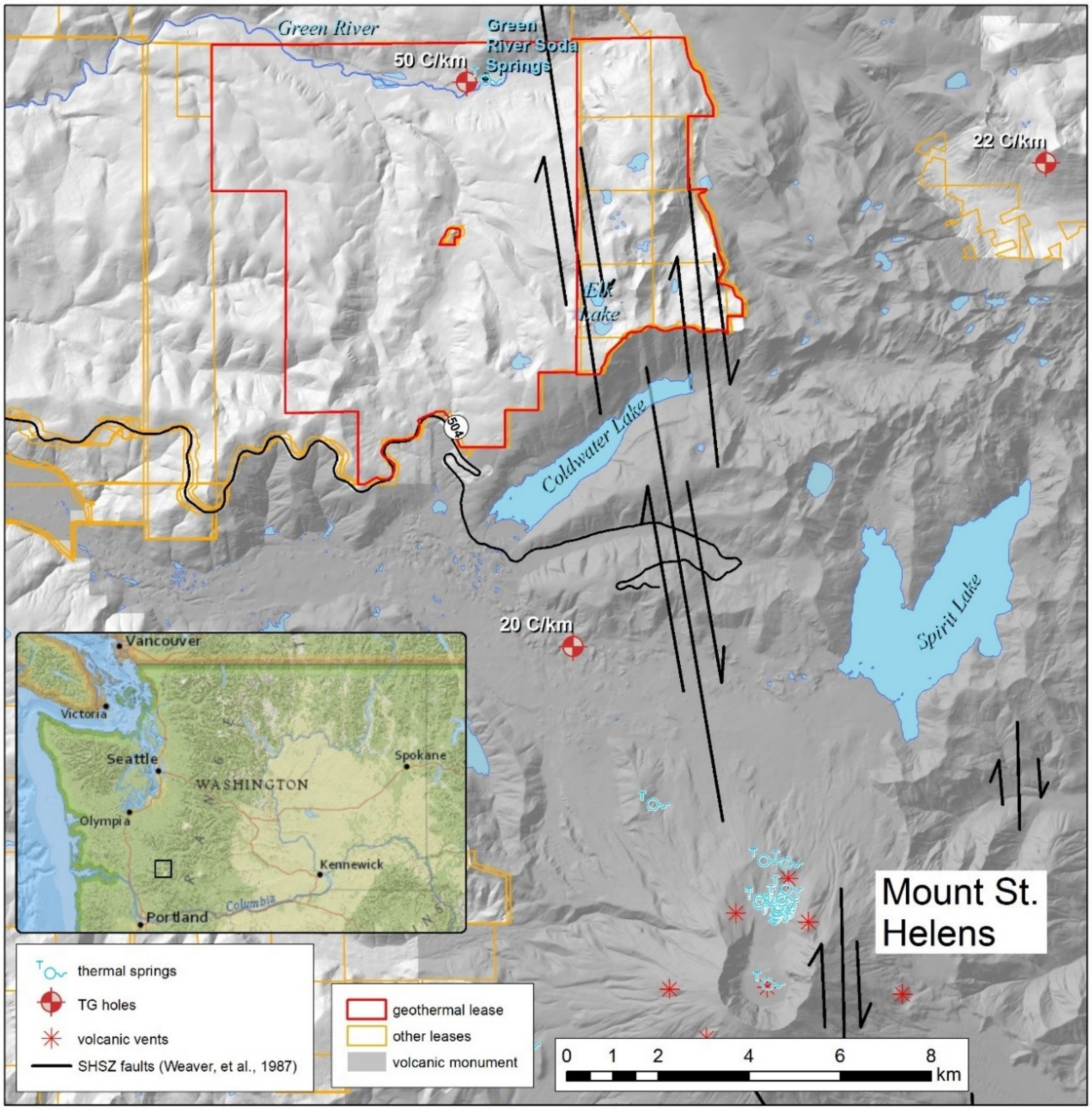

Figure 1: Map of the SHSZ north of Mount St. Helens with geothermal lease area in red, other lease holdings in yellow, and volcanic monument as darker shades of gray. Also shown are the faults modeled by Weaver et al. (1987), thermal springs, temperature gradient holes, and volcanic vents.

through the volcano with right-lateral slip sense (Weaver and Smith, 1983; McCaffrey et al., 2007). Previous passive seismic tomography studies have identified the three-dimensional structure of the Spirit Lake and Spud Mountain plutons 15 km north of Mount St. Helens mapped by Evarts et al. (1987) that bound the northern SHSZ to the east and west, respectively, as high velocity zones with a low velocity anomaly in between them (Lees and Crosson, 1989; Waite and Moran, 2009). The low velocity anomaly has attenuation and scattering of wavefields that is consistent with the presence of Tertiary marine sediments that fill the SHSZ fault zone (Moran et al., 1999; De Siena et al., 2014). The plutons are also apparent as highly magnetic anomalies in an aeromagnetic survey (Finn and Williams, 1987), a gravity survey that identified a buried intrusive complex adjacent to less dense sedimentary and/or shallow volcanic rock (Williams et al., 1987), and a regional MT survey which has identified igneous intrusion near Mount St. Helens as a highly resistive body (Stanley, 1984).

2.1 Geothermal Prospecting

Prior to the eruption, the area surrounding Mount St. Helens was a prime geothermal prospecting target among other Cascade volcanoes. This was because of the level of private and public land holdings designated for natural resource development, and its proximity to multiple population centers. In 1979 the heightened interest lead to a geothermal assessment of the area by the Washington Division of Geology and Earth Resources, which included three TG holes that were drilled in the fall of 1979. One of these holes was drilled north of the summit near the SHSZ along route 504 and was subsequently buried in the 1980 eruption. The hole was drilled to a depth of 125 meters and had a low temperature gradient of 19-25 °C/km with heat flow of 38 mW/m^2. The low temperatures encountered in this hole were thought to be the result of shallow groundwater flows sweeping away heat along the flanks of the volcano, rather than a true indicator of subsurface heat, which had been detected by aerial thermal infrared surveys taken in 1966 and 1977. In general, geothermal exploration has been problematic in the Cascades because of masked heat flows by precipitation and groundwater, and a lack of robust surface manifestations, which warrants a subsurface modeling approach to reduce the risk of geothermal prospecting (Korosec and Schuster, 1980).

Seismicity detected near Mount St. Helens nearly a decade prior to the eruption has suggested the presence of a NNW trending structure running through the volcano, which has been confirmed by the 1981 M5.2 Elk Lake Earthquake, its aftershocks, and thousands of additional earthquakes detected in the SHSZ after the eruption. The SHSZ earthquakes occur along a right-lateral blind strike-slip fault that extends as far as 30 km NNW. It has been suggested that active faulting associated with volcanoes can provide highly permeable pathways for the lateral migration of geothermal fluids (Korosec and Schuster, 1980) and that a geothermal exploration approach near Mount St. Helens should focus primarily on higher quality active and passive seismic monitoring (Schuster, 1981).

A geothermal exploration campaign during the spring and summer of 1983 was focused on the area surrounding the Green River Soda Springs 20 km NNE of Mount St. Helens (Figure 1) and included mercury soil sampling and drilling a TG hole. The mercury soil concentrations were not anomalously high for the Soda Springs because they are located on the flood plain north of the river, but high concentrations were found 0.5 km to the SE on the south side of the river and 1.5 km to the NW at higher elevations (Holmes and Waugh, 1983). A TG hole drilled 0.5 km to the west of the Soda Springs reached a depth of 142 meters and had a temperature gradient of 50 °C/km, three fractured zones that flowed 3-4 l/s, and an electrical resistivity of 2e-4 ohm-meters (Korosec, 1983). The geochemistry of the Soda Springs indicates that it is a mixture of upwelling geothermal fluids and meteoric recharge with an equilibrium reservoir temperature of 140-150 °C. The spring was also reported to be much warmer several decades ago (Korosec, 1984).

2.2 Washington State PFA Conceptual Model

The data gathered during Phase 2 of the Washington State PFA was used to improve the geothermal resource conceptual model by identifying features of the subsurface structure relevant to a geothermal resource. The 1:24,000-scale geologic mapping was used to identify the surface expression of the deeper faulting within the NNW trending SHSZ that were previously modeled by Weaver et al., (1987) and during Phase 1 using relocated earthquake hypocenters and focal mechanisms from the PNSN catalog (Figure 2a and b). The geologic mapping also found several relatively shallow ENE to ESE faults with geomorphic alteration and kinematic expression of left-lateral antithetical Riedal shear (e.g. Katz et al., 2004). A density contrast in the gravity survey and surface contact (Evarts and Ashley, 1993) was used to constrain the geometry of the Spirit Lake pluton to the east (Figure 2f). A less prominent near-surface seismogenic NNE trending fault in the SHSZ was also interpreted as the surface of the pluton (Figure 2a, b and f). The geometry of the Spud Mountain pluton to the west (Figure 2f) was identified by fault linkage mapped at the surface during Phase 2, density contrast in the gravity data, and a high resistivity boundary in the MT data at depth using a value common for saturated granite (>250 ohm-meters, Olhoeft, 1981) (Figure 2f). The results of a passive seismic tomography model reveal an anomalously high compressive to shear wave velocity ratio (Vp/Vs>1.9) zone trending NNW just west of the SHSZ which may indicate fluid-filled fractures and heat (O'Connell and Budiansky, 1979; Lees and Wu, 2000). The Vp/Vs anomaly is found at depths between 1.5-2.7 km in the northern part of the lease and 1.0-3.4 km in the southern part of the lease and is assumed to make up the bulk of the permeable reservoir volume (Figure 2d). This area also has a gravity low (ρ_r = 2,670 kg/m^3) with high horizontal gradient 'max spot alignments' at the interface of the granitic plutons and reservoir rock type that has a strong resemblance to the areal geometry of the high Vp/Vs anomaly (Figure 2d and f). Underlying the Vp/Vs anomaly is a large conductive MT anomaly (<10 ohm-meters), which covers the same area as the high Vp/Vs and gravity low anomalies and has the largest areal extent at ~6 km depth (Figure 2e). It is unclear if this anomaly represents clay rich lithology, or conductive geothermal brines, however the anomaly shallows to a depth of ~3 km near the Green River Soda Springs (Figure 2e), which supports the idea of geothermal fluids upwelling in that area.

The seismogenic faulting at depth in the SHSZ was previously modeled by Weaver et al. (1987) as a 40 km long right-lateral strike-slip fault system with an extensional right-step and change in fault orientation at the location of the volcano. The geometry and motion of the faults were constrained by earthquake focal mechanisms with strong alignment of right-lateral nodal planes within the SHSZ (Weaver et al., 1987). In the northern part of the SHSZ the main fault splits into two strands 1) a shallow NNE trending fault along the western edge of the Spirit Lake pluton, and 2) a deeper NNW trending fault identified as the Elk Lake earthquake sequence (Grant et al., 1984), with a bifurcation point between the two strands 10 km north of the volcano and 6 km deep. Another major seismogenic feature at Mount St. Helens is the magma chamber, which is surrounded by focal mechanisms that do not have the same linear trend as the faults and has an aseismic gap 7-11 km deep and 2 km wide representing a volume of ductile/molten rock (Barker and Malone, 1991). The magma chamber geometry (Figure 3, bottom right) and the fault geometry (Figure 2b) were used in a geomechanical displacement discontinuity model using Poly3D, a boundary element code that simulates stress/strain change in volumes surrounding faults, fractures, and cavities with displacements or residual tractions (Thomas, 1993). The results from simulating motion in the SHSZ (Figure 2c) were used as a proxy for off-fault fracture permeability at drillable depths (200 m, 2km, and 3km) during Phase 1 and 2 of the PFA (Norman et al., 2015; Forson et al., 2017). In the northern SHSZ a dilational stress anomaly located west of the fault bifurcation matches the thickest part of the high Vp/Vs anomaly, as well as an area with a higher density of 20-30 Ma dikes (Figure 2c). This suggests that the geometry and motion of the SHSZ could have been relatively constant since the Oligo-Miocene (Forson et al., 2017). Figure 3 is a rendering of the improved three-dimensional conceptual model, which shows conjectural flow paths depicting one of many points of meteoric water infiltration and deep circulation along the SHSZ, with potential upflow zones 1) within the damage zone west of the 6-km deep fault bifurcation, 2) along the large deep fault delineated by the Elk Lake earthquake sequence, and 3) in the area near the Green River Soda Springs where the conductive anomaly is shallow.

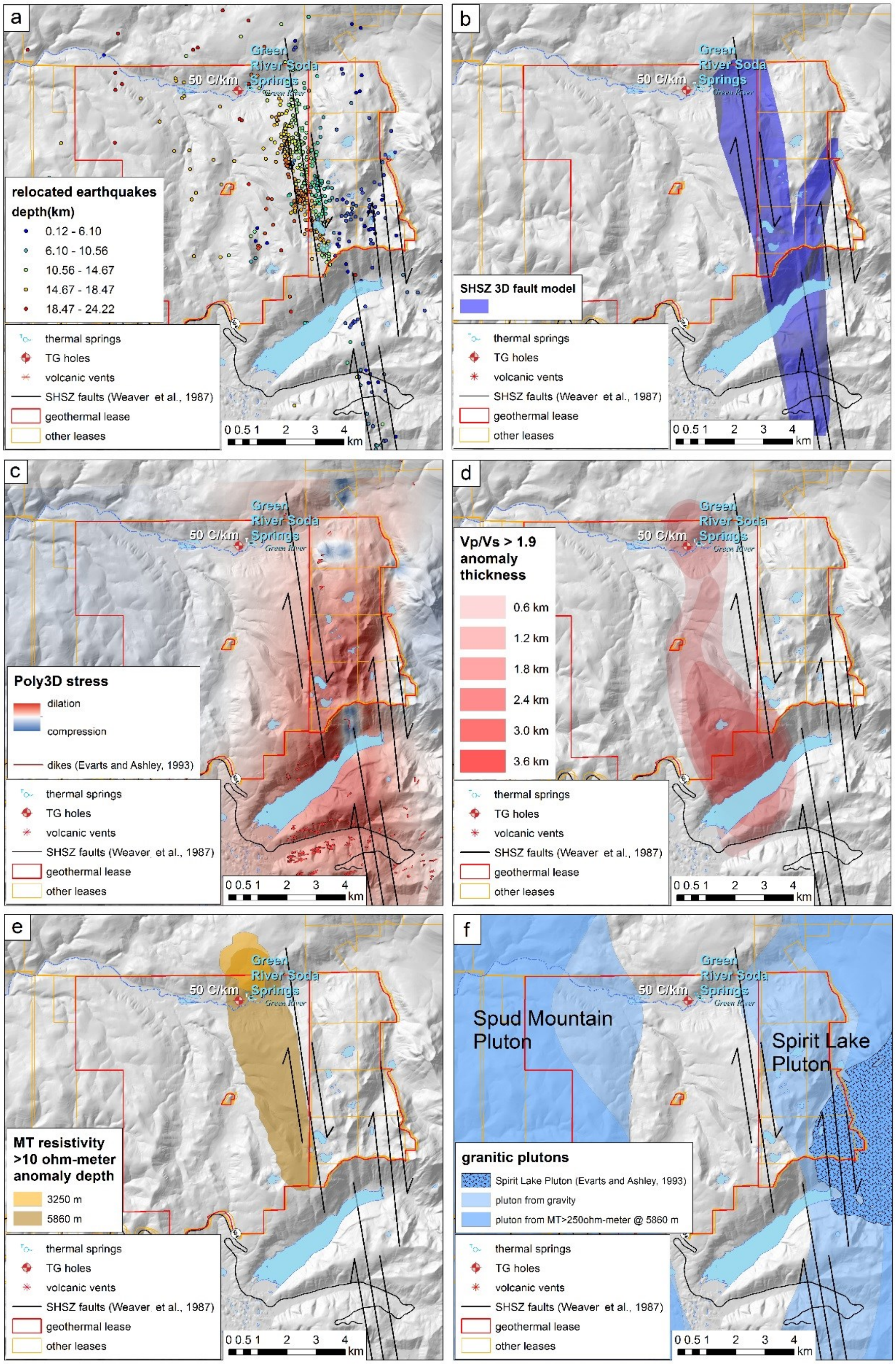

Figure 2: Geothermal lease area with various geophysical datasets that were modeled/interpreted for conceptual model: a) relocated earthquakes from the PNSN catalog which were used to make b) 3D fault model of the SHSZ faults – purple areas shows west-dipping planes. The 3D fault model was run in Poly3D to simulate c) local stress change, which matches d) the shallow Vp/Vs anomaly superimposed for multiple depths to show thickness. e) shows the conductive anomaly in the MT data, and f) is the Spud Mountain and Spirit Lake plutons which were mapped by Evarts and Ashley (1993) and interpreted from gravity and MT.

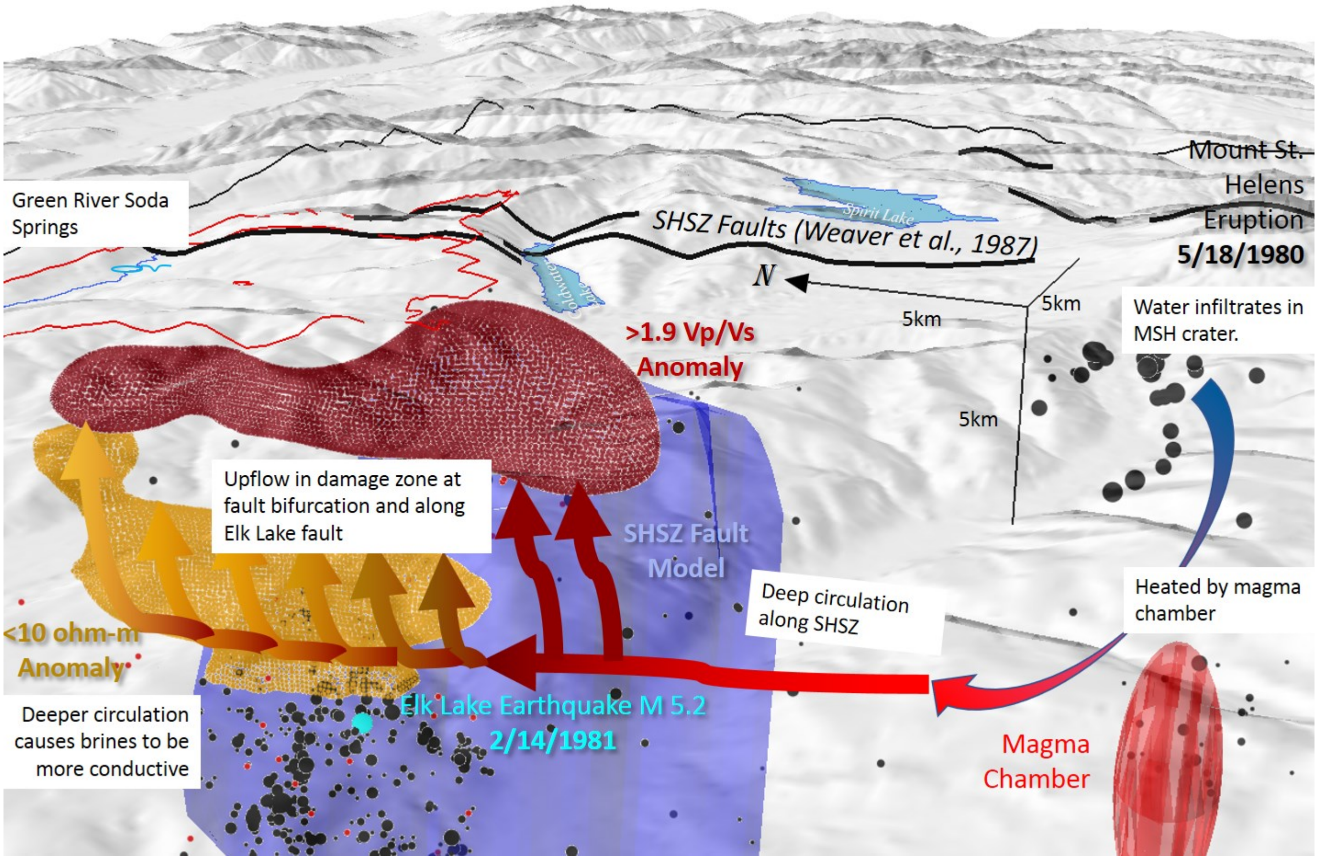

Figure 3: Three-dimensional conceptual model of the SHSZ north of Mount St. Helens looking east. The Vp/Vs>1.9 and MT<10 ohm-meter conductive anomalies are shown as maroon and orange isosurfaces whose geometries are constrained by the passive seismic survey and MT survey from Phase 2 of the Washington State PFA. Also shown are the seismogenic magma chamber in bright red and faults in dark blue used in Poly3D during Phase 1 and 2, with the Elk Lake earthquake in cyan in the middle of the Elk Lake Sequence. Other relocated earthquakes are shown as black dots with size proportional to earthquake magnitude, and red dots show relocated earthquakes during the Phase 2 PFA passive seismic survey. On the surface, the red outline is the geothermal lease area and the thick black lines show the fault model from Weaver et al., 1987, shown on Figure 1.

3. METHODOLOGY

The geophysical data summarized in Figure 2 and the conceptual model shown in Figure 3, provide the basis for speculation of a potential geothermal resource. Although more data is needed to make an accurate assessment, we feel the dataset is robust enough to warrant a preliminary analysis. In this section, we use a standard, accepted methodology to evaluate the potential for geothermal electricity generation. The analysis below is a necessary step to motivate additional exploration and investment in the site.

The volumetric reserve estimation method developed by the US Geological Survey (Muffler, 1978) is widely used in geothermal resource reporting codes that provide a standard for transparency, consistency and confidence that is satisfactory to investors, shareholders and capital markets. For example, the method is used by the Canadian geothermal reporting code (CanGEA, 2010) and the Australian Code for reporting of exploration results, geothermal resources and geothermal reserves (AGRCC, 2008). The method relies on calculating the volume of stored heat-in-place for a geothermal prospect area and makes reasonable assumptions about the percentage of that heat that is recoverable and the efficiency of converting that heat into electricity using typical design points for a geothermal power plant (Akin, 2017). Equation 1 quantifies stored heat-in-place, Q:

$$Q = V\{[C_r\rho_r(1-\phi)(T_i - T_f)] + [\rho_{wi}\phi S_w(h_{wi} - h_{wf})]\} \tag{1}$$

Where V is reservoir volume, C_r and ρ_r are the specific heat and density of the reservoir rock, ρ_{wi} is the density of water in the reservoir. T_i and T_f are the temperatures for produced and expelled geothermal fluid and h_{wi} and h_{wf} are their respective enthalpies. ϕ is porosity, and S_w is the liquid saturation of the reservoir fluid. Equation 1 typically has a third term that accounts for the steam component of reservoir fluid-in-place, but since the Vp/Vs anomaly is high the reservoir is assumed to not have a steam component since low Vp/Vs anomalies suggest either dry fractured rock or the presence of gas or supercritical fluids (O'Connell and Budiansky, 1979; Lees and Wu, 2000). Q is used to determine the power capacity, E:

$$E = \frac{Q\, R_f\, \eta_C}{F\, L} \tag{2}$$

Where R_f is the recovery factor used to determine the amount of stored heat that can be extracted by wells, η_c is conversion efficiency used for converting the stored heat to electricity, F is the plant availability factor which considers typical annual power plant outage times for equipment maintenance and/or malfunction, and L is a typical economic life of a geothermal resource.

A more thorough approach to defining parameters for these formulae would be to use Monte Carlo simulations for the uncertainty of the most significant unknown variables. However, since this is a preliminary resource assessment a deterministic approach is used with focus on the potential reservoir volumes and feed zones identified qualitatively from the geophysical surveys. The total volume of the Vp/Vs > 1.9 anomaly is 44 km^3, however the thickest part of the anomaly is outside the southern lease boundary (Figure 2d) so only 22 km^3 is accessible to commercial drilling. The potential feed zones and/or reserve storage volumes were based on the MT < 10 ohm-meter anomaly encountered at two inversion depths (Figure 2e) which is 18 km^3, and the seismogenic Elk Lake earthquake sequence fault which has an area of 42 km^2 (Wells and Coppersmith, 1994) and an average residual thickness of 500 m (Swyer et al., 2016) for a fault volume of 21 km^3. Table 1 summarizes the potential reservoir and feed zone volumes and modeling scenarios used in Equation 1. Scenario A is the Vp/Vs anomaly alone and is considered a base case for an accessible and permeable geothermal reservoir. Scenarios B and C adds the volumes from the two potential feed zones and/or deep fluid storage volumes. Scenario D optimistically considers the entire rock volume between the two granitic plutons as a potential reservoir rock that has homogeneous fracture permeability because it may be weaker and prone to fracture compared to the surrounding granite due to the lower density and suspected rock types (sediments, meta-sediments and volcanics) and a postulated feed zone along the vertical interface of granite and reservoir rock.

Table 1: Volumes for potential reservoir and feed zones modeled from Phase 2 PFA data and scenarios considered.

Modeled Volume	Geophysical data constraint	Volume	Scenario	Volume	Rationale
1) Fluid-filled fractured reservoir rock	Vp/Vs > 1.9	22 km^3	A) 1	22 km^3	Reservoir rock with high fracture permeability
2) Deep fluid circulation and upflow zone	MT < 10 ohm-meters	18 km^3	B) 1+2	40 km^3	Reservoir rock with high fracture permeability with deep fluid feed zone
3) Permeable fault zone with fluid storage and connective feedzones	Seismogenic Fault with 42 km^2 area, and 500 m residual thickness	21 km^3	C) 1+2+3	61 km^3	Reservoir rock with high fracture permeability with deep fluid feed zone and large fault for deep fluid circulation and storage
4) Rock volume between granitic plutons	Horizontal gradient max spot alignments along edges of plutons and MT > 250 ohm-meters for saturated granite at 5.9 km depth	297 km^3	D) 4	297 km^3	Weaker rock type (not granite) prone to fracture in SHSZ

Two reservoir temperatures are considered in this preliminary resource assessment 1) a lower temperature base case of 140 °C indicated by the Soda Spring geochemistry and 50 °C/km gradient nearby (Korosec, 1983 and 1984) and 2) 200 °C as an economically viable temperature required for steam flash. Although there is not yet any data to support it, a reservoir temperature of 200 °C may be plausible because of the shallow groundwater heat sweep phenomena in the Pacific Northwest, which may be masking higher temperatures at depth especially in the flood plain for Green River. Table 2 summarizes the other parameters used for the preliminary resource assessment and the sources of the data constraint. Temperature dependent parameters came from steam tables with an assumed a production/injection pipeline pressure of 2 MPa. Unknown parameters used typical and/or conservative values.

Table 2: Other parameters used for the preliminary resource assessment.

Parameter	Low	High	Source
T_i	140°C	200°C	**low:** geochemistry and 50°C/km **high:** temperature req'd for flash
T_f	55°C	-	typical value
h_{wi}	590 kJ/kg	852 kJ/kg	steam tables using line pressure of 2 MPa
h_{wi}	252 kJ/kg	-	steam tables using line pressure of 2 MPa
ρ_r	2,670 kg/m^3	-	gravity survey
ρ_{wi}	927 kg/m^3	865 kg/m^3	steam tables using line pressure of 2 Mpa
C_r	1 kJ/kg°C	-	typical value
φ	10%	-	high Vp/Vs: fractured rock
Sw	100%	-	high Vp/Vs: liquid saturation
R_f	0.08	-	typical value
η_c	10%	-	typical value
L	20	-	typical value
F	95%	-	typical value

4. RESULTS

Table 3 lists the results of the preliminary resource assessment for the various reservoir volumes and temperatures modeled within the geothermal lease holdings in the northern SHSZ. The lowest result of this analysis is 65 MWe which is sufficient capacity for a single power plant, and the highest result is 1.5 GWe which is comparable to the past maximum total generation at The Geysers in northern

California. These results are promising and are mainly a testament of the large area within the lease considered favorable for drilling based on the Phase 2 PFA geological interpretation of geophysical surveys. Although much of the land surrounding the volcano has been turned into a volcanic monument after the eruption, there are geothermal leases and private land available for development in the area. Electricity generated here could partly replace nearby coal-fired electricity generation and good-paying jobs at the Centralia Coal Plant which is scheduled to be retired in 2025 (http://transalta.com/us/2011/10/centralia-wa/).

Table 3: Estimated yearly power generation for the potential reservoir volumes and temperatures modeled for the SHSZ resource.

	Volume (km^3)			
Temp (°C)	22	40	61	297
140	65 MWe	118 MWe	180 MWe	878 MWe
200	115 MWe	209 MWe	319 MWe	1,554 MWe

5. DISCUSSION

The drilling campaign for Phase 3 of the PFA (Figure 4) was designed to target the potential reservoir feed zones, and to avoid the problem of masked heat from precipitation and groundwater flow by drilling deeper temperature gradient holes at higher elevations. The holes will also have core and cuttings measured for thermal conductivity to calculate heat flow, which was not done for the 50 °C/km hole drilled in 1981. Knowing heat flow and thermal conductivities and comparing them to other background TG holes nearby with known heat flows (20 and 22 °C/km, Figure 1) will help determine if there is anomalous heat flow above a deeper convective system that brings heat to shallow depths accessible by drilling. This drilling strategy therefore also has the scientific benefit of testing the multiple hypothesis regarding reservoir volume and feed zone and will help guide a more cost-effective campaign of exploratory drilling and resource development.

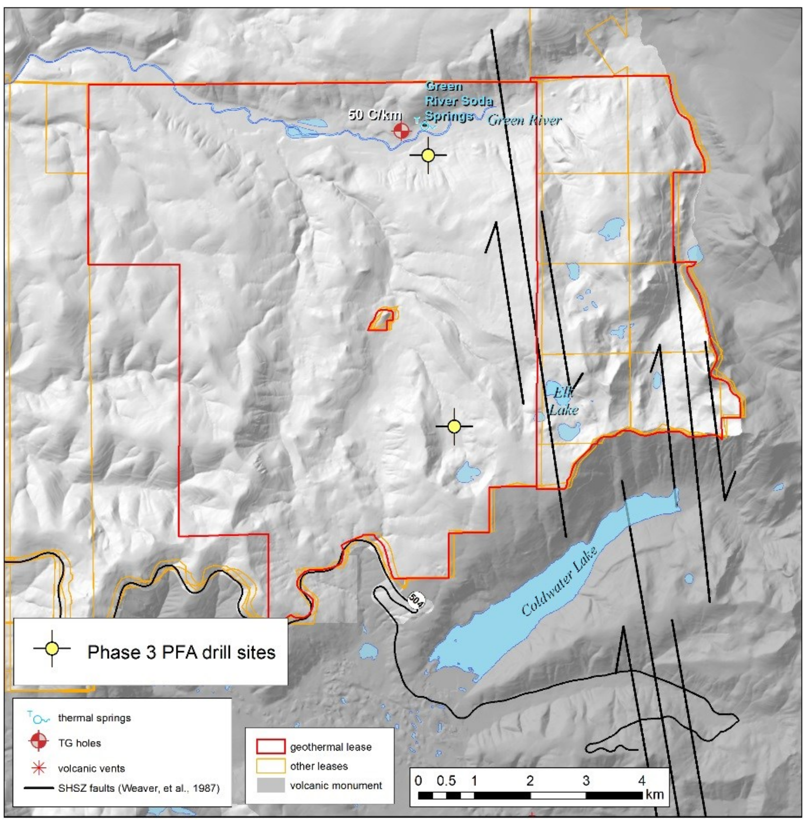

Figure 4: Map of Phase 3 drill sites for temperature gradient holes.

Other proposed and funded activities for Phase 3 of the PFA will focus on scientific understanding of kinematics and neotectonics of the SHSZ as well as the other two prospect areas in Washington, and how it controls the subsurface permeability structure. These activities will include detailed structural mapping to distinguish larger faults from fractures within fault damage zones to further validate the geomechanical model, and thin sections, XRD mineralogy, and XRF elemental chemistry of outcrop, cuttings, and core samples to assess and analyze observed hydrothermal alteration and porosity development surrounding fault zones (e.g. Davatzes et al., 2005; Fetterman, 2010). While the Pacific Northwest Region has proved to be one of the most difficult areas regarding complex tectonics and three-dimensional crustal stress-strain relationships with large hidden active faulting, the knowledge gained from the Washington PFA methodology can be applied to any fault driven geothermal resource with or without proximity to volcanic centers across the western United States, as well as all around the Pacific Ring of Fire.

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