Thermal Modeling and EGS Potential of Newberry Volcano, Central Oregon

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ABSTRACT

Newberry Volcano, located in central Oregon in the Deschutes National Forest, is a large bimodal Quaternary volcanic edifice that covers 1600 km². Various periods of geothermal exploration in and around the volcano over the last 30+ years has resulted in a robust dataset of wellbore temperatures, cores, gravity data, and other geophysical surveys. Wells drilled on the flanks of Newberry have an average geothermal gradient of 130°C/km and show a roughly circular heat flow anomaly centered on the caldera. Geologic data suggest a typical interval of ~200,000 years between large caldera forming eruptions. Using these data along with new industry collected gravity data and recent tomographic studies; a 2-D finite-difference heat conduction program was used to model the heat source under the volcano. The available temperature data on the west flank of the volcano can be explained by silicic sill intrusions recurring at a 200,000 year rate over the 500,000 year lifetime of the volcano.

1. INTRODUCTION

The purpose of this study is to constrain the nature of the heat source beneath Newberry Volcano in order to quantify the thermal energy potential of the area. Newberry Volcano is located in Deschutes County, Oregon, about 35 km south of the city of Bend. The volcano is within the Deschutes National Forest and the caldera and a portion of the north flank have been designated the Newberry Volcano National Monument. Newberry is in the back-arc of the Cascades volcanic arc, at the junction of three geologic provinces: the Cascade Range to the west; the Basin and Range to the south and southeast; and the high lava plains to the east. It is a large bi-modal Quaternary volcano and is one of the largest Quaternary volcanoes in the continental United States (Figure 1).

Geothermal exploration by various groups has been ongoing at Newberry Volcano since the late 1970's (Fitterman, 1988; Spielman & Finger, 1998; Cladouhos et al. (2012); Waibel at al., 2013). Exploration activity has resulted in numerous geologic maps, geochemistry data, geophysical surveys, and thermal gradient wells on the volcano. Thermal gradient drilling located a potential geothermal target in the upper west flank of Newberry (Figure 2). In 1995, California Energy drilled two production scale wells (CE 86-21 and CE 23-22) on the northwest rim of the caldera. These wells confirmed temperatures in the subsurface of \sim 315°C at 2.7 km depth. Due to low permeability, these wells were abandoned (Spielman & Finger, 1998). In 2006, Northwest Geothermal drilled two additional production tests (NWG 55-29 and NWG 46-16) on the western flank. These wells encountered temperatures of 300°C at depths of 2.7-3.1 km. Well 55-29 encountered open fractures; however, the fractures did not appear to be interconnected based on the initial flow test. Well 46-16 encountered open fractures with hydrothermal minerals and sustains a \sim 4.1MPa (600 psi) wellhead pressure. The well bridged at \sim 1,700 m (\sim 4,600 ft) so a full well test was not possible to fully evaluate the hydrothermal system. Altarock Energy conducted an Enhanced Geothermal System (EGS) experiment in the 55-29 well during 2012 (Cladouhos et al., 2013; Petty et al., 2013). The goal is to create fracture permeability in the subsurface and ultimately circulate fluid from 55-29 to another well that will be drilled to intersect the fracture system.

Geothermal energy exploration at Newberry has resulted in a large temperature dataset primarily focused on the northern west flank with distributed data on all sides of the volcano (Figure 2). Newberry represents a unique site for characterizing the thermal regime of an active volcano because 17 (>1000 m) deep heat flow wells surround the site. No other active volcanoes in the United States have as many high quality, deep temperature and thermal conductivity constraints (Blackwell, 1994; Spielman & Finger, 1998). Additionally, and unlike well data near many other volcanoes, 15 of the 17 well sites have approximately linear temperature gradients, allowing for highly accurate heat flow estimates and temperature to depth predictions at an active volcano. We use the temperature and conductivity measurements extracted from these wells to place first-order estimates on the regional thermal regime at Newberry, and from this, constrain the size and location of potential heat sources under the volcano.



Figure 1: Physiographic province map of Oregon showing the location of Newberry Volcano (MacLeod and Sherrod, 1988). MH- Mount Hood; MJ- Mount Jefferson; TS- Three Sisters; CL- Crater Lake.



UTM zone 10. Meters



2. GEOLOGY

Newberry volcano is positioned near the junction of three geologic provinces, the Cascade Range to the west, the High Lava Plains portion of the Basin and Range to the south and east and the Blue Mountains to the northeast (Figure 1). Newberry Volcano has been active for the past 500,000 years and has had at least two caldera-forming eruptions (Donnelly-Nolan et al., 2004). The present central caldera is roughly 7 km wide west-east and 6 km wide north-south. The entire volcanic edifice has the shape of an elongate shield, 60 km north-south and 30 km east-west. It covers an area of approximately 1600 km² and has a volume around 450 km³ (MacLeod & Sherrod, 1988). The volcanic rocks are predominantly basalt and basaltic andesite flows, pyroclastic deposits and cinder cones. The most recent major caldera-related eruptions resulting in significant silicic ash and pyroclastic deposits occurred approximately 300,000 and 80,000 years ago. A large-volume basaltic eruption occurred about 72,000 years ago, resulting in the widespread Bend Lavas which extend approximately 70 km to the north of the central caldera. About 6,000 years ago numerous basaltic eruptions occurred along a northwest fracture zone. The most recent eruption, a silicic obsidian flow and associated pumice fall vented from within the caldera, has been dated at 1,300 ybp (MacLeod and Sherrod, 1988).

The current summit caldera is likely the result of multiple caldera collapse events based on the apparent nested caldera walls. This is most readily seen on the Northwest and South portions of the caldera (Figure 2). Two voluminous ash-flow tuff units mapped on the flanks of Newberry Volcano have been proposed as evidence of two large caldera creating events. The tuff of Tepee Draw (Qtp on the map by MacLeod and Sherrod, 1995) has an age around 300,000 years (Donnelly-Nolan et al., 2004). The tuff of Paulina Creek Falls is the result of a second caldera forming eruption (Donnelly-Nolan et al., 2004). The tuff has not been directly dated but is believed to postdate the rhyolite of Paulina Peak (83±5 ka) and predate the Lava Top Butte basalts (75-80 ka) (Jensen et al.,

2009). Both of these tuffs have an estimated erupted volume of several 10s of km^3 (Linneman, 1990). The pattern of the nested caldera walls and lineaments from lidar analysis of the western flank support the idea of at least two major caldera forming events, with the oldest offset to the west of the modern day caldera (Figure 2). Using the estimated age of the volcano of 500,000 years, the apparent rate of caldera forming eruptions is ~200,000 years.

3. HEAT FLOW

Preliminary analysis of heat flow for 17 wells in and around the caldera show a bulls-eye pattern with the highest heat flow within the caldera and decreasing values with increasing distance (Figure 3). Values for the two intra-caldera wells (RDO-1 and USGS-NB2) are estimates of the conductive heat flow, as wells have significant hydrothermal activity making the values from Blackwell (1994) a convective heat flux. The general symmetry of the heat flow anomaly argues for a heat source centered roughly under the caldera. Because of the basic the radial symmetry of the heat flow pattern, we created a 2-D time-dependent heat flow model constrained with available gravity, tomography (Beachly et al., 2012), and magnetotulluric (MT) data with the goal of putting constrains on the size and magnitude of the heat source beneath the volcano. Gravity and MT data are from Northwest Geothermal internal reports, details of the surveys can be found in Waibel et al. (2012) and Waibel et al. (2013). Initial calculations show that the small young magma body used by Sammel et al. (1988) and imaged by Beachly et al. (2012) do not have a significant effect on the thermal regime at the location of the existing wells. Instead, the thermal regime is more likely the result of multiple intrusive events over the life of the volcano.



Figure 3: A. Map of measured heat flow in mW/m² with well locations. The circle with a cross is the approximate center of the caldera from which distances were calculated. The area within the shaded black region is the Newberry Volcano National Monument. B. Plot of heat flow vs distance from the center of the caldera. On both plots, red points are west flank wells and black crosses are other wells.

4. MODEL

Modeling was completed using a 2-D finite difference numerical model. Based on the repeated caldera forming eruptions at Newberry, it is likely that there are episodic intrusions. In the model, a single large intrusion is used to represent the cumulative thermal energy input of many smaller intrusions. Conductive heat transfer is a diffusive process; therefore, the present thermal regime is an average of all past intrusive activity. The simple approach used here shows the integrated response to the past intrusive activity at Newberry Volcano (Erkan et al., 2005). The exact intrusive history and geometry is unknown and is likely far too complex to be accurately resolved. Donnelly-Nolan et al. (1988, Figure 5) and Beachly et al. (2012, Figure 14) present schematic interpretations of the subsurface of Medicine Lake Volcano and Newberry Volcano that demonstrate the complex nature of past intrusive events.

4.1 Base Model

The available temperature data are not on a true radial cross section, are more scattered across on the western flank. A 2-D section of the west flank was created compositing the wellbore, and gravity, and topography data. In the caldera, an end point for modeling was chosen within the central pumice cone (Figure 3). From this point 20 km long 2-D slices of topography and gravity data were created with data spacing of 25 m along each profile. The slices rotate about the end point to cover the area from 230° to 310° in 0.5° increments. This swath encloses all of the well data on the western flank. The slices were averaged to generate a single topography and gravity profile that captures the general shape of the topography and the gravity anomaly. These profiles were loaded into the software GM-SYS[©] for gravity modeling. The gravity data were used to produce a 2 ³/₄-D model of the structure and lithology of the western flank to a depth of 10 km below sea level. Wellbore lithology data were used to generalize the shallow portions of the model, while 3-D MT and seismic tomography data were used to constrain the deeper part of the model. The

gravity model was then loaded into the software MATLAB^{$^{\odot}$} and converted into density and thermal conductivity grids (Figure 4). Measured thermal conductivity values were used when possible (Blackwell, 1994), otherwise lithologic averages were used (Birch and Clark, 1940). A constant value of 0.85 KJ/Kg K was used for heat capacity.



Figure 4: Cross sections with thermal conductivity and density values used in the model.

4.2 Temperature Data

The available wellbore temperature data were collected at a smaller spatial interval than the resolution of the model. To simplify the temperature data, the measured wellbore data were converted to isotherms. Isotherms from 100° C to 300° C at 50° C intervals were used. Due to shallow hydrologic effects, the upper 100 to 1000 m of all of the wells on the west flank are at or near isothermal. The base of the shallow groundwater flow is not constant across the volcano. The highly variable depth and temperature of the flow zone made modeling temperature up to the topographic surface impractical. Therefore, the 50° C isotherm was determined from well data. This isotherm produced a smoother boundary and was used to set the upper constant temperature boundary for the 2-D model. The base of the model has a constant conductive regional heat flow input of 90 mW/m² for all model iterations (Blackwell and Richards, 2004; Blackwell et al., 2011). The side boundaries of the model were reflective.

4.3 Model Results

Tomography and waveform modeling have been used to constrain different sized magma bodies centered under the caldera (Beachly et al., 2012). The tomography results are consistent with a large hot-fractured pluton or a magma chamber on the order of \sim 60 km³ in volume. Forward waveform modeling by Beachly et al. (2012) established a smaller, better constrained 1.6 to 8 km³ magma body at a depth of 3 to 6 km. The thermal effects of rectangular bodies consistent with these estimates were used in the 2-D model for this study. Clearly, a small body centered under the caldera cannot explain the observed temperature distribution. Solutions are dependent on the initial temperature of the magma and the duration of the simulation, however, all such bodies restricted to the current caldera *produce isotherms with a greater dip then are observed in the well data* (Figure 5).



Figure 5: Results of 2-D model for a magma body under the Newberry Caldera consistent with results from Beachly et al. (2012). Magma body, shown by black outlines, temperature is 1000 °C, model time is 500,000 years. Model temperatures fail to match the observed temperature field.

The long term thermal history of the volcano was modeled using the following thermal inputs. Two sets of models were tested for this study. The first set of models has the lower boundary of the magma body fixed at the base of the model similar to modeling completed by Erkan et al. (2005). For the second set of models the base of the magma body was varied along with the other dimensions. For both models a continuum from a single magma pulse to a constant magma body were calculated at 100,000 year intervals. For all model iterations the total model time was 500,000 years (the age of the volcano) and magma temperature was 1000°C. The intrusion temperature of 1000 °C was used to represent a 750° to 850 °C granitic intrusion with 150° to 250 °C additional heat to approximate latent heat (30 to 50 cal/gm). Volcanic ages suggest the large caldera forming eruptions happen approximately every ~200,000 years at Newberry (Donnelly-Nolan et al., 2004).

The first set of models has the lower boundary of the magma body fixed. A single instantaneous chamber intruded 500,000 years ago can fit the well data; however the original body would need to be on the order of 3600 km^3 , if the body is assumed to be a symmetric cylinder. For a continuously recharged body, the top of the body is at -5800 m elevation and has a radius of 7200 m with a volume of ~685 km³. For a body with periodic recharge every 200,000 years, the top of the body would be at -3700 m and have a radius of 8080 m (Figure 6). The intermediate model can reproduce the observed temperatures for a variety of magma bodies. The size of the body is dependent on the rate of reinjection.



Figure 6: Results of the fixed base models. A) The observed temperature isotherms and the wells used to generate them are shown. Solid black line at the top of the figure (at 2000 m) is the topographic surface. Boxes in the lower left are the boundaries of the various magma bodies that fit the observed temperatures. The background contour map is the final temperature field for the model with a 200,000 year recharge rate. B) Shows the modeled temperatures at each isotherm. Black lines are the temperature value of the isotherm and black dotted lines are ± 5 °C.

The second set of models has a variable lower boundary of the magma body. A single instantaneous chamber is similar to the fixed base model, where the best fitting body would have to be exceedingly large (\sim 4000 km³). For a continuously recharged body, the top of the body is at -5800 m elevation and has a radius of 7200 m with a volume of \sim 685 km³. For a body with periodic recharge every 200,000 years, the top of the body would be at -1768 m and have a radius of 9360 m (Figure 7). The intermediate model can reproduce the observed temperatures for a variety of magma bodies. The size of the body is dependent on the rate of reinjection.



Figure 7: Results of the free bottom models. A) The observed temperature isotherms and the wells used to generate them are shown. Solid black line at the top of the figure (at 2000 m) is the topographic surface. Boxes in the lower left are the boundaries of the various magma bodies that fit the observed temperatures. The background contour map is the final temperature field for the model with a 200,000 year recharge rate. B) Shows the modeled values at each isotherm. Black lines are the temperature value of the isotherm and black dotted lines are ± 5 °C.

5. ENERGY CALCUALTIONS

The amount of heat-in-place in an EGS system is an important parameter to constrain because it sets the limits on the production capacity of the entire system. For the following estimates a minimum reservoir temperature of 250°C was used, the upper threshold of the minimum temperatures suggested by Cladouhos et al. (2009). Additionally, the depth was limited to 3.5 km below the surface for drilling cost considerations. In order to evaluate the EGS potential from these models the methodology from Beardsmore et al. (2010) was used. The final temperature results of the free bottom model with 200,000 year reinjection rate model were used for this calculation (Figure 7). The total available heat (H, exajoules EJ) for the volume between 250°C and 3.5 km was calculated with the following equation:

$$H = \rho C_{p} V \left(T_{x} - T_{p} \right) * 10^{-18}$$
⁽¹⁾

Where ρ , C_p , V, T_X , and T_R are rock density (2700 kg/m3), heat capacity (850 J/kg °C), initial temperature (°C), and base temperature (°C), respectively. The base temperature is the theoretical temperature to which the reservoir can be reduced by fluid circulation. The recommendation from Beardsmore et al. (2010) of 80°C above the mean annual surface temperature was used. The heat-in-place was converted to MW_T and MW_e assuming a 30 year life cycle of heat extraction. The MW_e estimate includes a thermal cycle efficiency value (η_{th}).

$$\eta_{th} = 0.00052 \quad *T + 0.032 \tag{2}$$

Where *T* is the reservoir temperature. Equation 2 is from Beardsmore et al. (2010).

The entire volume was divided into 50°C intervals and the volume of each interval was calculated assuming radial symmetry. Energy values are tabulated for a series of concentric cylinders with 1 km thicknesses (Figure 8). Volumes listed in Figure 8A are the volume of the full cylinder. The percentage of each cylinder that is outside of the monument, and therefore accessible, was used to limit the final energy calculations.



Figure 8: A. Table with calculated volumes, heat-in-place, and MW potential for concentric cylinders. B. Cross of model results. Gray filled area is the region used for volumes and energy calculations. Area of each concentric cylinder shown as dotted lines. Bottom axis is distance from the center of the caldera in meters. C. Map view of Newberry Volcano showing location of each cylinder, the National Monument boundary, and topography.

6. CONCLUSIONS

Data from geothermal exploration shows that the subsurface beyond the limits of the caldera at Newberry Volcano has been effected by a magmatic heat source of some kind. Seismic techniques have been used to show evidence for a small modern day magma chamber centered under the caldera. The thermal effects of a chamber of this size, however, cannot explain the observed temperature distribution on the flanks of the volcano. In order to approximate the temperatures seen, larger and deeper sources are required. Seismic, gravity, and magnetotelluric techniques can only resolve the subsurface at the time of the survey, resulting in a view of the cumulative effects of magmatic processes over time. The temperature field on the other hand is disturbed long after the original source has crystalized. This anomaly can be used to make predictions about the past thermal regime and the types of sources that could produce the current field. There is still a lot of uncertainty in this kind of modeling due to unknown thermal properties, complex intrusive histories, and limited knowledge of the modern temperature field. Some credibility is added to thermal models when they are paired with known ages from surface exposures. At Newberry radiometric ages show that there have been at least two caldera forming eruptions over the presumed 500,000 year life time of the volcano occurring at ~200,000 year intervals. This is an important constraint on potential sources that can reproduce the observed temperatures. From this modeling, the current thermal regime at Newberry is likely the result of large (~350 km³) sill like intrusions of silicic magma under the caldera and the upper flanks of the volcano. Crisp (1984) suggests that the ratio of intrusive to extrusive volumes of continental setting is 10 to 1, which is consistent with the erupted volume estimates for Newberry. There is likely an associated increase in heat flow below the sill caused by deeper (mid-crust?) mafic melts; this was not included in the modeling because it is not expected to have a significant thermal effect on the observed temperatures.

The total energy potential of the modeled magma body is nearly 175 EJ within the entire volume and ~80 EJ outside of the nation monument above 250°C and shallower than 3.5 km. The total amount of energy used by the United States in 2012 has been estimated at ~100 EJ (EIA, 2014). It is not possible to produce and convert all of the heat at Newberry to useable energy at 100% efficiency. The energy estimates are more to show the scale of the energy potential of the site, without making too many assumptions about energy conversion efficiencies (Beardsmore, et al., 2010). Outside of the monument boundaries there is the potential for hundreds of megawatts of EGS electrical production at drill depths of 2-3.5 km. This makes Newberry a prime candidate for further EGS field testing.

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