HYDROTHERMAL STRUCTURE OF NEWBERRY VOLCANO,
CENTRAL CASCADE RANGE

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Abstract

Numerous studies of the geothermal and hydrothermal regime of Newberry Volcano with the prospects of geothermal development have yielded largely inconclusive results as to the precise nature of the internal structure of the volcano. The presence of a large igneous intrusion is widely accepted and an integral part of the hydrothermal structure and alteration of Newberry Volcano. Cathles et al. (1997) assert the tendency of hydrothermal systems to lack a consistent intensity throughout the existence of the hydrothermal regime. Instead, a hydrothermal regime is likely to fluctuate in intensity on two time-scales. One timescale put forth by Cathleen et al. (1997) establishes a general maximum duration of 800,000 years. Within this duration, the intensity fluctuation of a hydrothermal system will operate on a shorter time cycle, with periods of maximum intensity lasting no longer than 10,000 years old. Lake samples from Paulina Lake, located in Newberry caldera, yield ion concentrations which support the hypothesis that the Newberry Volcano hydrothermal regime is relatively young and less than 10,000 years old.
INTRODUCTION

Several studies have pursued the possible existence of a magma body within Newberry Volcano (Figure 1), specifically for geothermal development. Seismic tomography and the presence of fissure-vent deposits between areas of basaltic andesite commonly have silicic inclusions that have been interpreted as the result of basaltic magma rising along the edge of a silicic magma body (MacLeod and Sherrod, 1988; Zucca and Evans, 1992). Drilling within the caldera met high temperatures which support, but do not confirm, the presence of a magma body with the volcano (Sammel et al., 1988). More convincing results from (Sammel et al., 1988) suggest the abnormally high temperatures found at depths in excess of only 80 meters are more likely due to convection of the hydrothermal system within the volcano.

(Cathles et al., 1997) contend that, in general, hydrothermal regimes do not exhibit constant heat or fluid flow over their entire histories. The flux of hydrothermal convection results reflects two timelines of hydrothermal activity. The long-term timeline set forth by Cathles et al. (1997) constrains hydrothermal activity to a maximum of 800,000 years. However, within this 800,000 year time period, hydrothermal activity is not persistent and only continues for 10,000 year increments. This study, in conjunction with previous studies of Newberry Volcano, concludes that the current hydrothermal activity is acting within one of these 10,000 year time spans.

In the winter of 2004, I conducted fieldwork at Newberry for few days and collected field measurements and brought water samples to Carleton College to investigate the chemistry of the lake. This included anion and cation analysis using Dionex 600 Ion Chromatography.
Figure 1: Location map showing sampling sites, Newberry National Volcanic Monument.
**Regional Geology**

Newberry Volcano is located 60 km east of the main north-south crest of the Cascade Range Province and on the western edge of the High Lava Plains (Figure 2). The volcano covers an area of about 1200 km² and rises to an elevation of 2450 m. More than 400 cinder cones cover the flanks of the volcano, ranging from 600,000 to less than 10,000 y.B.P. Within Newberry Volcano lies Newberry Caldera which has developed over several stages of collapse to its current area of around 250 km² (MacLeod and Sammel, 1982). Tephra and ash-flow deposits, small domes, explosion breccias, and obsidian flows can be found within the caldera. Annual precipitation within the caldera is about 890 mm. After accounting for stream discharge, evapotranspiration, and evaporation losses from the lakes, it is estimated that about 180 mm remain for groundwater recharge (Sammel et al., 1988).

Newberry Volcano is unique in its location as it is associated with Cascade Range mountain-building as well as Basin and Range extension. This extension yields three major fault zones which converge at Newberry Volcano (Figure 2). The Miocene and Pliocene aged Brothers Fault, comprised of normal faults, extends from the northeast side of Newberry Volcano without offsetting Quaternary lava flows (MacLeod and Sherrod, 1988). The Sisters Fault Zone intersects the northwest flank of the volcano and offsets some of the earlier Newberry flows. The Walker Rim Fault is the third fault to converge at Newberry Volcano, and offsets early Newberry flows. It has been suggested that the Walker Rim Fault and the Sisters fault zone may be extensions of the same fault zone, partially buried under Newberry Volcano, because they both offset early Newberry flows.
Figure 2: Major fault zones near Newberry Volcano include the Sisters Fault Zone, Brothers Fault Zone, and the Walker Rim Fault Zone.
Unlike other Cascade Range volcanoes, Newberry Volcano is a stratocone volcano. This shape results from the proportion of low-viscosity material, and the smooth gravity field southeast of Newberry Volcano results from this uniform distribution of flows and volcanic sediments. The positive residual gravity anomaly below the volcano is interpreted to be due to a large intrusive complex but the nature of the intrusion remains undetermined and scientists are hesitant to classify the intrusion as a magma chamber (Gettings and Griscom, 1988; Williams and Finn, 1985).

Basin and Range tectonics have largely determined present day crustal properties; seismic refraction results indicate minimal thickness (7.4 km/s) of lower crustal rocks directly under Newberry Volcano in comparison to the east and west of the volcano (Catchings and Mooney, 1988). Catchings (1988) also note that the 37-km crustal thickness adjacent to Newberry Volcano is remarkable in light of the extension of the crust, especially in east-central Oregon. Continued crustal under-plating, an unusually thick Tertiary crust, or a voluminous intrusion, such as a magma chamber, are all suggested explanations for this crustal thickness (Catchings, 1988).

**Existing models**

The hypothetical hydrothermal system of Newberry Volcano is based on models which show that the convection cells are driven by buoyancy forces, recharge of meteoric water from above the cells and constricted by permeability. Although many models were created in an attempt to better understand the hydrothermal possibilities of Newberry Volcano, the preferred models have some common characteristics (Sammel et al., 1988). As a general rule, topographic relief of the water table greatly influences the flow rates and patterns of ground water, but hydrothermal systems have the added complexity
contributed from heat. Geothermal fluids are likely to move up and out from the magma chamber as heat from the chamber is transferred to the fluids and they become more buoyant. Flow rates at this depth (about 920 m in Newberry Volcano) are vastly determined by the temperature of the magma chamber. As the chamber cools or as the fluids travel away from the heat source, convection rates will decrease.

One model suggests that higher temperature gradients in lower portions of drill holes located on the flanks of Newberry Volcano are due to a cumulative effect of older intrusions instead of a magma chamber or even one dominant, larger intrusive body. These cumulative effects are maintained by the increased thermal gradients at deeper locations, which grow with permeability because an overlying isotherm also grows with permeability and insulates deeper portions of the hydrothermal system (Sammel et al., 1988).

Swanberg et al. (1988) have set forth several additional models. Each of these models includes a rain curtain that extends to the water table, a depth estimated to be about 490 meters (Figure 3). In contrast, the location of the water table is elusive and depth estimates are often guesses at best. Swanberg et al. (1988) define a rain curtain as a “zone of hydrologic disturbance where cool meteoric water percolates downward and spreads laterally, therefore masking the surface expression of geothermal activity.” A rain curtain can conceal subsurface geothermal activity to varying degrees, in some cases completely negating any surface expression of geothermal activity. In all of these models the volcanic pile becomes more conductive and the electrical conductivity varies more with increased hydrothermal alteration. These changes may also be due to higher temperatures or increased rock alteration (Swanberg et al., 1988) so each model may not
Figure 3: Hydrologic diagram including the camouflaging effects of a rain curtain on the surface expression of hydrothermal activity.
actively employ these last two features as parts of the mechanisms driving the hydrothermal system.

Drill holes contributing to the conductivity and gamma ray logs also yielded temperature logs which confirm the presence of an isothermal zone, a rain curtain, that extends about 1 km deep (Swanberg et al., 1988). Hydrothermal mineralogy indicates the hydrothermal regime in Newberry Volcano is supported by convection from a deep thermal source (Sammel et al., 1988). Permeability, temperature, and fluid composition all primarily control hydrothermal alteration, but modeling of Newberry hydrothermal activity has focused on convective heat flow. Models suggest that this heat flow only takes place in localized areas of high vertical permeability, such as intrusive conduits and ring fractures (Sammel et al., 1988), and it is unlikely that temperatures in the caldera hydrothermal system have significantly exceeded their present values for an extended time. Studies of Newberry hydrothermal fluids indicate that the most extensive alteration and leaching in the bottom of interflow breccias and vesicular basalt imply a phase-two fluid system consisting primarily of water and CO$_2$ (Sammel et al., 1988).

The first model has the rain curtain extending between 350 and 400 meters (Blackwell and Steele, 1987). The remaining isothermal interval, between about 400 meters and the water table (placed at about 490 meters), is left to intrahole fluid flow. This model is the most likely because it places the water table near 500 m, where there exists a documented change in lithology and permeability: between 150 and about 450 meters depth there are basaltic tuffs and sandstones to a rhyodacite sill of basal flow breccias between 450 and 710 m (Figure 4).
Figure 4: General lithostratigraphy of Newberry Volcano, adapted from Keith and Bargar, (1988).
The second model has meteoric water percolating below the water table to about 1005 meters, where the meteoric water exits the volcano via highly permeable horizons illustrated by the well logs. The rain curtain runs through a suite of rocks whose porosity and permeability differ greatly from the rocks below the extent of the rain curtain. Temperatures recorded during drilling did not exceed ambient temperatures above 500 m, (i.e. above the water table). This model is also favored by the fact that characteristics of the volcanic rocks are not consistent over the bottom of the isothermal section. Keith (1988) concludes that the permeability of the volcanic pile decreases dramatically at 500 meters where the lithology changes from pumiceous lithic tuff (470 to 501.4 m) to dense rhyodacite lava flow which is somewhat brecciated near the top of the section (around 502 m). The permeability change in the column offers a plausible location for the rain curtain.

A third model also extends the rain curtain to about 1005 meters (Swanberg et al., 1988). The interval between 1005 and about 1158 meters exhibits some fluid flow. The second and third models are supported by an inverse relationship between gamma ray and electrical conductivity logs below 945 meters (through the non-isothermal section). Laterally flowing geothermal fluids, which promote rock alteration, are probably the source for this inverse correlation. The lack of an inverse correlation in the isothermal section would represent a lack of migrating geothermal fluids (Swanberg et al., 1988).

Supporting the rain curtain hypotheses are the indications that meteoric water usually recharges geothermal systems (Sammel, 1983). Later findings of (Craig, 1966) show that the isotopic exchange between rock and water generally yields an $^{18}$O enrichment of the water. Furthermore, the oxygen isotopic compositions of water and
minerals aid the distinction between meteoric and magmatic fluids, and ultimately indicate the degree of the reaction between the rock and water (Taylor, 1968).

Comparisons of hydrothermal quartz, calcite, and siderite from core samples from Newberry Volcano show that the $^{18}$O values of these minerals decrease with increasing temperatures. Interpretations of these hydrothermal minerals indicate they precipitated in isotopic equilibrium with water currently present in the overlying lakes of Newberry Caldera (Carothers et al., 1987). Some of these $^{18}$O values probably result from precipitation in water produced by mixing various amounts of deep hydrothermal water with meteoric water recharged within the caldera. Major dissolved chemical constituents found in spring water at Newberry Volcano include bicarbonate, sulfate and sodium (Sammel et al., 1988). Although these results came directly from a hot spring, it is likely that this water source yields a combination of meteoric water and hydrothermal fluids (Sammel et al., 1988).

Despite the probable effects of the rain curtain, ionic concentrations of Paulina Lake and discharge of the hydrothermal system are unexpectedly high and support estimates that the Newberry hydrothermal regime is young, with current activity beginning less than 10,000 years ago.

**METHODS**

Water was sampled from 11 locations around Paulina Lake in mid-November, two of which are snow samples to use as a standard for meteoric water in the caldera (Figure 1). The snow samples were collected at the first and last sampling locations (labeled as ‘station 2’ and ‘station 11’), hence the data points 1 and 2, and 10 and 11 at the same locations (Figure 1). Weak fumarolic discharge in addition to thermal springs
and wells have been detected in Newberry caldera, (Figure 1) and the sampling locations were purposely chosen at a maximum distance from these discharges with the hypothesis that the water sampled would contain a minimum concentration of this discharge water. Although a minimum concentration of discharge water was expected, an average of the discharge was sought with the intention of obtaining results that may represent more than one spring.

At each location, a YSI-meter indicated the salinity, temperature, pH, and dissolved oxygen of the water electronically from a submerged probe. About 50 mL of water was collected from each of the 11 locations and was evaluated using an ion chromatograph for the presence and concentrations of 7 anions and 6 cations (Table 1).

**RESULTS**

**Temperature:**
The water temperatures of Paulina Lake varied at each station from about 2.6 °C to just under 5°C, with one sample near the dam measuring just below freezing (Table 1).

**Conductivity:**
The conductivity properties for the water sampled are relatively similar, with the exception of the water at station 1, which more closely resembles the snow samples than any of the lake water samples. The remaining lake water samples all read around 350 mS (Table 1). The specific conductance also showed little variation with the change in location, as values measured around 600 mS (Table 1).

**Dissolved Oxygen:**
The percent concentrations of dissolved oxygen and the dissolved oxygen saturation of each water sample were recorded and charted against location, but the values vary and no correlations are apparent with the sample site. The relative amounts of percent concentration and saturation are somewhat constant (Table 1).
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**Cations:**

Using an ion chromatograph, each sample was tested for six cations and seven anions. Of the six cations tested for, Li\(^+\), Na\(^+\), K\(^+\), Mg\(^{2+}\), and Ca\(^{2+}\) were detected (Table 1). None of the cations vary greatly in concentration between locations. Calcium varies the most between locations, ranging from just below 30 mg/l to just below 50 mg/l (excluding the snow sample, which did not register any calcium ions, Figure 5).

Although there are no apparent correlations between location and cation concentrations, there are correlations between some of the cation concentrations. When magnesium, potassium, and lithium concentrations are compared, their relative concentrations are quite constant (Figure 5).

**Anions:**

Of the seven anions tested for, Cl\(^-\), NO\(_2^{-}\), and SO\(_4^{2-}\) are present in Paulina Lake. Sulfate, nitrate, and chloride are all present in the water samples, and nitrate is in the snow samples (Figure 6, Table 1). Sulfate and chloride concentrations are relatively constant and only vary relative to each other at locations 2 and 4; at location 2 there is a spike in sulfate concentration, and at location 4 there is a sharp increase in chloride concentration.

**DISCUSSION**

Sammel et al. (1988) created a model of the Newberry hydrothermal regime based on the assumption that a small silicic magma body intruded 10,000 years ago into a thermal system generated by 100,000 years of conductive cooling of a larger underlying intrusional complex. The Newberry hydrothermal regime has been described as part of a young, transient system (Keith and Bargar, 1988), and tends toward places of high vertical permeability (intrusive conduits and ring fractures, (Sammel et al., 1988). These
Figure 5: Observed cation concentrations of Paulina Lake.
Figure 6: Observed anion concentrations of Paulina Lake.
observations support the hypothesis put forth by Cathles (1997) that most hydrothermal systems operate in short (less than 10,000 years) spurts of hydrothermal activity over an extended period of time, as long as 800,000 years. While the longer timescale of 800,000 years may be too long for the Newberry hydrothermal regime, the 10,000 year short-term timescale suggested by both (Sammel et al., 1988) and (Cathles et al., 1997) is not an unlikely one. Furthermore, geothermal activity at Newberry Volcano has not been greater than at present (Keith and Bargar, 1988), but this does not mean that the geothermal regime has operated at this magnitude for all of its history. The only sure conclusion is that the magnitude of the geothermal regime has been extensive enough to induce hydrothermal alteration in the lithology of Newberry Volcano.

Swanberg et al., (1988) suggest that the mafic, glass-rich basalts are more apt to alter to highly conductive clay minerals, such as smectite, which are more potassic and show a stronger gamma ray signature (from $^{40}$K). If this is the case, then these basalts deeper than 945 meters are a possible source for the relatively high potassium values found in Paulina Lake.

A bar graph of a selection of the average cation concentrations of the water and the snow samples gives an interesting and somewhat suggestive view of the data (Figure 7). The cation concentrations of the averaged water samples are twice as large as the snow samples. This feature has a few implications: Environmental processes such as evaporation and subsequent precipitation could act as a filtering system, concentrating the ions in the lake water while leaving precipitation water (snow, in this study) depleted in these cations, or the higher concentration of cations in the lake water could be coming from a hydrothermal source.
Figure 7: Average concentrations of Na+, K+, Mg+2, and Ca+2 observed in the lake water and snow samples.
A consideration of the role of the water cycle forces us to reconcile not only the much greater concentrations of cations in Paulina Lake relative to the snow samples, but also to acknowledge the anions detected in this study, which also exist in higher abundance in the lake water relative to the snow. It is interesting that the concentration of anions in the water relative to the snow is not nearly as great as that of the cations. Characteristics of precipitation over the Newberry area likely fall somewhere between what is seen in the Olympic Peninsula and in the Colorado region. The rainwaters of both of these regions have a similar total concentration of solutes, but the ionic ratios are different (Drever, 1997). Despite these differences, these regions give a general idea of what can be expected of ionic concentrations of precipitation over the Newberry area: The Olympic Peninsula and the Colorado regions both have significant anion and cation concentrations relative to a seawater standard (Drever, 1997), while Paulina Lake water does not have a significant anion concentration. Although climactic processes are surely a working component of Newberry hydrology, the unexpected anion concentration of Paulina Lake indicates that there are perhaps additional processes contributing to Newberry hydrology.

It is not at all unusual for climactic processes alone to be an inadequate explanation for groundwater or surface water hydrology and the hydrologic system of Newberry Volcano is not an exception. The fact that Newberry Volcano possesses a hydrothermal regime indicates that there is a prominent subsurface component to the Newberry hydrologic system. Once these hydrothermal fluids reach the surface, as they do in Newberry Caldera, the surface hydrology is inevitably altered. Surface and subsurface processes must be considered when trying to explain characteristics of the water. The hydrologic regime of Newberry Volcano is not an exception to this rule, but
rather an exemplar, as the hydrothermal aspect of Newberry hydrology is a dominant component and a likely explanation for the increased ionic composition of Paulina Lake relative to precipitation.

**CONCLUSION**

While it is difficult to determine what proportion of the hydrothermal fluids surface in the Newberry Caldera, further insight into the Newberry Volcano hydrothermal regime can be gained from compositional studies of the caldera lake water. Ion data collected from Paulina Lake, in corroboration with documented thermal intensity of the Newberry geothermal system, supports the hypothesis that hydrothermal regime of Newberry Volcano is a young, transient system less than 10,000 years old.

**ACKNOWLEDGMENTS**

I would first like to thank Bereket Haileab, my advisor, and the Geology Department at Carleton College for letting me use their facilities. I am also very grateful for the help of Don Moeller, without whom this project would have been impossibility. Lastly, I appreciate those of my peers who have a sense of humor that rivals my own.
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