

## Mafic Heat Sources for Snake River Plain Geothermal Systems

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### ABSTRACT

A large number of hydrothermal systems use energy from mafic magmatic systems. These include systems in the Reykjanes peninsula, Iceland; the Puna District in Hawaii, and Ocean Spreading Centers that represent the largest manifestation of geothermal energy on the planet. For several years, we have been investigating the potential for commercial high-temperature geothermal development in the Snake River Plain in Idaho, a very large basaltic province associated with the Yellowstone mantle plume. Although the province is characterized by high heat flow, we believe that the presence of high-temperature geothermal systems within reasonable drilling depths will require relatively shallow magmatic heat sources. Several studies now relate the geometry of mafic heat sources to the rates of magma supply versus tectonic extension. High extension with respect to magma supply results in feeder dikes and rapid ascent to the surface whereas high magma supply with respect to extension produces sills or plutons. We have proposed that the Graveyard Point Sill, located in western Idaho, is an analog for the buried mafic heat source of the Mountain Home geothermal system. On the basis of field mapping, we estimate that this high-level intrusive had an average thickness of 100 m and a total volume of about 3 km<sup>3</sup>. It is estimated that this body was emplaced at a temperature of 1200° C. We are presenting numerical models to evaluate the cooling history of this intrusive, and its potential as a heat source for the Mountain Home geothermal system.

### 1. INTRODUCTION

In one of the classic papers in geothermal geology, Smith and Shaw (1975) presented their model for igneous-related geothermal systems. They state:

“..basic rocks (basalts, andesite, and comparable magmas) are formed in the mantle and/or lower crust and rise to the surface through narrow pipes and fissures; the individual magma pulses are volumetrically small, and such systems contribute little stored heat to the upper crust until magma chambers begin to form at high levels. With the exception of the large oceanic volcanoes, basic magmas do not form large high-level storage chambers out of context with derivative silicic magmas..”

Since that paper was written, a number of geothermal systems have been identified in basaltic terrains (Wohlitz and Heiken, 1992). In addition, concepts of basaltic igneous systems have also evolved, and we have been influenced by concepts from the investigation of seafloor magmatism at mid-ocean ridge (MOR) spreading centers and their associated hydrothermal systems (Karson et al., 2015). We will discuss some basalt-related hydrothermal systems in more detail below. Karson et al. attribute magmatic processes to the interaction of magma budget, or rate of magma supply, and rate of extension. In general, fast spreading ridges have a high magma budget, and the voluminous eruption of basalt flows can obscure evidence of faulting. In contrast, slow spreading centers have more limited magma budgets, and their morphology reflects the dominance of tectonic processes, similar to continental rift zones. Plume-related volcanism that is found in the Snake River Plain (SRP) and Hawaii is characterized by an extreme magma budget.

Our interest in this topic was initiated by our drilling in the Snake River Plain (SRP) that identified an active geothermal system, with a measured temperature of about 150° C, at Mountain Home Air Force Base (Nielson et al., 2012). Although no intrusive heat sources were identified in that drilling, it was clear from the presence of hydrothermal breccias that the system originally had temperatures of at least 340° C. This was subsequently confirmed by fluid inclusion analysis (Atkinson et al., (2017). An initial conceptual model (Nielson and Shervais, 2014) proposed that a layered mafic intrusion was the heat source, and that the Graveyard Point sill (White, 2007) would serve as an exposed analog. Our interest in characterizing the heat source was further encouraged by the US Department of Energy’s Play Fairway approach where conceptual models play a key role in geothermal play risk analysis (Nielson et al., 2015).

This paper will summarize features of several important geothermal systems that derive energy from mafic magmatic systems. In these discussions, we will investigate magma budgets and potential magmatic heat sources. We will then test our hypothesis that the Graveyard Point sill is a viable analog for a heat source at the Mountain Home geothermal system.

## 2. Mid-Ocean Ridge

Ocean Spreading Centers represent the largest source of geothermal energy on the planet. They also are the principal centers for basaltic volcanism. Although poorly exposed on land, the MOR systems have been extensively studied by geophysical methods as well as ocean drilling. The MOR spreading centers have been categorized (Karson et al., 2015) as ranging from Ultraslow (<20 mm/yr) to Superfast (>120 mm/yr). The corresponding magma budget is high for the faster and low for the slower spreading centers. This interplay is reflected in the morphology where young lava flows dominate at the fast spreading centers whereas tectonic features define the morphology of slower centers. High-temperature hydrothermal vents (black smokers) are much more common in the axial zones of fast-spreading ridges and in axial valleys of intermediate rate spreading centers and less common in slower spreading centers.

A significant feature of the magmatic architecture of spreading centers is the presence of sheeted dike complexes that can make up to 90% of the rock. These typically occur in the lower part of the upper crust and are shallower in centers with higher spreading rates. From a thermal standpoint, a dike complex would act like a magma chamber.

Axial magma chambers (AMC) have been identified by geophysical surveys (Canales et al. 2006) at a number of MOR spreading centers. These bodies are typically 1 to 2 km wide, 50 to 100 m thick and located at depths of 1 to 2 km. Their geometry tends to correlate well with hydrothermal vents. AMC's are nearly continuous beneath fast spreading centers whereas they are rare beneath slow spreading centers. AMC's tend to be shallower in faster spreading centers, similar to sheeted dike complexes.

## 3. Iceland

In Iceland, the classic location for a high-temperature hydrothermal system with a basaltic heat source is on the Reykjanes peninsula where the Mid-Atlantic Ridge extends to land. Here a scientific hole has recently been drilled to a depth of 4659 m and temperatures of at least 427° C (www.iddp.is; Friedleiffson and Richter, 2010; Friedleiffson et al., 2014). The surface of the Reykjanes peninsula is characterized by northeast trending faults and associated eruptive centers. The upper 1 km contains hyaloclastic rocks and marine sediments, but below that the rocks are mostly pillow basalts and intrusive rocks. This is a slow spreading center with a rate of extension of 21.9 mm/yr (Sigmundsson and Saemundsson, 2008).

## 4. Hawaii

The Hawaiian Islands are an example of magmatism related to a mantle plume. The Puna geothermal field is located in the Kilauea Lower East Rift Zone on the island of Hawaii. The system was discovered in 1976 with the drilling of the HGP-A well that encountered a maximum temperature of 356° C. The magmatic plumbing system of the East Rift Zone has been studied for many years. Magma is generated in the upper mantle and rises to form an upper reservoir system at a depth of 2 to 6 km (Duffield et al., 1982). Most of the exposed intrusive rocks are dikes, but the Uwekahana laccolith is exposed in the wall of the Kilauea caldera and is 300 m long and has a maximum thickness of 30 m (Casadevall and Dzuizin, 1987). In older volcanoes where erosion has exposed more of the magmatic plumbing system, dike complexes are found that can make up 50-70% of the rock (Walker, 1987). Teplow *et al.* (1994) document a dacite melt intersected by injection well KS-13 at depth of 2480 to 2488 m in the Puna field. Although there are no exposed flows of dacitic composition, they speculate that this body is differentiated from basalt and has a temperature of about 1050° C. On the basis of thermal arguments, these authors suggest a body with a minimum circular radius of 1 km and a thickness of at least 100 m.

Active extension and dike intrusion provides a continuous source of basaltic magma. The Hawaiian Volcano Observatory (HVO) web site comments on the magma budget of Kilauea, and based on ground deformation as well as surface observations, it is estimated that 600,000 m<sup>3</sup>/day is supplied to the volcano with about half of that being erupted and the remaining amount is stored within the volcano.

## 5. Snake River Plain

The Snake River Plain (SRP) volcanic province is part of the largest heat flow anomaly in the US (Blackwell and Richards, 2004). It is subdivided into eastern (ESRP) and western (WSRP) segments that have different structural orientations and geologic histories. The ESRP represents the track of the Yellowstone hotspot – a deep-seated mantle plume that has remained relatively fixed in space as the North American plate moved to the southwest (Smith et al., 2009). As the plate moved over the plume, a number of large silicic caldera complexes formed through melting of continental crust. As the magma chambers beneath these calderas solidified and were able to sustain brittle fracturing, basalts were able to reach the surface and form the extensive lava flows that are seen today. Seismic studies have defined a zone of high velocity in the middle crust inferred to represent a mid-crustal sill complex (Smith et al 2009); chemical and isotopic variations in basalts show that this sill complex comprises a series of layered magma chambers, which evolved by fractional crystallization and magma recharge, and fed the surface eruptions (Shervais et al, 2006; Jean et al., 2014).

Resurgent basalt volcanism (900-200 ka or less) formed long after the plume passed, driven by back-flow of plume material to the West. This resurgent basalt volcanism is also plume-derived and postulated to be associated with delamination of subcontinental lithospheric mantle (Shervais and Vetter, 2009). Throughout much of the SRP, large volume basalt flows have obscured faulting that is largely responsible for their feeder systems.

Payne et al. (2012) show that the SRP presently has a rate of extension, and that it is structurally separate from the adjacent Basin and Range (B&R) province. Young faulting consistent with B&R extension is present within the SRP, but it is comparatively minor. We have analyzed surface structural trends in the context of reservoir permeability. However, there are buried structures identified by geophysics, and the alignment of basalt eruptive centers is probably related to the development of the SRP (Shervais et al., 2016).

## 6. Thermal Modeling

The Graveyard Point sill (White, 2007) is exposed on the western side of the SRP and has been proposed as the analog for the heat source for the geothermal system intersected in MH-2 (Nielson and Shervais, 2014). Exposures of the sill have been cut by faults and eroded. Mapping suggests that the sill has an average thickness of 100 m; although the upper contact has been eroded through most of its outcrop area. Currently, exposures cover an area of 5 km x 3 km for a volume of 1.5 km<sup>3</sup>. We estimate that the original thickness was 200 m and lateral dimensions were 5 km x 3 km for an original volume of 3.0 km<sup>3</sup>.

A simulation of the sill hydrothermal cooling history was performed to determine whether the maximum temperatures deduced from fluid inclusions in the Mountain Home core could develop through emplacement of the sill at a depth of about 2 km and how long the thermal pulse lasts after emplacement. There is also evidence of boiling from two-phase fluid inclusions at temperatures of 340-350 °C that should be observable in the simulations.

Simulations of the hydrothermal system and sill cooling history were performed using the coupled thermal-hydrological-chemical simulator TOUGHREACT V3.3 (Sonnenthal et al., 2014; Xu et al., 2011). TOUGHREACT V3.3 considers multiphase fluid and heat flow with temperature-dependent heat capacities and thermal conductivities, along with kinetic and equilibrium mineral-water-gas reactions, aqueous and gaseous species diffusion and advection. Although it does not have a supercritical water equation of state module (or magma crystallization) it can simulate conductive heat transport in grid blocks that are initially, or attain, magmatic and/or supercritical temperatures for water. Therefore the surrounding hydrothermal system can be adequately modeled with a simplified cooling model for the intrusive body. All simulations were performed assuming fully water-saturated conditions using the EOS1 (pure water) equation-of-state module.

An idealized 2-D dual permeability numerical model of the sill, host rocks and associated fault is shown in Figure 1. The dual-permeability model considers global matrix-matrix flow, global fracture-fracture flow, and local fracture-matrix flow. That includes heat conduction and advection, as well as fluid (water and/or steam). The fault is given anisotropic permeability with a fracture density twice that in the surrounding host rock. The matrix permeability in the fault is also increased to reflect breccia zones. The local fracture-matrix interface area is given by the number of fractures in each direction times the fracture-matrix area of each fracture locally. Here it is assumed there are 3 sets of equal spacing in X, Y, and Z.

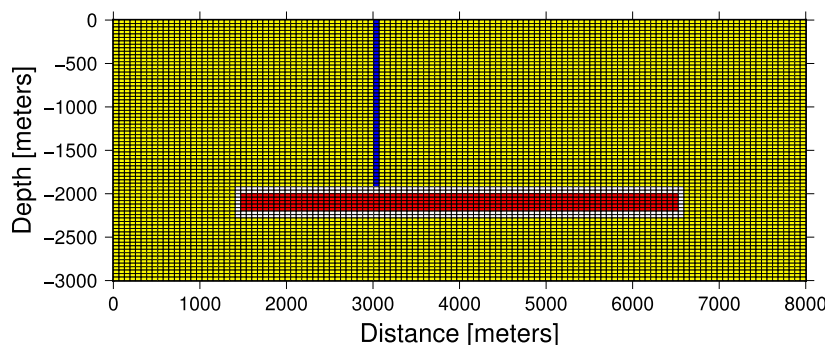


Figure 1. 2-D Numerical mesh showing sill (red), host basalt (yellow), fault (blue), and contact zone (white).

Estimated hydrological, thermal, and transport properties are given in Table 1.

Table 1. Hydrological, Thermal, and Transport Properties

Parameter	Basalt Fracture	Basalt Matrix	Fault Fracture	Fault Matrix	Sill	Contact Zone
$\phi$	0.01	0.10	0.02	0.15	0.0	0.0
$k_x$ ( $m^2$ )	$1.0 \times 10^{-15}$	$1.0 \times 10^{-17}$	$6.24 \times 10^{-9}$	$1.0 \times 10^{-15}$	0.0	0.0
$k_z$ ( $m^2$ )	$1.0 \times 10^{-15}$	$1.0 \times 10^{-17}$	$10^{-15}$	$1.0 \times 10^{-15}$	0.0	0.0
Fracture Spacing (m)	10 (3 sets)	-	5 (3 sets)	-	-	-
$k_{thermal}$ (constant)	$4.841 \times 10^{-2}$	4.841	$4.841 \times 10^{-2}$	4.841	4.841	4.841
$Cp_{grain}$ (J/kg/K)	1522.3	1522.3	1522.3	1522.3	1522.3	1522.3
$\alpha$ (1/T(K))	$3.0 \times 10^{-5}$	$3.0 \times 10^{-5}$	$3.0 \times 10^{-5}$	$3.0 \times 10^{-5}$	0.0	$3.0 \times 10^{-5}$
$\beta$ (1/Pa)	$3.0 \times 10^{-9}$	$3.0 \times 10^{-9}$	$3.0 \times 10^{-9}$	$3.0 \times 10^{-9}$	0.0	$3.0 \times 10^{-9}$
$\tau$	0.008	0.2	0.008	1.0	1.0	1.0

A steady-state thermal-hydrological simulation (1 Ma) was first performed with a temperature gradient set to give about 200 °C at 2 km depth. The magma temperature was set to 1200 °C, based on temperatures calculated from Graveyard Point chilled margin composition in the range of 1185 – 1205 °C (White, 2007). It was assumed there was a fault present prior to sill intrusion, which acts as upward conduit for fluid flow (Figure 2).

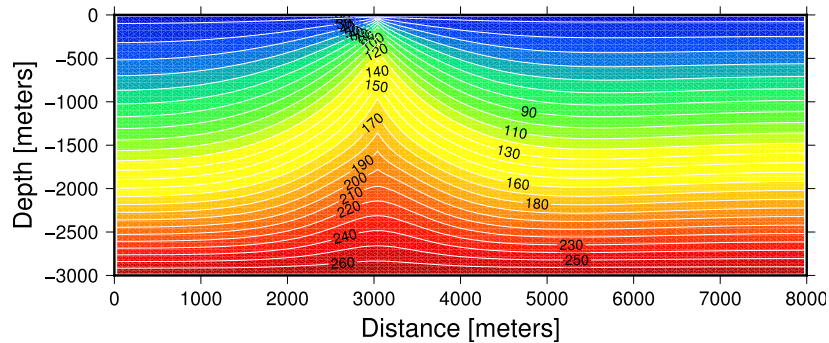


Figure 3. Steady-state (1 Ma) temperature field prior to sill emplacement, and post-faulting, using constant and uniform thermal properties.

Simulated temperatures in fractures for the first 1000 years after sill emplacement are shown in Figure 4. There is a strong development of upward flow in the fault, with predominantly conductive cooling elsewhere. The lower boundary was treated as fixed temperature and no-flow. The side boundaries are no-flux for heat and mass. The top boundary is fixed temperature and pressure (atmospheric) and open to fluid flow.

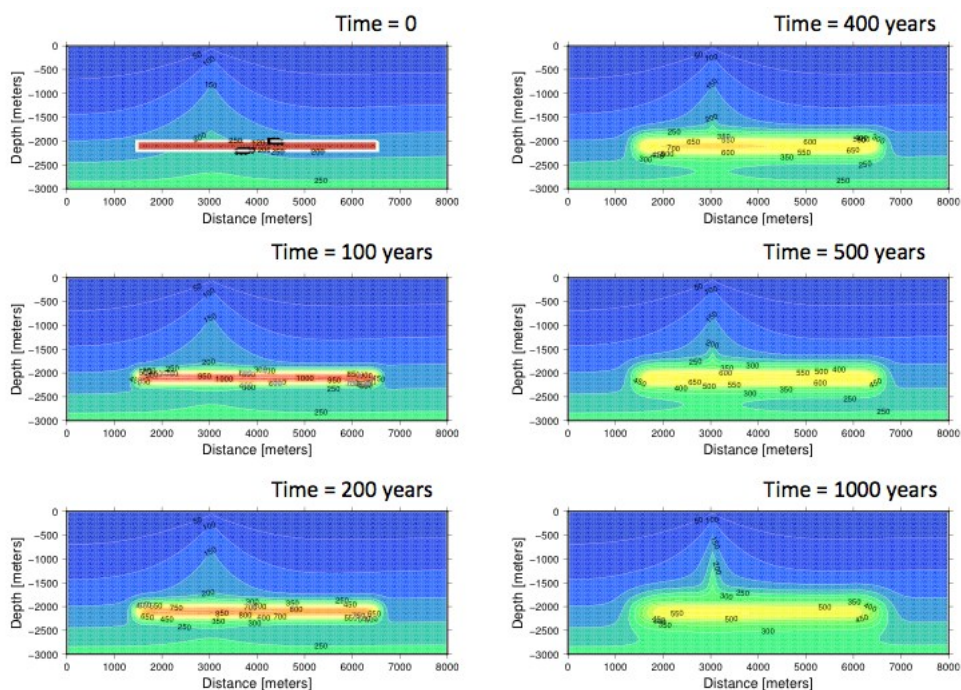


Figure 4. Contoured temperatures in fractures from the time of sill emplacement to 1000 years.

The time evolution of temperatures as a function of depth in the fault is shown in Figure 5 (left). There is a clear near isothermal boiling zone (heat pipe) just above the contact zone extending over a depth of nearly 200 meters. The temperature evolution at a depth of 1740 m (approximate depth of observed 2-phase high-temperature fluid inclusions) is shown in Figure 5 (right). The maximum temperature reached about 341 °C at 1740 m depth after about 900 years post-emplacement. This temperature is within 10 °C of the maximum fluid inclusion temperatures measured at about the same depth (1748 m in the well).

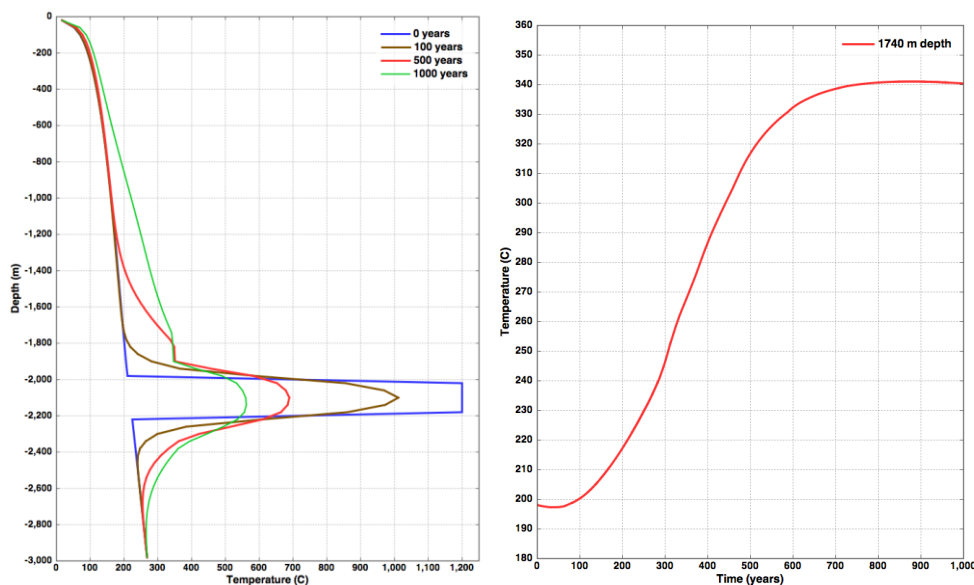


Figure 5. Temperature in the fault zone crossing the sill vs depth over time (left). Temperature evolution in fault (fracture continuum) up to 1000 years at 1740 m depth (right).

Another simulation with modified temperature-dependent heat capacities and revised thermal conductivities was run to 20,000 years to evaluate the length of time such an intrusive body can provide significant heat to drive a hydrothermal system (Figures 6 and 7). The maximum temperature in this simulation at 1740 m only reached 323 °C, owing to more vigorous heat loss via convection (see double temperature hump). Still though, temperatures were significantly elevated over the initial value after 20,000 years.

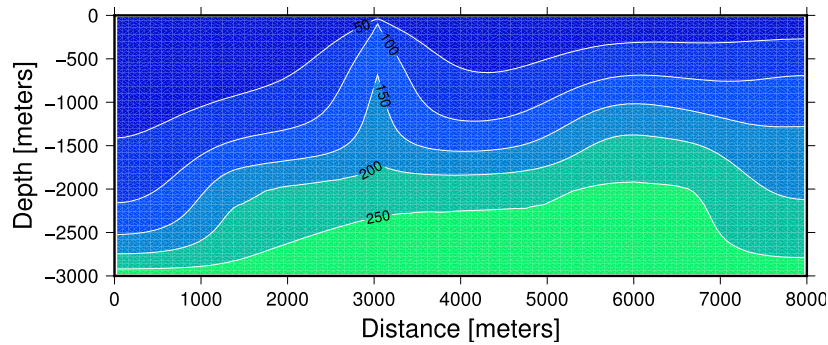


Figure 6. Temperature distribution 20,000 years after sill intrusion showing strong thermal perturbation and upward flow in fault. Simulation employed temperature-dependent and revised thermal properties, which led to enhanced convective flow.

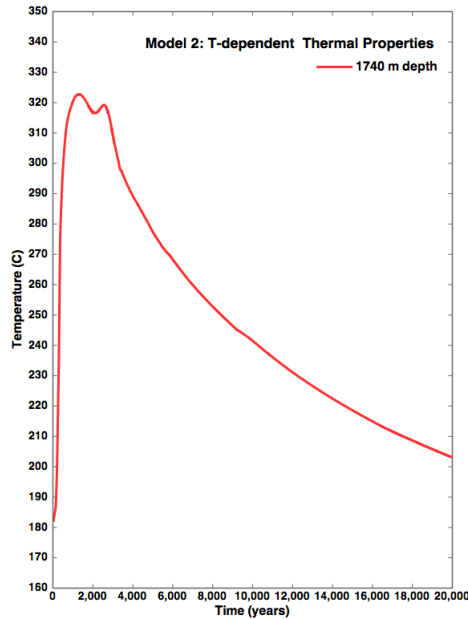


Figure 7. Temperature evolution in fault (fracture continuum) up to 20,000 years at 1740 m depth. Simulation used temperature-dependent and revised thermal properties.

### 7. Conclusions

Explored geothermal systems in basaltic terrains are associated with areas having a high magma budget. There have been limited observations of the heat sources for these systems, but we believe that they are either sheeted dike complexes or sills. Although there were no intrusive rocks encountered in the drilling of the MH-2 hole at Mountain Home Air Force Base in Idaho, petrographic evidence shows that the fluid entry is hosted by a hydrothermal breccia that was formed close to a magmatic heat source. We have proposed that the Graveyard Point sill is an analog for this heat source.

Simulations using TOUGHREACT V3.3 and estimated size, emplacement temperature and depth of emplacement of the Graveyard Point sill demonstrate that our hypothesis concerning the heat source is valid. We believe that the simulations can be refined with additional data, particularly dating of the hydrothermal brecciation event.

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