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ABSTRACT

Basin & Range (B&R) geothermal systems raise vexing heat and mass balance questions. In systems without magmatic heat sources, observed temperatures of >200 – 280°C at depths of a few km require deep circulation of meteoric fluids in regions with steep geothermal gradients, apparently along structurally localized conduits. Previous heat and mass balance modeling studies (Moulding and Brikowski, GRC 2014) matched fluid temperatures and flow rates seen at the Dixie Valley geothermal field via a steeply plunging conduit (representative of a fault stepover or intersection) within a very low uniform permeability host rock (< 2 x 10^{-17} m²), with regional crustal heat flow of 85 mWm². These results also indicate that Basin and Range geothermal systems can be spatially isolated along strike of normal faults, allowing for the possibility of numerous discrete systems in geothermally active areas.

Current modeling efforts address specific rock properties that may be important factors for the development of the non-magmatic B&R geothermal systems and may help predict geothermal favorability for other sites. These properties include (1) low permeability of host rock materials which appears critical for the development of these systems (2) insulating properties of basin sediments and volcanics which may play an important role in some of the hotter systems (i.e. Dixie Valley), (3) anisotropic (layered) permeability in fluid source regions (basin sediments) which can enhance the supply of fluids for these systems, and (4) narrowing of the conduit at the surface discharge zone to limit penetration of cold surface fluids into the geothermal system, which is more consistent with observations and could explain why so many of these systems have been blind discoveries.

Introduction

Initial 3-dimensional polygonal heat and mass balance models for Dixie Valley-type settings emphasized geometric effects of a limited-cross-section upflow conduit (Moulding and Brikowski, 2014). These models investigated a 40 x 26 x 12 km polygonal model (Figure 1) using TOUGH2-eos1sc (Pruess et al., 1999; Brikowski, 2001). The models successfully reproduced observed temperatures and flow rates seen at Dixie Valley (285°C at 3km depth and flow rates of ~5 L/s, pre-production, Allis et al., 1999) with remarkably narrow vertical flow conduits under a variety of permeability distributions in host and conduit.

Figure 1. View of 40 x 26 x 12 km polygonal mesh, 7740 total cells. Dipping plane (green) represents (normal) fault domain, conduit domain represented by dense (yellow) cells along center of fault plane.
Results from these models can be summarized by two generalized end members shown in Figure 2. These models show the thermal evolution of a point at 3 km depth in a moderate permeability “conduit” (permeability, $k = 10^{-13} \text{m}^2$) confined to a steeply-dipping normal fault – simulating a rupture in a dilational zone as a result of a seismic event or other crustal movement. One end member has a “wide” (1200m x 200m) conduit (high hydraulic conductance), with the maximum temperature and flow rate occurring within several hundred years. The other in a “narrow” (200m x 200m) conduit with maximum temperatures and flow rates occurring within tens of thousands of years.

The volume of rock affected by heat flow into these systems also appears to be limited. Both conduit models primarily extract heat from an elongate zone within the fault plane extending no more than 10 km along strike (Fig.3). These results suggest that several concurrent but discrete systems can exist in geothermally active areas (consistent with geochemical observations at Dixie Valley, Blackwell-Smith-2007).

While these geometrically-based results resolve several conundrums arising from geothermal observations in the Basin and Range, their sensitivity to assumed rock properties requires further investigation. Issues tested here include the potential impacts of continuously variable permeability vs. depth (low constant value was assumed in previous models), insulating (low thermal conductivity) aspects of accumulated basin sediments and volcanics, anisotropic hydraulic conductivity in shallow fluid source beds, and limiting penetration of cool surface waters by narrowing the discharge zone from the conduit at the surface.

Crustal scale permeability-depth curves have been proposed by Ingebritsen and Manning (2010). Our previous models assumed a uniform low permeability of host rocks ($< 2 \times 10^{-17} \text{m}^2$) because at higher permeability horizontal fluid flow cools the overall domain.
so geothermal systems cannot develop. But geologically, a uniform, low permeable host rock may be oversimplified - some variation of permeability in this domain inevitably exists. An average permeability of < 2 x 10^{-17} \text{ m}^2 may be geologically accurate but needs further testing. The effect of varying permeability according to the Ingebritsen-Manning curve, as well as a few other depth variable permeability domains is discussed in the current modelling results section below.

Thermal characteristics of basin materials can also be quite influential in these model geothermal systems. These materials include “playa” sediments – sands, siltstones and clays, and some volcanic materials – andesites and basalts - with relatively low thermal conductivities acting as insulators for the geothermal system. These basin materials are bounded by host rock materials with higher thermally conductive granites and granodiorites allowing “refraction” of heat flow from areas of low conductivity (basin fill) to the adjacent basement rocks - (Thakur et al., 2012). The role of variable thicknesses of this thermally insulating basin fill is explored below.

Hydraulic parameters of playa sediments (anisotropic hydraulic conductivity) most likely limit vertical flow of hot fluids in the basin, but allow horizontal flow to supply fluids to the conduit. Isotopic studies indicate that most of the waters in the Dixie Valley geothermal system are Pleistocene in origin, and, based on age constraints, most likely from basin sediments (Nimz et al., 1999). Such anisotropic permeability is typical of sediments, particularly on the most downthrown side of alluvial basins as in the Dixie Valley geothermal system.

Finally, in previous “wide” conduit models (Figs. 2a, c), there is significant downflow of cool surface fluid into the conduit, inconsistent with field observations. These fluids “cool” the modelled geothermal system after several hundred years (fig. 2e). However, several geologic processes may act to seal the top of the conduit (such as hydrothermal precipitation of calcite or silica, or deposition of clays, etc.), limiting the downflow of these fluids. The effect of a surface “seal” is modeled by narrowing the top of the conduit to a smaller (200 x 200 m) discharge zone to minimize this downflow.

**Current Model Results**

**Varying Host Rock Permeability With Depth**

Models were run, varying the permeability of host rock with depth. Ingebritsen and Manning (2010) estimate average permeability of rock (k, \text{ m}^2) decreasing with depth (z, \text{ km}) based on regional thermal and mineralogic data in tectonically active areas according to:

\[
\log k = -14.32 \log z
\]  

(1)

Permeabilities vs. depth calculated from this estimate were assigned to each cell within the TOUGH2 polygonal mesh (average permeability \log[-16.1], an order of magnitude higher than assumed in the uniform permeability case). As is done in all of the models, the initial background thermal conditions are created by running a model with set permeabilities for the host rock and a “closed” conduit (i.e. conduit k = fault domain k) to thermal equilibrium. Given that elevated permeability, when a conduit is opened in the equilibrated model using these estimated permeabilities, the thermal state is not hot enough to produce the fluid temperatures seen in B&R geothermal systems.

Additional tests were run varying the permeability (logarithmically) with depth of the host rock from k = 10^{-15} \text{ m}^2 to k = 10^{-16} \text{ m}^2, and from k = 10^{-16} \text{ m}^2 to k = 10^{-18} \text{ m}^2. Only the models with permeabilities between k = 10^{-16} \text{ m}^2 to k = 10^{-18} \text{ m}^2 (average \log[-17]) had background thermal conditions hot enough to produce B&R thermal anomalies. The results of these models are not presented here, but confirm the general observation that very low permeability host rocks are required to create the modelled geothermal anomalies, regardless of how that permeability is distributed.

**Thermal Conductivity and Anisotropic Permeability of Basin Materials**

Previous models used a 4 km thick basin fill sequence, 1.25 \text{ Wm}^{-1}\text{C}^{-1} thermal conductivity, background crustal heat flow of 85 \text{ mWm}^{-2}, and an isotropic permeability of 10^{-17} \text{ m}^2. The host rock thermal conductivity = 2.5 \text{ Wm}^{-1}\text{C}^{-1}. For this study a second model was created with a playa thickness of 1.6 km (figure 4).

Basin materials include “playa” sediments – sands, siltstones and clays - with thermal conductivities ranging from 0.8 to 2.1 \text{ Wm}^{-1}\text{C}^{-1} (Eppelbaum et al., 2014), and some volcanic materials - andesites and basalts – with thermal conductivities ranging from 1.7 to 2.26 \text{ Wm}^{-1}\text{C}^{-1} (Eppelbaum et al., 2014). Host rock materials consist of...
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some granites and granodiorites with thermal conductivities of 2.6 – 3.1 Wm⁻¹°C⁻¹, along with some volcanics, Jurassic gabbros, and Triassic sedimentary rocks with variable thermal conductivities. This complex variability makes it difficult to definitively assign an average thermal conductivity for basin fill and host rock materials, so for simplicity, the average values of 1.25 Wm⁻¹°C⁻¹ and 2.5 Wm⁻¹°C⁻¹ were used again for these models.

Three model configurations were tested: (1) a uniform thermal conductivity – assigning 2.5 Wm⁻¹°C⁻¹ to both basin and host rock materials, (2) a 1.6 km thick, 1.25 Wm⁻¹°C⁻¹ thermal conductivity basin model, and (3) a 4 km thick, 1.25 Wm⁻¹°C⁻¹ thermal conductivity basin model. Thermal equilibrium background models show the insulating effects of these various configurations (figure 5). The effect of this refraction on the development of geothermal systems was tested by using a uniform thermal conductivity for both the basement and basin rocks (2.5 Wm⁻¹°C⁻¹).

When a wide conduit is opened in the uniform thermal conductivity model (2.5 Wm⁻¹°C⁻¹ basin and host rock) a geothermal system develops that does not produce the maximum temperatures seen at Dixie Valley (238°C vs. 280°C at 3 km depth), but are still in the range of the some B&R geothermal systems (figure 6). The maximum temperature reached (at 3 km depth) when a conduit is opened in the 1.6 km deep, 1.25 Wm⁻¹°C⁻¹ background model is less than that for the 4 km models (273°C vs 296°C), but still within the range seen at Dixie Valley.

**Supply of Fluids From Anisotropic of Basin Materials**

The thermal evolution B&R systems are a result of both the thermal equilibrium background state, and the available sources of fluids for these systems. Hydraulic anisotropy of basin materials (primarily playa sediments) may both be a significant source of fluids and an insulating factor in these systems (limiting advective heat transport with lower vertical permeability). Three anisotropic basin permeability models: [1] 10⁻¹⁵m²(h) x 10⁻¹⁷m²(v), [2] 10⁻¹⁵m²(h) x 10⁻¹⁷m²(v), [3] 10⁻¹⁶m²(h) x 10⁻¹⁷m²(v); and two isotropic basin permeability models: [1] 10⁻¹⁶m², and [2] 10⁻¹⁷m² were tested, using the wide conduit - 1.6 km basin configuration (fig. 7).

These models indicate that anisotropy of 10⁻¹⁵m²(h) x 10⁻¹⁷m²(v) (horizontal to vertical ratio: 100:1) can increase the net flow from the conduit by a few L/s (20-40%) over isotropic systems, and may have some thermally insulating properties. Vertical permeability < 10⁻¹⁶m² appears necessary to direct fluids from the playa into the conduit.

![Figure 5](image1.png)

**Figure 5.** Cross section (perpendicular to range bounding fault) for thermal equilibrium background models (before conduit rupture) 3 thermal conductivity model configurations tested. Playa permeability: anisotropic, 10⁻¹⁵m²(h) x 10⁻¹⁷m²(v). Host rock thermal conductivity: 2.5 Wm⁻¹°C⁻¹.

![Figure 6](image2.png)

**Figure 6.** Thermal evolution of conduit at 3 km depth in wide (1100m x 200m) conduit opened in background models with high and low thermally conductive basin fill sediments (and anisotropic permeability of 10⁻¹⁵m²(h) x 10⁻¹⁷m²(v)).

![Figure 7](image3.png)

**Figure 7.** Thermal evolution of conduit at 3 km depth, and net flow from models with variable anisotropic and isotropic playa permeability. Recall current conditions at Dixie Valley at this depth are 250°C and 5 L/s, and maximum temperatures are 285°C.
**Limiting Surface Downflow into Conduit**

In wide conduit models presented so far, downflow of fluids into the conduit supply a significant portion of the fluids for the geothermal systems (figure 8 shows the total upflow, total downflow and net flow for several models). As noted above, this downflow is not observed at Dixie Valley, and isotopic data indicate that most of the fluids in these systems are Pleistocene in origin – from valley materials.

A series of models were therefore run to limit the supply of surface fluids by narrowing the top of the conduit (discharge zone) from 1100 x 200 m² to 200 x 200 m², (fig. 8) by reducing the permeability of these cells. This would simulate some type of surface “sealing” from precipitation of cementing materials, impermeable fault gouge, or clay minerals. In these “sealed” models, the surface downflow is negligible (< 1 L/s), and combined with anisotropic playa materials – can easily supply the estimated volume of fluids (pre-production) produced by these systems (Allis et al., 1999).

**Discussion and Conclusions**

Development of the geothermal systems in these models is an interplay between background equilibrium geothermal gradient, the opening of a deeply-penetrating conduit, and the supply of fluids into that conduit which acts as a “heat exchanger” to “mine” heat at depth. The factors influencing the background thermal equilibrium needed for these systems are the high regional crustal heat flow (85 mWm⁻²), low permeability of “host” rock (< 2 x 10⁻¹⁷m² to avoid background advective dissipation of the heat), and low thermal conductivity of at least some units in the basin to help insulate the system. We have assumed a “wide” (1100 x 200 m) conduit model going to a depth of 7.5 km for models presented here, but the depth of these conduits may differ in actual geothermal systems. Finally, the supply of fluids into the conduit is likely influenced by the anisotropy of the playa sediments, and some mechanism of limiting the supply of surface fluids entering the conduit.

Permeability model tests strongly support the concept of a low permeability host rock as a pre-condition for these systems to develop. Permeabilities of 10⁻¹⁷m², although low, are not out of range for unfractured granites or other crystalline rocks that are likely to be a large component of the host rock at Dixie Valley.

The insulating properties of low thermal conductivity basin materials on the background equilibrium thermal gradient significantly influences the maximum temperatures that can develop when conduits are opened in these systems, but may not be a pre-condition for B&R geothermal systems to develop. A “thinner” package of low conductivity basin sediments (1.6 km depth) produces lower temperature geothermal systems than “thicker” packages (4 km depth), but not drastically. Similarly, a uniform thermal conductivity of host and playa rocks (2.5 Wm⁻¹°C⁻¹) will not produce the maximum temperatures seen at Dixie Valley, but can produce the somewhat lower temperatures observed in other B&R systems.

Anisotropic playa materials will direct basin fluids into the conduit, with 10⁻¹⁵m²(h) x 10⁻¹⁷m²(v) anisotropic playa models bolstering the total upflow by ~2 L/s (almost 40%). As isotopic data point to a Pleistocene, basin source for fluids in the Dixie Valley geothermal system (Nimz et al., 1999), anisotropy and low vertical permeability of the playa sediments play an important role in the development of these systems.

Some type of “sealing” (or upward narrowing of the conduit) at the top of the conduit system appears to be the only way to limit the downflow of fluids into these systems. As downflow of large quantities of surface fluids (as seen in figure 8) is not observed at Dixie Valley, these results suggest that some mechanism of limiting the flow of surface waters into the conduit is a pre-condition for these systems to develop. Cooling-related near-surface mineral precipitation seems to be the most probable mechanism by which this occurs.

What has not been shown in the models presented here are variable conduit depth models. Previous modelling efforts have shown that shallower conduits produce lower temperature thermal anomalies (Moulding and Brikowski, 2013), and
it is presumed that deeper conduits will produce greater anomalies. This, in conjunction with the thermal and hydraulic conductivity properties of the host and basin rocks discussed above probably determines the maximum temperatures that can develop from these systems.

Previous modelling results have produced temperatures and flow rates observed at Dixie Valley (Moulding and Brikowski, 2014) and results presented here address the sensitivity of various rock properties in the development of these systems. Low permeability host rock, low thermal conductivity and anisotropy of basin fill sediments, and sealing (or narrowing of the conduit) appear critical to the development of these systems. All of these may be important factors for play fairway analysis in the identification of new geothermal prospects.

References


