THE SUBSURFACE GEOMETRY OF A NATURAL GEOTHERMAL RESERVOIR

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ABSTRACT

The geometry of a geothermal reservoir constrains the exploitable resource volume and the sustainable power capacity. That geometry is typically illustrated by a conceptual model and is primarily defined using a pattern of natural state isotherms. Prior to drilling, surface exploration methods set out to constrain the reservoir geometry even though the shape is highly uncertain. Subsequently, it is useful to develop a range of conceptual models that could fit the available data and to use well-defined reservoirs as analogues. The uncertainty associated with the reservoir geometry will, however, remain significant until it is extensively drilled, so considering alternative geometries is an aspect of ongoing resource capacity assessment and makeup well targeting.

We present initial results of research that uses case histories to define the geometry of reservoir permeability in relationship to the geologic architecture. The results are presented as a continuum that may be used as a practical tool for developing alternative conceptual models or selecting of analogue reservoirs. Development of this continuum has highlighted causal relationships between the geologic architecture and reservoir permeability, and we discuss two examples in detail: structures (faults & fractures) and intrusive rocks. Establishing these causal relationships is expected to yield a reduction in the uncertainty associated with estimating resource volume to the degree that the geologic architecture itself is predictable.

1. INTRODUCTION

The research we present here relates to natural geothermal reservoirs, as opposed to engineered systems, and focuses on those reservoirs whose dominant temperature is greater than around 120 °C. We follow the terminology proposed by Grant and Bixley (2011) that differentiates between a geothermal system and reservoir, where the former is the entire subsurface hydrologic system related to the geothermal field and the latter is the exploitable resource of hot, permeable rock (Figure 1).

In a discussion of reservoir-scale permeability, it is worth differentiating between the 'permeable reservoir' and 'economic permeability'. The permeable reservoir is the volume of rock with sufficient permeability to host convection and is demarcated by large areas with a low temperature gradient (i.e., a vertical well will have an isothermal temperature profile rather than a conductive one). Economic permeability lies within the permeable reservoir and is where fluid will flow into or out of a well. It is sometimes referred to as the reservoir sweet spot(s) or, when detected along a well path, the feedzone(s). Differentiating between the 'permeable reservoir' and 'economic permeability' is important because the amount of permeability required for convection is several orders of magnitude lower than economic permeability (Hanano, 2004), and the presence of the former does not guarantee the latter. However, the geometry of reservoir permeability demarcates the volume inside which economic permeability could be located.

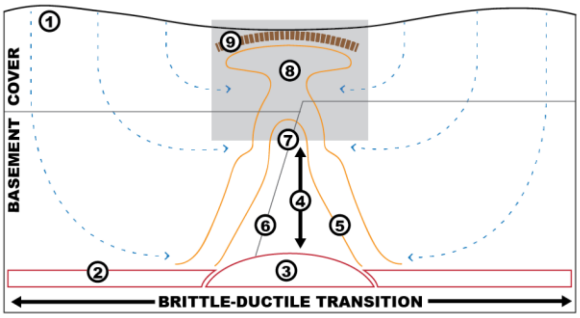

Figure 1: A graphical definition of the difference between the geothermal system and reservoir where the entire figure is the 'system' and the 'reservoir' lies within the grey box. Meteoric recharge is regionally driven by topography (1). It encounters background heat flow (2) and a thermal anomaly (3) whose depth is uncertain (4). Then the now hot, buoyant fluid rises vertically as indicated by the temperature contours (5). Deep-rooted basement structures (6) may play a role in localizing the fluid as it rises through the upflow zone (7) and into a reservoir (8) where overlying high-smectite altered rocks (9) form a leaky cap. The area highlighted by the grey box equates to the extent of the reservoir geometries depicted in Figure 2. This base of this figure was adapted from Ratouis and Zarrouk (2016).

1.1 Conceptual Models

Creating a systematic definition of the geothermal reservoir—commonly referred to as the *conceptual model*—is an indispensable step in resource exploration and development. However, as described below, not all conceptual models are equivalent in their construction, scope, or purpose. One of the earliest conceptual models to appear in the published literature is White's (1968) definition of Steamboat Springs. Its format is archetypal: explanatory text with diagrammatic sections that typically comprise hydraulic arrows, temperature isotherms in section or a vertical temperature profile, and the inferred geologic sequence. Grant and Bixley (2011) provided clear guidelines for conceptual models by saying that, to be useful, they should be simple and, to be complete, they should describe the chemistry, temperature, pressure, phase distribution, permeability, geology, alteration, geophysical character, well flows, and natural surface discharges. For the purposes of the present discussion, we differentiate between those conceptual models that seek to meet that guideline (herein referred to as 'definitions' of a reservoir) and those that reduce reservoir complexity to a sub-set of elements that are of interest (a 'working characterization').

There are a range of published definitions that the geothermal scientest can use as a template. Most of them are resesrvior-specific (e.g., Benoit, 1999; Boseley et al., 2010; Whittome and Salveson, 1990), and some include a description of reservior evolution (e.g., Moore et al., 2008). Henley and Ellis (1983) proposed two generic definitions—one for a silicic volcanic terrain and another for active island-arc volcanos—that have had great influence on conceptual model development over the years. Cumming (2009; 2016) similarly offered two generic definitions: one with a broad, fracture-hosted upflow and another where the upflow is narrow and fault hosted. However, they assume much less available data than those presented by Henley and Ellis (1983), thus ensuring their utility as templates for the early exploration stages of reservoir development. Some definitions apply to a group of similar reservoirs: For example, Hochstein and Sudarman (2015) systematically defined a cluster of Indonesian reservoirs that are associated with stratovolcanoes. There are also definitions that tie geothermal reservoirs to their fossil equivalents, such as Rowland and Simmons (2012) or Simmons and Browne (2000). All of these definitions are near-complete when compared to the Grant and Bixley (2011) guidelines.

When compared with the example definitions above, working characterizations could be considered incomplete. However, they do not aim to be complete in all details. Instead, they are devised to deepen our understanding of a particular feature, such as fluid chemistry (Giggenbach, 1995), thermodynamics (Kaya et al., 2011), and structural favourability (Curewitz and Karson, 1997; Faulds et al., 2013; Hinz et al., 2016; Rowland and Sibson, 2004). Working characterizations are also a useful conceptual tool that can, amongst other things, assist with the development of a complete reservoir definition. In the next section we propose a working characterization for the relationship between the geometry of a reservoir and the geologic architecture.

Note that a definition and working characterization are based on internal characteristics, so they are distinct from a classification based on context. For example, geothermal reservoirs are commonly classified in terms of plate tectonic setting (e.g., Acharya, 1983; Chi and Lin, 2015; Moeck, 2013; Muffler, 1976). Classification can help us understand how geothermal reservoirs relate to their context and why they occur where they do.

2. A CONTINUUM OF RESERVOIR GEOMETRY

In the present study, we focus on the geometry of the permeable reservoir as opposed to the distribution of economic permeability. This geometry can be complex when a single reservoir is considered in intimate detail. However, an extensive literature review has revealed certain commonalities that allowed us to develop a working characterisation. We have separated discussion of reservoir permeability from heat source, chemistry, and phase distribution. This simplification combined with a focus on commonalities has helped us to systematically identify causal relationships between the geometry of reservoir permeability and the geologic architecture.

We propose that geometry of reservoir permeability can be expressed as a continuum with three members: focused, influenced, and unconstrained flow (Figure 2). We describe the three members below along with a 'no flow' situation for comparison. The focused end-member of the continuum can be equated with the commonly used phrase 'fault-hosted reservoir'. However, we have elected not to use that phrase because there are geologic features other than faulting that may create a similar geometry. We have also chosen not to use the phrases 'volcanic-hosted reservoir' or 'distributed permeability'. Those terms cover the continuum from strongly influenced to somewhat unconstrained, and therefore they do not offer sufficient resolution for the present research.

(A) No Flow

Temperature increases consistently with depth along a conductive gradient. If the heat flux is sufficient to create buoyant fluid, the conductive gradient would be maintained by permeability below the threshold for natural convection. That threshold is 10^{-15} m^2 for a temperature of 200-250°C (Hanano, 2004).

(B) Focused Flow

The host rock has permeability near or below the limit for natural convection and the reservoir is restricted to structural damage zones—such as those associated with faults, fissures, or intrusions—or localized lithological unit(s) with a comparatively high-permeability. Reservoir permeability that is focused within structural damage zones is typically highly anisotropic and reservoir pressure may be compartmentalized. Shallow reservoirs focused within lithological units are commonly tabular and stacked on top of a deeper reservoir.

Dixey Valley, Nevada USA, is a classic example of focused flow because the reservoir is localized within the damage zone of the Stillwater Fault (Benoit, 1999). Silangkitang, a reservoir within the Sarulla prospect area Indonesia, is also focused around a major fault (Gunderson et al., 2000; Moore et al., 2001). Puna, Hawaii USA, is focused within what is thought to be a step-over in the Kilauea Lower East Rift Zone (Lewis-Kenedi et al., 2010), which is a rift comprising dike-induced fissures where faults and laterally moving magma are co-located. At Yangbajing on the Tibetan Plateau, the deep part of the reservoir is hosted in granite and focused within faults. It underlies, and feeds, a shallow (50-200 mVD), laterally extensive reservoir that is focused within valley fill comprised of alluvial-diluvial sandstone, conglomerate, tillite, and weathered granites (Jianyun et al., 2015).

Mori, Japan, tends toward the focused end of the continuum but could also be designated as a reservoir with highly influenced flow. This reservoir is restricted to the Nigorikawa Caldera with permeability dominated by fracturing in caldera wall thought to have formed during the eruption and the damage zones surrounding post-eruption intrusions (Hanano et al., 2005; Osada et al., 2010). If the neck of the caldera and eruption-related caldera-wall fracture zones were wider, this reservoir would have been better described as influenced. The Mori example therefore illustrates a rough geometric criterion for focused: reservoirs at this end of the continuum have a height/length is much greater than their width.

(C) Influenced Flow

The reservoir follows the geologic architecture, such that it is bent around or contained within major contrasts in permeability created by abutting lithologies, alteration, or major faults. Variable degrees of permeability anisotropy and pressure compartmentalization may exist.

Hatchobaru, Japan, resembles the above examples of focused flow because the reservoir extent is thought to be controlled by large faults (Fujino and Yamasaki, 1984; Hirowatari, 1991). However, the reservoir permeability at Hatchobaru is not focused on a single structure, instead it is comprised of several structures and zones of reservoir between them. Consequently, like Mori, Hatchobaru is a case that could be designated as highly influenced.

Similar to Hatchobaru, Ohaaki, New Zealand straddles a contact between pre-tertiary basement and recent volcanic deposits. At Ohaaki, extensive drilling has found no economic permeability below the top 100 m of the basement (Mroczek et al., 2016). The temperature, however, continues to increase with depth. This could indicate a situation similar to the interpretation for Hatchobaru, where fluid rises along multiple, discrete fault paths. Alternatively, fluid rising through the basement could be above the limit of convection and below what is required for economic permeability. Regardless of the mechanism of flow in the basement, the geometry of Ohaaki reservoir permeability appears more unconstrained than Hatchobaru.

Reservoirs where edges are shaped by the presence of low-permeability lithology or alteration are influenced. The extent of the deep, permeable reservoir at Ngatamaiki, New Zealand, is truncated in the northwest by a cluster of at intrusive bodies (Boseley et al., 2010; Chambefort et al., 2016). Similarly, the truncation of Patuha, Indonesia, in the east is thought to be due to uplifted basement (Layman and Soemarinda, 2003).

For vapour-dominated reservoirs, the permeability outside the reservoir must be low or the must be edges tightly sealed by alteration. Otherwise, the sub-hydrostatic reservoir would be flooded by regional groundwater. Vapour-dominated reservoirs often appear to have a simple geometry that is either mushroom-like or a series of local up-doming vapour-rich zones mounted over a broad deep reservoir (Bogie et al., 2015). However, despite their visual resemblance to the unconstrained end-member, vapour-dominated reservoirs like Darajat, Indonesia, are defined herein as influenced because hydrothermal alteration plays a leading role in their extent (Moore et al., 2008).

(D) Unconstrained Flow

A hypothetical end-member where all of the geologic architecture beneath the clay cap is above the limit for convection and, therefore, it has little influence on the shape the hydrothermal plume in the natural state. Permeability inside and outside the reservoir is similar. The reservoir will form on a lean or vertically like a mushroom depending on hydrologic forces such as topography (Ratouis and Zarrouk, 2016).

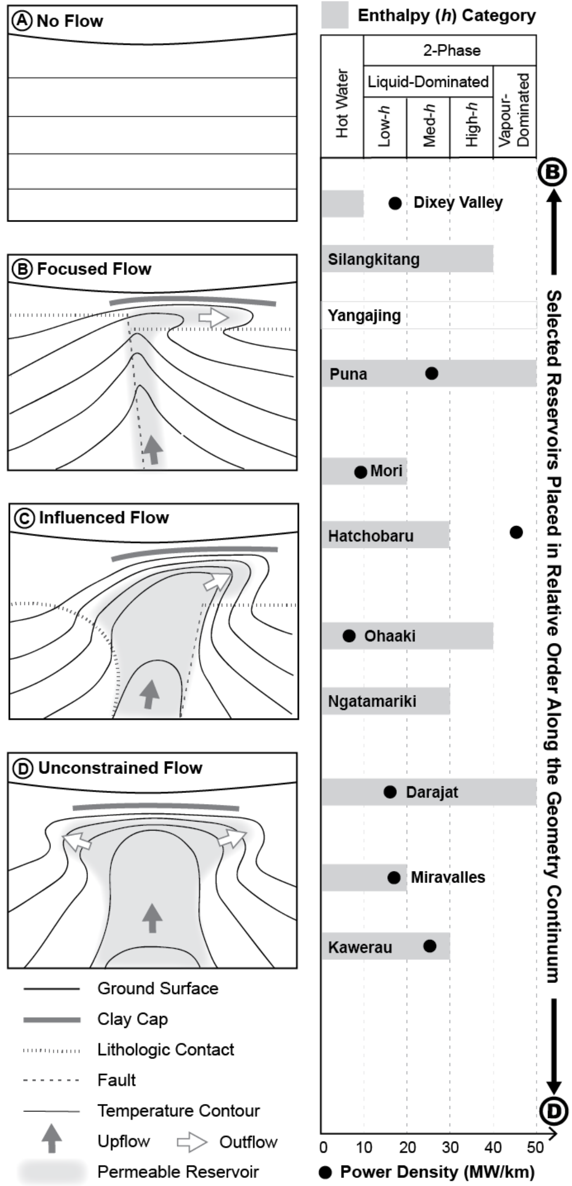

Figure 2: (LEFT) Cross sections representing three members on a continuum of reservoir permeability geometry: focused (B), influenced (C) and unconstrained flow (D). A conductive profile where no flow is occurring (A) has been provided for reference. Note that only those geologic elements that influence the extent of the permeable reservoir are represented on the sections. The extent of these sections is highlighted by the grey box in Figure 1. (RIGHT) Selected geothermal fields plotted in relative order along the continuum with power density (Wilmarth and Stimac, 2015) and enthalpy category (Gunderson et al., 2000; Hanano et al., 2005; Iovenitti and D'Olier, 1985; Kaya et al., 2011; Rivera Diaz et al., 2016b) included for reference.

In reality, the unconstrained end-member does not exist because all reservoirs are influenced by the geologic architecture in some way. However, there are a number of reservoirs that tend toward this end of the continuum, such as Miravalles, Costa Rica (Vega Zuniga et al., 2005) and Kawerau, New Zealand (Milicich et al., 2016) In a relativity unconstrained reservoir, we would expect the outflow and side recharge to be a prominent features. In the case of Miravalles and Kawerau all of the production occurs along the outflow.

2.1 Limitations

In the previous section we described a continuum of reservoir permeability geometry and illustrated it using case studies. However, this working characterization has a number of limitations that fall generally into two categories: limitations associated with the way the continuum was developed and those related to the degree of idealization.

The working characterization was developed based on an extensive review of published case studies. Setting aside the fact that published literature represents only a small proportion of the collective industry knowledge about reservoir permeability, there are two ways that the kind of literature available is a limitation:

1. Published geothermal literature is skewed toward large, relatively accessible reservoirs (perhaps because these are the ones with the longest development history) and negative case studies are very rare. Furthermore, the amount of drilling required to define a reservoir geometry is usually greater than any company would invest in a reservoir with insufficient permeability for wells to flow. It follows that very low permeability reservoirs may not be represented by the geometry spectrum.

2. Absolute measures of permeability (such as injectivity and productivity index, permeability thicknesses or transmisivities) are rarely included in papers discussing the spatial character of reservoir permeability. In some cases, this may be because the absolute magnitudes are considered commercially sensitive. However, it may also be because the conceptual model case studies are often authored by geologists, so omission of quantitative permeability data may be due to a discipline’s preference to present one data type rather than another. Without quantitative data on permeability magnitude, it is difficult to say if particular geometries tend to have certain ranges of reservoir or economic permeability.

Without empirical permeability data to hand, we can still reason that once above the limit for convection at a given temperature, there may be little or no relationship between overall permeability magnitude and geometry. This augment arises from two observations. First, there is a recognized relationship between gross permeability magnitude and enthalpy such that developed high enthalpy reservoirs tend to have an overall lower permeability magnitude than those with intermediate or low enthalpy (Kaya et al., 2011; Rivera Diaz et al., 2016a; Scott et al., 2016). Despite this systematic relationship, we have, to date, found no systematic correlation between geometry and reservoir enthalpy (Figure 2).

The continuum of geometries we present is heavily idealized and, if taken a face value, we can shoe-horn a reservoir into multiple geometries. For example, if you slice the central upflow of an influenced reservoir at just the right angle, it could resemble the unconstrained end-member. This highlights that the aim is not to fit reservoirs to a single place on the continuum, but to facilitate discussion about the geometry of reservoir permeability.

A further issue related to idealization is touched on above in the descriptions of Yangbajing, Hatchobaru, and Ohaaki: geometries may be stacked with depth as the gross geologic context changes from a crystalline or metasedimentary basement through recent volcanics/sediments to near-surface, poorly lithified rocks. The control these changes in gross geologic architecture can have on the geometry of reservoir permeability highlights the value of quantifying regional geology when exploring a resource. Before drilling, the regional geology is the best source of information about what is present at depth. In the next section we expand this discussion of how the geologic architecture influences reservoir geometry.

3. GEOLOGIC CONTROL OF GEOMETRY

In this section we describe the way structures (faults and fractures) and intrusive rocks influence reservoir geometry. However, there is a great range of geologic elements that make up the architecture that is relevant to the distribution of reservoir permeability, such as the gross changes in geologic context mentioned above, and this is the subject of ongoing research. For simplicity, we include secondary alteration in the term geologic architecture. Even below those clay-altered formations that typically cap geothermal reservoirs, the distribution of current and relic alteration may dictate the distribution of reservoir permeability. Alteration also plays a leading role in mechanical rock properties (Wyering et al., 2014) and therefore needs to be considered in relation to structural damage.

Although the discussion here is limited to geology, it is important to consider the significant role hydrology plays in the geometry of the permeable reservoir. As described above, those reservoirs tending toward the unconstrained end-member will be particularly influenced by the regional hydrology that is driven by factors like topography and surface bodies of water. Implicit in the usage of the term ‘permeable reservoir’ in this work, is the understanding that we are referring to the reservoir of hot (>120°C) geothermal fluids. The pressure balance between cool, shallow groundwater and hot buoyant fluid will, therefore, also influence the extent of the reservoir. For instance, cool shallow waters may flow over the top of reservoirs or find their way down through the same kinds of architecture that is likely to conduct hot fluid upwards. Cold-water downflows often become more apparent after production starts. For example, localized cold downflow initiated was initiated by pressure drop at Ohaaki during the early testing period (Hunt and Bromley, 2000) and this has been related to permeable conduits from surface to depth created by rhyolite domes and their roots (Rissmann et al., 2011).

3.1 Structures

Structure is a catch-all term for the brittle deformation of rock in response to stress. It is dominantly comprised of two groups of features: faults (places where brittle deformation has resulted in measurable offset in a rock unit) and fractures (brittle deformation without appreciable offset). The relationship between structure, in particular large faults, and the geometry of a geothermal reservoir is complex and sometimes contradictory because as often as faults are agents of permeability enhancement, they may also reduce it. The movement history (magnitude of rupture(s) and approximate timing), associated secondary mineralization, mechanical properties of the host rock, and any interplay with other nearby structures will all influence the nature of a structure's permeability (Rowland and Simmons, 2012). The relationship a structure has with the present and past tectonic regimes is also key because it dictates the initial rupture and reactivation, and therefore the likelihood a structure is still open to flow (Barton and Zoback, 1992; Barton et al., 1995).

Within the present discussion of overall reservoir geometry, we are primarily concerned with faults whose offset is in the 10s of meter scale and above because they are likely to include either or both of the following elements:

1. Fault damage zones. Significant damage zones at reservoir depths commonly result in enhanced in-plane (along- or up-strike) permeably. In places where the host rock permeably is low, fault-adjacent damage may enhance permeability enough to allow a focused reservoir to form, as is the case at Dixey Valley. However, faults traversing low-strength rock may create a low permeability damage zone where plastic deformation has reduced total porosity.

2. Fault core. A well-developed fault core commonly includes clay minerals that may baffle fluid flow from one side to the other. At Oguni, Japan the north and south reservoirs are separated (no pressure connection) by a very low permeability zone interpreted as a fault (Yamada et al., 2000). Similarly, a large structure baffles flow from a hot injection area to the production area at Rotokawa, New Zealand (Sewell et al., 2015).

The capacity of a structure to enhance or reduce permeability can vary both laterally and vertically due to differences in displacement magnitude, host rock properties, and the temperature. They may also vary through time in response to repeated seismic rupture or mineralization during the inter-seismic period.

The displacement of rock by faults can influence the vertical locations and thicknesses of dominant reservoir- or cap-hosting formation(s). For example, at Oguni, Japan, a fault offset has been cited as the reason why the larger northern reservoir has a thicker occurrence of a key reservoir-hosting rock (dacitic pyroclastic rocks of the Shishimuta Formation Yamada et al., 2000).

Smaller faults could enhance the permeable fracture network and, when considered at the reservoir-scale, they can be thought of as part of the overall structural grain. In cases where fluid flow follows the structural grain, fluid pathways are relatively direct. Where the flow direction crosses the structural grain, flow pathways are more tortious and widely spread (Buscarlet et al., 2015).

3.2 Intrusive Rocks

For the purposes of the following discussion, we have made a gross distinction between large and small intrusions. Large is when a single intrusive phase is at the 100s of meter scale and above. Small is up to the 10s of meter scale. Both small and large intrusions can occur in multiple phases and, in some cases, small intrusions can be sufficiently plentiful that they dominate the rock composition. Intrusive rocks typically have a very low internal porosity, but their progress through the crust can create a damage zone with high secondary porosity (Rowland and Simmons, 2012). However, in some cases an intense halo of alteration may form around an intrusion (e.g., Chambefort et al., 2017) which can, in turn, result in significant porosity reduction (Wallis et al., 2015).

Solitary small intrusions would have little influence on the overall geometry of a geothermal reservoir. However, a high frequency of small intrusions may reduce total permeability thus forming a gradational edge to the reservoir. At Krafla in Iceland (Arnórsson, 1995) and Puna in Hawaii (Kauahikaua, 1993) the average permeability decreases with depth as the rock composition is increasingly dominated by intrusions.

There are several published examples of large intrusions influencing the geometry of a geothermal reservoir. In three cases from Japan, the damage zone associated with a large intrusion influences the geometry or the reservoir permeability. At Matsukawa, the main permeable zones occur along the edges of a diorite porphyry and quartz diorite, and the upflow is thought to follow the ascent path of the intrusive (Hanano, 2003). Yamagawa and Fushime have both developed in the damage zone around a dacite intrusion (Okada et al., 2000; Sasada et al., 2000). A large intrusion may also influence the shape of a reservoir with an otherwise distributed geometry. For example, Ngatamariki, New Zealand, has a >5 km^3 intrusive complex made up of at least three distinct intrusive events. This very low porosity rock truncates deep permeability in the north-north-western sector of the reservoir such that the permeability wraps around this buried low-permeability zone (Boseley et al., 2010; Chambefort et al., 2016).

Eruptions of magma to surface have intrusive roots. While these intrusive roots may influence geometry in the same ways mentioned above, their hydraulic connection to eruptive units above may also play a role. Ohaaki contains buried rhyolite domes with intrusive roots. The reservoir temperature data indicates the presence of a near-vertical and spatially discrete hydrothermal plume beneath the buried rhyolite domes that has been interpreted as preferred permeability along the eruptive pathway (Rissmann et al., 2011). Vertical conduits like these may be used by either hot upflows or cool downflows depending on the pressure balance.

Intrusions that have not yet fully cooled have been intersected in geothermal reservoirs including Karaha–Telaga Bodas, Indonesia (Nemčok et al., 2007) and Kakkonda, Japan (Doi et al., 1998). Magma has also been intersected by deep drilling at Krafla, Iceland (Scott et al., 2015) and Puna, Hawaii (Teplow et al., 2009). Published accounts of neo-intrusives are rare and they have a high degree of thermodynamic and chemical complexity. For these reasons they are not treated in detail here. However, the intersection of a neo-intrusive at Kakkonda does raise an interesting point about inferring what exists below the maximum drilled depth. The deepest portion of the conceptual model prior to deep drilling inferred that fault-hosted permeability that conducted fluids upward through the basement from a deep heat source (McGuinness et al., 1995). Intersecting a neo-intrusive so close to the production reservoir may have therefore been somewhat surprising. This case history reflects the high degree of uncertainty associated with estimating the nature and proximity of a heat source (Figure 1, Point 4).

5. APPLICATION

Within the context of our research, the core purpose of the working characterization is to systematically identify causal relationships between the distribution of reservoir permeability and geologic architecture. However, the continuum of reservoir geometries presented herein may be used as a practical tool for developing alternative conceptual models for a reservoir under exploration. The continuum also facilitates comparison between reservoirs in terms of their permeability alone. These practical applications are described below.

5.1 Develop Alternative Models

A conceptual model guides resource exploration, determine drilling risk, and forms a basis for numerical models that test resource viability and sustainability. In the early stages of exploration, available data is very plan-view so little can be said with confidence about the subsurface shape of the reservoir beyond the shape of the cap. As illustrated in Figure 2, a focused reservoir may have the same shaped clay cap and surface feature arrangement as a reservoir that lies at the distributed end of the continuum. However, the former would have a much lower volume of potentially exploitable permeability. It is, therefore, useful to develop a range of conceptual models that could fit the available data to:

1. Explore the uncertainty associated with estimates of reservoir volume and consider end-members that can fit the data.

2. Plan an information gathering strategy that eliminates geometries that would yield sub-economic reservoir volumes to minimize sunk cost in resources that are not presently viable.

A developed geothermal reservoir will invariably require makeup wells to maintain a supply of fuel for the lifetime of the power station. This can require exploring the edges of the known reservoir. Understanding the relationships between the geologic architecture and reservoir geometry will assist the geothermal scientist to determine the likelihood that a reservoir extends in one direction or another.

5.2 Compare Geothermal Reservoirs

Geothermal exploration is characterized by limited amounts of subsurface data, particularly when compared to oil and gas or minerals exploration. Therefore, defining the subsurface requires a relatively great amount of inference. Judicious application of analogues is one method of improving the quality of inference. A system that facilitates comparison between reservoirs, such as the working characterization we described above, assists with section of appropriate analogues. The description of the continuum of reservoir permeability identified a number of analogues for consideration (e.g., Kawerau to Miravalles or Hatchobaru to Ohaaki), and these kinds of comparisons will be the subject of future work.

7. CONCLUSION

We presented a working characterization comprising a continuum of geometries that describe the extent of geothermal reservoir permeability in relationship to the geologic architecture. Reservoir permeability is defined here as the volume of rock with sufficient permeability to allow convection. This is distinct from economic permeability which is several orders of magnitude higher (Hanano, 2004). However, characterizing the limits of the permeable reservoir places boundaries on where to look for economic permeability.

We have idealized geothermal reservoirs in a way that focuses on the relationship between the geologic architecture and reservoir permeability. There is, however, a complex interplay between geologic, geochemical, thermodynamic, and hydrodynamic factors that influence permeability, but limiting the scope has helped us distil a number of causal relationships of interest. These include a range of geologic factors that influence reservoir permeability, two of which we described here: structures (faults and fractures) and intrusive rocks.

The results of our research, to date, may be used as a practical tool for discussing similarities and differences between various reservoirs, as well as developing alternative conceptual models for a reservoir under exploration. We will also use this continuum of geometries as a conceptual tool in future research that aims to reduce the uncertainty associated with targeting economic permeability.

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