GRC Transactions, Vol. 42, 2018

The Relationship between Geothermal Fluid Flow and Geologic Context: A Global Review

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Keywords

Global Review, permeability, structure, intrusive and basement rocks, conceptual model

ABSTRACT

Geothermal fluid flow is related to geologic context from the global or district scale down to the reservoir scale. We present a discussion of that relationship which is based on a review of high-temperature geothermal reservoirs worldwide. Initially we focus on large-scale geological controls on productive geothermal reservoirs, such as the role crustal-scale structural discontinuities play in localizing highly productive geothermal reservoirs. We present five district-scale case studies including: The Taupō Volcanic Zone in New Zealand, the Great Sumatra Fault in Indonesia, the East African Rift System that hosts geothermal development in Kenya and Ethiopia, the spreading plate boundary that bisects Iceland, and the Great Basin in western USA.

In the second half of this paper we review the control geological context has on the natural state reservoir geometry. We demonstrate that the degree of influence a geological discontinuity (e.g., structure, contact zone or unit with high hydraulic potential) has on reservoir geometry, typically reflects how focused that resource is. Focused reservoirs have high well-to-well temperature gradients and complex thermal geometry. Broad reservoirs with low temperature gradients between wells show less influence from geological discontinuities in the natural state. We conclude with an exploration of the influence basement or intrusive rocks have on the geometry of reservoir permeability and the distribution of productive zones. We illustrate these interplays between geology and reservoir geometry using published cases from a range of geological settings.

1. Introduction

Considering the relationships between geology (lithology, structure and alteration) and permeability, from global, through district, and down to reservoir scale, enables us to identify favorable conditions for reservoir localization. This also permits us to quantify the diversity of reservoir geometry. To undertake this work, we conducted a global review of developed, high-temperature geothermal systems using published literature. Herein we summarize the results of review to date.

The paper is structured according to scale, with the global distribution of geothermal systems presented first. District-scale controls on the localization of geothermal systems are then explored using five case studies. For the reservoir scale, we start by proposing a framework for comparing the geometry of the permeable reservoir and then explore one kind of geologic context—the role crystalline rocks play in reservoir permeability. The discussion of reservoir architecture and crystalline rock is contextualized by a set of conceptual models compiled from the published literature.

2. Global-Scale Distribution of Reservoirs

It is well known that tectonic processes, including subduction zones, spreading ridges and rifts, and intraplate hot spots like Hawaii or Yellowstone, drive a high heat-flux though Earth's crust and that these are ideal conditions for localizing high-temperature geothermal reservoirs (Acharya, 1983; Chi and Lin, 2015; Moeck, 2013; Muffler, 1976). This relationship is illustrated by the way most of the 159 developed reservoirs cluster along active plate boundaries (Figure 1). These same tectonic settings are foci for volcanism, a more punctuated method of fluxing heat from the crust. Traces of magmatic input are common in reservoir fluids (Giggenbach, 1995). However, some reservoirs show no sign of magmatic input, including systems in the Great Basin (Simmons et al., 2017) and the back-arc setting of Honduras (Laughlin and Goff, 1991).

The map in Figure 1 plots developed geothermal systems and, therefore, illustrates the distribution of those that possess three key criteria for sustaining an energy project—sufficient temperature and permeability, and a benign (or manageable) chemistry (Cumming, 2016). However, there is bias in this distribution of developed reservoirs because there are also social, cultural, environmental, and economic reasons that preclude reservoir development. The process of development, to a greater or lesser extent, characterizes the subsurface. Nearly 70% of energy developments have < 50 MWe installed but 11 geothermal systems host > 300 MWe of installed generation (ThinkGeoEnergy, 2017). The earliest development was in 1905 at Larderello, Italy (Parri and Lazzeri, 2016). Then in the late 50's to early 60's global geothermal development ramped up with projects in Japan, Russia, the US, and New Zealand (ThinkGeoEnergy, 2017).

3. District-Scale Controls: Five Case Studies

We reviewed five districts that host geothermal development: The Taupō Volcanic Zone in New Zealand, the Great Basin in the US, the Great Sumatra Fault in Indonesia, the Iceland Ridge, and the East African Rift System that traverses the eastern corner of the African continent (Figure 2).

These case studies illustrate a range of tectonic settings and enable us to investigate the control regional structure may have on the localization of reservoirs.

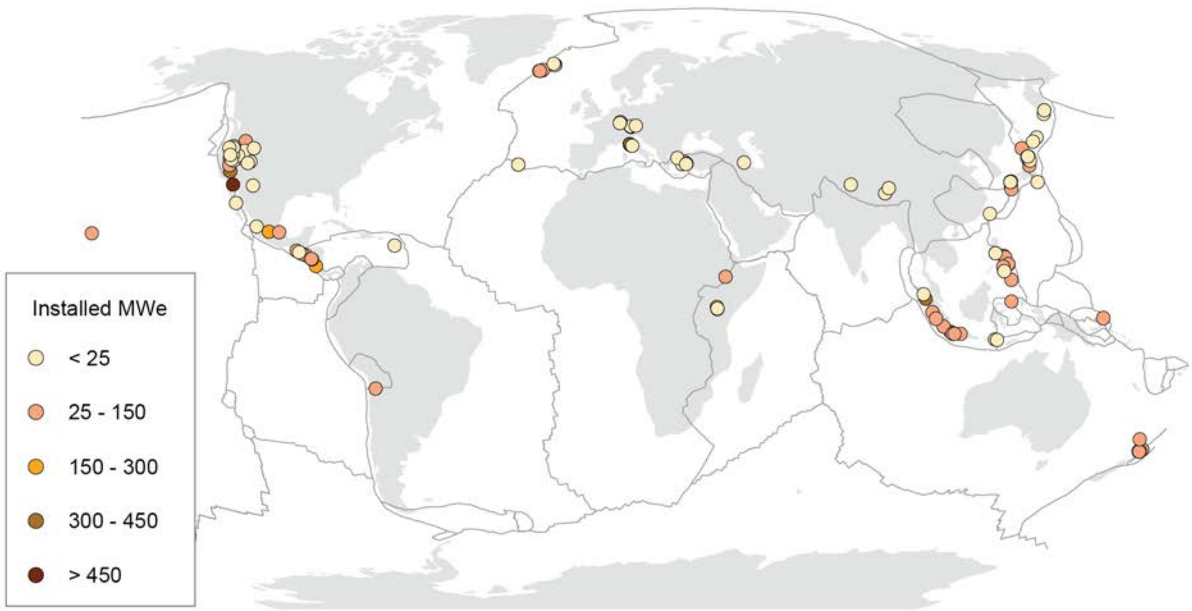


Figure 1: Global distribution of geothermal systems developed for electricity (compiled from Bird, 2003; NaturalEarth, 2017; ThinkGeoEnergy, 2017)

3.1 Great Basin, US

The Great Basin (GB: Fig. 2) is a ~600 km wide district that initiated between ~16-18 Ma ago as a result of evolving plate interactions along the North American Cordilleran margin during the Cenozoic period (Dickinson, 2002; Dickinson, 2006; Porter et al., 2014). Today, the GB comprises elongate horsts or tilt blocks that form ranges with sedimentary basins in the intervening fault-angle depressions (Dickinson, 2002). Strike-slip faults and pull-apart basin geometries are prevalent on the western boundary (Walker Lane fault system, eastern Californian shear zone) and this area overlaps with the numerous <8 Mya old volcanic centers of the Cascade Arc.

Many studies have assessed the role structure plays in the localization of geothermal systems within the GB (including Bell and Ramelli, 2009; Blewitt et al., 2003; Cashman et al., 2012a; Cashman et al., 2012b; Coolbaugh et al., 2003; Faulds et al., 2006; Faulds et al., 2012a; Faulds et al., 2012b; Faulds et al., 2013 and others). Overall, these studies find that the largest reservoirs are located at the tips of major fault zones and at dilatational fault intersections where major graben-bounding faults are intersected by transversely orientated transfer faults that are undergoing oblique slip. Reservoirs also typically localize at steps, fault intersections, and overlapping or terminating locations but rarely form at displacement maxima or mid-segments of normal faults (Faulds et al., 2011). Faulds et al. (2012b) found that the distribution of reservoirs correlates with areas of higher strain rate; although the presence of recent (<0.5 Mya) magmatism may also play a role.

3.2 Great Sumatra Fault, Indonesia

The Great Sumatra Fault (GSF: Figure 2) is a 1660 km long, segmented, right-lateral strike-slip fault system that bisects Indonesia's largest island (Bellier and Sébrier, 1994; Sieh and Natawidjaja, 2000). This mega-shear initiated in the mid-Miocene through a pre-Tertiary basement that is dominated by metasediments, Tertiary age volcanic rocks and intrusions, and sedimentary basin deposits (Barber et al., 2005). A subduction-related, late Pliocene to Quaternary series of volcanic centers is spatially coincident with the GSF but a causal link between the GSF and distribution of volcanism is debated (Bellier and Sébrier, 1994; Sieh and Natawidjaja, 2000). The geometrically complex, segmented form of the GSF is unusual. In contrast with the San Andreas Fault in the US, which has a single step-over discontinuity wider than one kilometer, the GSF has more than a dozen such discontinuities with widths that range between ~5 and 12 kilometers (Sieh and Natawidjaja, 2000). Similarly, the San Andreas Fault only has two large bends whereas the GSF has ~8 (Sieh and Natawidjaja, 2000).

Around 30 high temperature geothermal systems have been identified in Sumatra (Hochstein and Sudarman, 1993), but only five are developed or currently under development. Sumatra contains systems whose location appears strongly correlated to the GSF (e.g., Muara Laboah: Mussofan et al., 2018) and others whose position appears more related to the volcanic arc (e.g., Sibayak: Hochstein and Sudarman, 1993). The five developed systems occur close to the ends of segments defined by earthquake clusters (Figure 2, Burton and Hall, 2014). These seismogenic segments closely resemble those defined geologically by Sieh and Natawidjaja (2000) on the basis of geomorphological features, including fault bends and step overs, and the distribution of rock type. None of the geologically defined surface ruptures cross the seismogenic segments but some surface ruptures were combined into a single seismogenic segment. Burton and Hall (2014) argue that the latter is reasonable because surficial fault manifestations are secondary to the deep structure that seismicity defines. When all Sumatran reservoirs are considered, the spatial relationship to seismogenic segments disappears.

3.3 Iceland Ridge

In Iceland the oceanic spreading ridge traverses on-shore to form a complex series of rift segments and transform zones (Khodayar et al., 2010) that accommodate ~18 mm/yr of spreading between the Eurasian and North American plates (Sigmundsson, 2006). The ridge comprises three purely divergent segments: the Northern, Western and Eastern Rift Zones, where the latter two lie subparallel in the south (Ziegler et al., 2016). The plate boundary comes onshore at the Western Rift Zone and traverses the South Iceland Seismic Zone before extending northward though the Eastern and Northern Rift Zones (Figure 2).

All of Iceland's 33 geothermal systems are located within these rifts (Ármannsson, 2016). Similarly, active volcanism, which consists of central volcanoes and dike-fed fissure eruptions, is found along the rift axis (Sigmundsson, 2006). The relationship between volcanic features and the geothermal systems of the Iceland Ridge is remarkable. At Krafla, the deep upflows are thought to be localized by fissure swarms (Langella et al., 2017) and Nesjavelliar, a reservoir within the Hengill system, is contained within a rift that extends northward from a central volcano (Zakharova and Spichak, 2012). However, the active transfer zones that cross the north and south extents of the Iceland Ridge also appear to play a role in localizing geothermal fluid flow (Khodayar et al., 2010; Lupi et al., 2010): All developed reservoirs are clustered on these intersections (Figure 2).

3.4 Taupō Volcanic Zone, New Zeeland

The Taupō Volcanic Zone (TVZ: Figure 2) is a ~300 km long, NE-trending arc that includes an anomalously hot and highly productive central silicic segment (Wilson and Rowland, 2016). This arc is widening (~12 mm/year in the central TVZ: Wallace et al., 2004), and extensional strain is accommodated by a series of NE-striking rift segments and NW-to-NNW trending transfer zones whose geometry is, in part, controlled by inherited structures (Rowland and Sibson, 2004; Seebeck et al., 2014). The central TVZ contains deep (>3000 m) rift basins through metasedimentary basement that are infilled with the products of ~2 My of volcanic evolution from a typical andesitic arc to a vigorous silicic system dominated by caldera-forming eruptions (Wilson et al., 1995). Accordingly, rift basins have complex stratigraphy, dominated by quasi-layer cake volcaniclastic products, their reworked equivalents (dominantly lake deposits), and lavas, and is pierced by intrusions and associated domes (Downs et al., 2014 and references therein).

In central TVZ, twenty-three active geothermal systems are delimited (Bibby et al., 1995), and seven of these have been developed for electricity generation. Modern geothermal activity forms two belts parallel to the rift fabric either side of the Taupō Fault Belt, which though currently lacking geothermal activity, has hosted systems in the recent past (Kissling et al., 2018). The greatest heat output occurs in, and on the flanks of, the Taupō-Reporoa Basin, which is rapidly subsiding yet lacks the fault morphology apparent in the Taupō Fault Belt to the west (Rowland et al., 2010). The exceptional heat output in this basin may reflect, in part, its tectonic position at the margin of the dominantly extensional TVZ and the right-lateral strike slip North Island Fault System, and also its magmatic position above the axis of the arc (Rowland et al., 2010). Geothermal systems also occur on NW to NNW alignments that are contiguous in places with alignments of young (<61 ka) silicic vents, and spatially coincident with transfer zones between rift segments that are inferred to align with basement structures (Rowland and Sibson, 2004; Rowland et al., 2010). Based on geomorphic and geophysical data (Henderson et al., 2016; Rowland et al., 2016), such transfer zones appear to be contiguous with major faults of the Hauraki Rift, a lithospheric scale feature that lies to the north of the TVZ and parallels major sutures between basement terranes. Most developed systems cluster where the Hauraki Rift intersects the TVZ. Kawerau is the only system that falls outside this cluster. However, basement structures associated with the North Island Fault Belt intersect the TVZ in this area (Figure 2).

3.5 East African Rift System

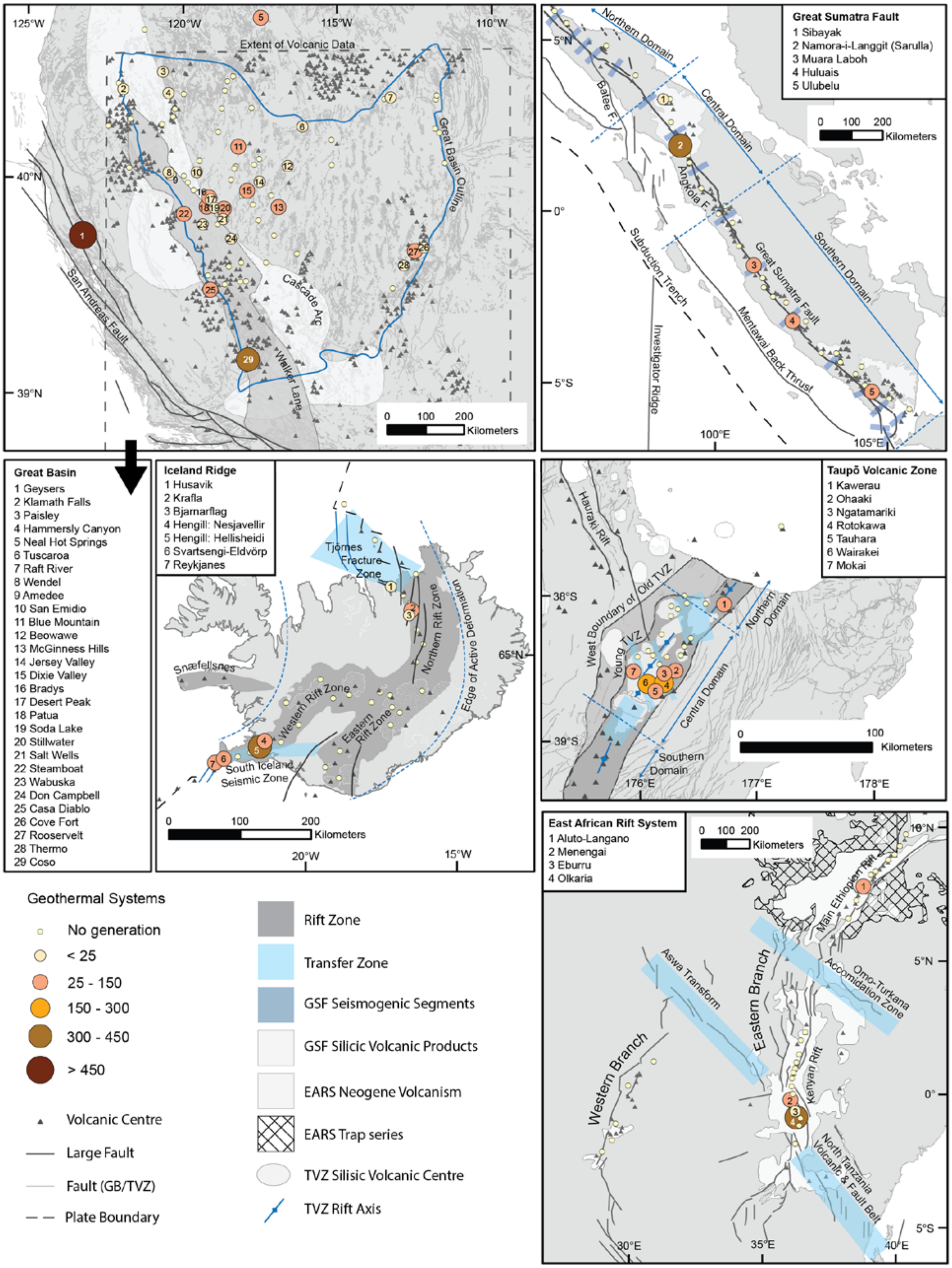
The East Africa Rift System (EARS: Figure 2) is a continental rift organized into branches, each a narrow zone of thinned crust that is aligned along pre-existing continental weaknesses and is intruded by asthenospheric mantle (Chorowicz, 2005). These narrow zones of deformation comprise graben systems that are linked and segmented by transfer zones (Ebinger et al., 1999). Overall, the East African Rift System has an average spreading rate of 3.2 mm/yr with rates > 6 mm/yr in north of the Aswa transform and < 4.3 mm/yr to the south where two rift segments accommodate for the relative eastward movement of the Somalian plate from the Nubian plate (Stamps et al., 2008).

There are around 30 geothermal systems reported in the EARS (Demissie, 2010; Pürschel et al., 2013), and four have been developed to date. All but one of the developed geothermal systems are located within the central portion of the Kenyan rift where it takes a sharp bend from its overall norward trend to a northeast orientation. The diffuse Aswa transfer zone meets the rift at this bend before continuing southeast of the Kenyan Rift to form the North Tanzania volcanic and fault belt (Figure 2, Chorowicz, 2005). Aluto-Langano geothermal system is associated with a dormant volcanic center within the Main Ethiopian rift (Abebe et al., 2016).

3.6 Key District-Scale Findings

At the district scale, our review confirms the increasingly well-established links between structure and geothermal circulation (Blewitt et al., 2003; Curewitz and Karson, 1997; Faulds et al., 2012b; Faulds et al., 2013; Hinz et al., 2016; Micklethwaite and Cox, 2004; Rowland and Sibson, 2004; Rowland and Simmons, 2012). Previous reviews of the relationship between structure and geothermal systems within the Great Basin (Faulds et al., 2013) and arc settings (Hinz et al., 2016) showed that geothermal systems are commonly associated with interaction zones and intersections, while rarely associated with simple fault traces. Hinz et al. (2016) demonstrated that the most favorable tectonic settings for productive geothermal systems are extensional, transtensional-extensional and transtensional-strike slip. Our district-scale case studies agree with these findings and highlight the role of regional transfer zones (e.g., South Iceland Seismic Zone or Aswar transfer in East Africa: Figure 2). Inherited structure, such as that which localize the Hauraki Rift in the TVZ, appear to influence the geometry of these transfer zones as well as the productivity of geothermal systems. In the case studies, we repeatedly found a strong spatial relationship between district-scale structure and developed geothermal systems, but these relationships do not hold when undeveloped resources are included. It is possible that developed reservoirs represent a special subset of favorable sites where regional structure preferentially localizes systems with attributes that are favorable for energy development.

Figure 2 (NEXT PAGE):Five district-scale case studies illustrating the relationship between geothermal reservoirs and geologic setting: Great Basin (Blakely et al., 2007; Faulds et al., 2006; Faulds et al., 2012b; Porter et al., 2014; USGS, 2017), Great Sumatra Fault (Barber et al., 2005; Burton and Hall, 2014; Hochstein and Sudarman, 2015; Natawidjaja, 2018; Sieh and Natawidjaja, 2000), Iceland Ridge (Ármannsson, 2016; Arnórsson et al., 1983; Bourgeois et al., 2005; Khodayar and Björnsson, 2014; Khodayar et al., 2010), Taupō Volcanic Zone (Heron, 2014; Rowland and Sibson, 2004; Wilson and Rowland, 2016), and East African Rift System (Chorowicz, 2005; Demissie, 2010; Pürschel et al., 2013). Compiled from published literature as cited and adapted from Wallis et al. (in review).


Great Basin
1 Geysers
2 Klamath Falls
3 Paisley
4 Hammersly Canyon
5 Neal Hot Springs
6 Tuscarora
7 Raft River
8 Wendel
9 Amedee
10 San Emidio
11 Blue Mountain
12 Beowawe
13 McGinness Hills
14 Jersey Valley
15 Dixie Valley
16 Bradys
17 Desert Peak
18 Patua
19 Soda Lake
20 Stillwater
21 Salt Wells
22 Steamboat
23 Wabuska
24 Don Campbell
25 Casa Diablo
26 Cove Fort
27 Roosevelt
28 Thermo
29 Coso
Extent of Volcanic Data
Great Basin Outline
Cascade Arc
Walker Lane
San Andreas Fault
Great Sumatra Fault
1 Sibayak
2 Namora-i-Langgit (Sarulla)
3 Muara Laboh
4 Huluais
5 Ulubelu
Northern Domain
Central Domain
Southern Domain
Batee F.
Angkola F.
Subduction Trench
Investigator Ridge
Mentawai Back Thrust
Iceland Ridge
1 Husavik
2 Krafla
3 Bjarnarflag
4 Hengill: Nesjavellir
5 Hengill: Hellisheidi
6 Svartsengi-Eldvörp
7 Reykjanes
Tjörnes Fracture Zone
Northern Rift Zone
Edge of Active Deformation
Snæfellsnes
Western Rift Zone
Eastern Rift Zone
South Iceland Seismic Zone
Taupō Volcanic Zone
1 Kawerau
2 Ohaaki
3 Ngatamariki
4 Rotokawa
5 Tauhara
6 Wairakei
7 Mokai
Hauraki Rift
West Boundary of Old TVZ
Young TVZ
Northern Domain
Central Domain
Southern Domain
East African Rift System
1 Aluto-Langano
2 Menengai
3 Eburru
4 Olkaria
Main Ethiopian Rift
Aswa Transform
Eastern Branch
Western Branch
Omo-Turkana Accomodation Zone
Kenyan Rift
North Tanzania Volcanic & Fault Belt
Kilometers
Geothermal Systems
No generation
< 25
25 - 150
150 - 300
300 - 450
> 450
Volcanic Centre
Large Fault
Fault (GB/TVZ)
Plate Boundary
Rift Zone
Transfer Zone
GSF Seismogenic Segments
GSF Silicic Volcanic Products
EARS Neogene Volcanism
EARS Trap series
TVZ Silisic Volcanic Centre
TVZ Rift Axis

4. Reservoir-Scale Controls

In geothermal resource development, the foremost tool for describing the nature of a reservoir is the conceptual model. White's (1968) definition of Steamboat Springs was one of the earliest conceptual models to appear in published literature and its format is archetypal: diagrammatic sections that typically comprise hydraulic arrows, temperature isotherms or a vertical temperature profile, and relevant components of the geology and alteration. Sections are typically accompanied by explanatory text and may, as illustrated by the vignettes presented in Figure 4, also include details like fluid geochemistry and phase.

An existing nomenclature that accompanies the conceptual model. Some terms most reflect the liquid geochemistry (amagmatic, volcanic), while others describe reservoir thermodynamics (liquid-dominated, vapor-dominated). Distributed and fault-hosted are the common terms deployed to describe the geometry of the permeable reservoir—a core area of interest in our review. However, we found this existing terminology too binary to describe the gambit of reservoirs reviewed. Furthermore, fault-hosted, the inverse of distributed, was too genetic—faults are not the only feature that host a non-distributed reservoir.

In response, we proposed a framework for discussing the architecture of the permeable reservoir that uses a continuum between two geometrical end-members, termed focused and unconstrained flow (Figure 3: Wallis et al., 2017). Rather than a system of absolute categorization, this continuum is a tool for comparing reservoirs and considering the degree of influence that geological features may have on the geometry of the plume. As illustrated by Figure 4, the plume is defined by the natural state distribution of isotherms. If reservoir paragenesis is simple and without a complexly overprinted record of the system waxing and waning, then patterns of hydrothermal alteration, mineral geothermometers, and fluid inclusions may also be used.

A focused reservoir is restricted to structural damage zones, such as those associated with faults (e.g., Dixie Valley, in the GB: Benoit, 1999), fissures (e.g., Puna, Hawaii: Lewis-Kenedi et al., 2010), or intrusions (e.g., Yamagawa: Sasada et al., 2000). Lithological unit(s) with comparatively high-permeability may also result in focused reservoirs that are elongate in the horizontal dimension (e.g., Yangbajing: Jianyun et al., 2015). As illustrated by the Dixie Valley and Hatchobaru-Otake in Figure 4, the temperature distribution of a relatively focused reservoir tends to be complex and include steep gradients. The permeability of a focused reservoir is typically highly anisotropic and may be compartmentalized. Subsequently, fluid flow within adjacent reservoir zones may have different chemistry, temperature, or pressure.

At the other end of the continuum is a hypothetical member where all of the geological architecture, aside from the clay cap, is above the limit for convection. Therefore, an absolutely unconstrained reservoir will form vertically above the upflow zone and mushroom symmetrically near surface. Depending on hydrologic drivers, such as topography or large bodies of surface water, the plume may be somewhat inclined (Ratouis and Zarrouk, 2016). Although no reservoir reviewed to date is absolutely unconstrained, this geometry is the true antithesis of a focused reservoir.

A range of geometries lie between the focused and unconstrained end-members where the permeable volume and, therefore, geothermal plume may bend around or be contained within major contrasts in permeability created by abutting lithologies, alteration zones, or major faults.

For instance, the southeastern extent of the Putaha reservoir in Indonesia is truncated by what is thought to be up-faulted, low-permeability basement rock (Figure 4: Layman and Soemarinda, 2003). A single system can comprise multiple reservoir geometries. For example, both Rotokawa and Nagamariki comprise a deep, relatively unconstrained reservoir that is overlain by a focused intermediate aquifer that is constrained within a layer of rhyolite lavas sandwiched between zones of smectite-altered rock (Figure 4, Boseley et al., 2010; Sewell et al., 2015).

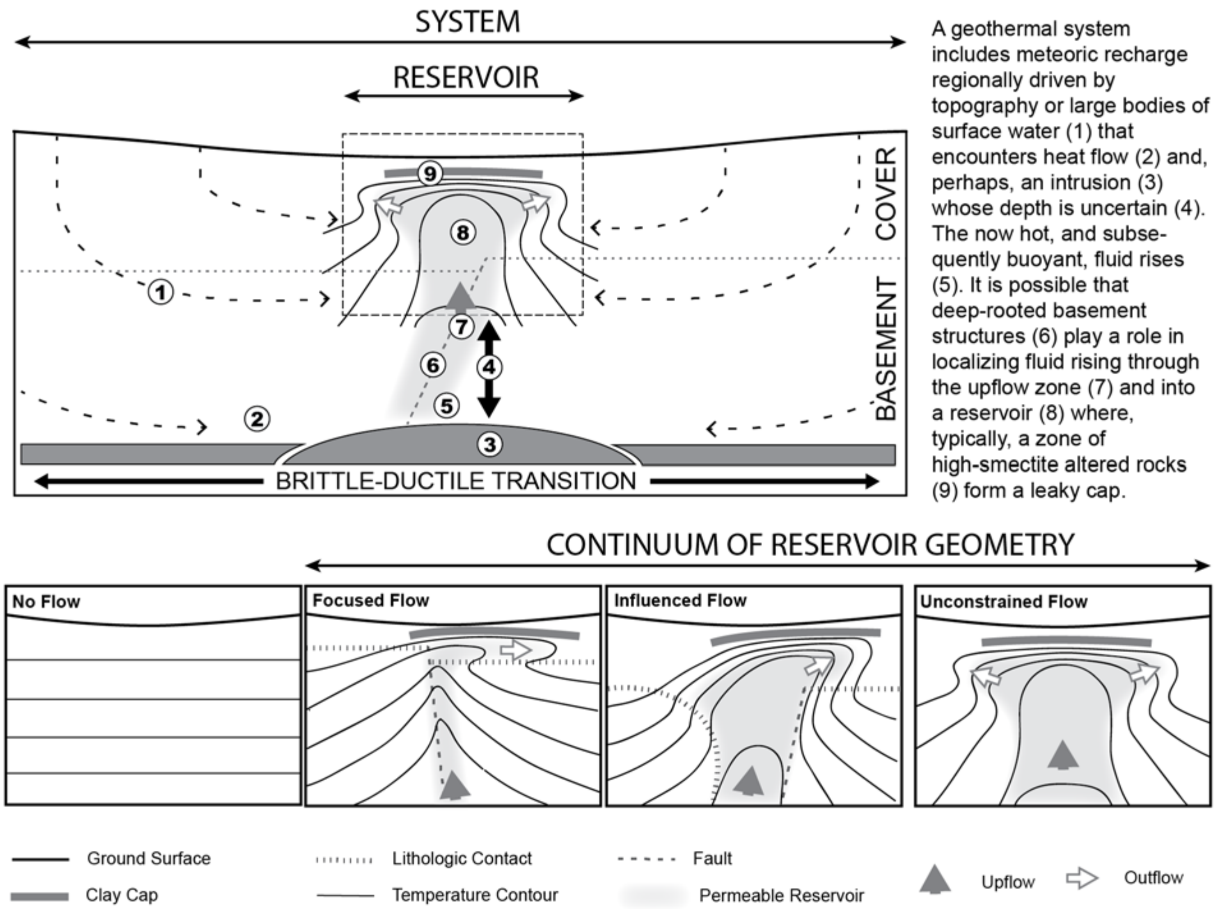
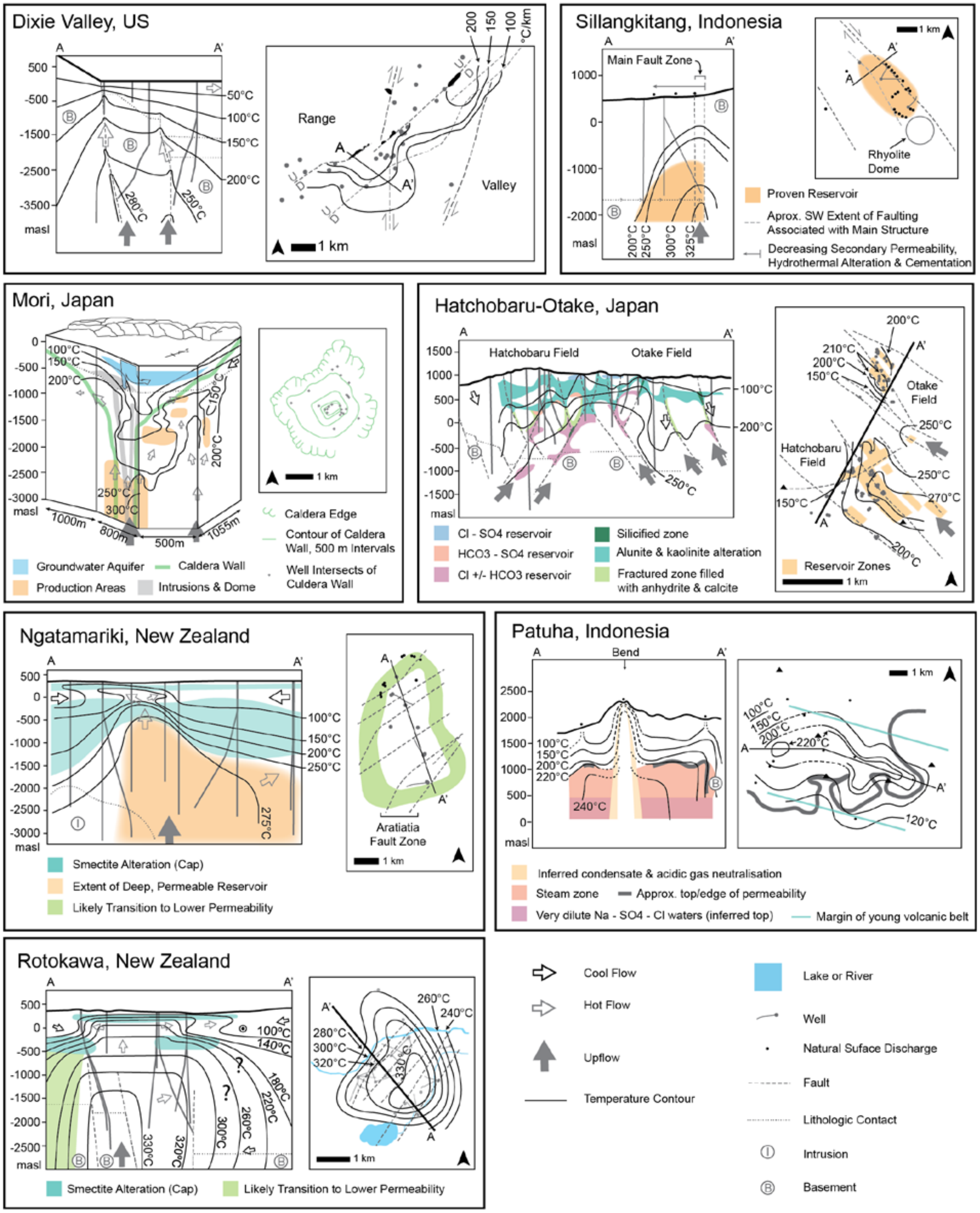


Figure 3: (UPPER) A graphical definition of the geothermal system and a reservoir within it; noting that several reservoirs may be associated with a single system. The dashed box equates to the extent of the reservoir and the geometries depicted in the lower half of the figure. (LOWER). Cross sections representing the continuum of reservoir permeability geometry from focused to unconstrained flow. Along this continuum, the geothermal plumes are variously influenced by geologic context. Figure adapted from Wallis (2017).

Figure 4 (NEXT PAGE): Conceptual model vignettes that have been compiled from published studies of eight geothermal systems: Dixie Valley (Blackwell et al., 2000; Lovenitti et al., 2011), Sillangkitang (Gunderson et al., 2000; Hickman et al., 2004; Moore et al., 2001), Mori (Hanano et al., 2005), Hatchobaru-Otake (Fujino and Yamasaki, 1984; Hirowatari, 1991), Patuha (Layman and Soemarinda, 2003), Rotoaka (Sewell et al., 2015; Wallis et al., 2013), and Ngatamariki (Boseley et al., 2010; Buscarlet et al., 2015; Chambefort et al., 2016). Compiled from published literature as cited and adapted from Wallis et al. (in review).



Dixie Valley, US
A
A'
masl
50°C
100°C
150°C
200°C
280°C
250°C
200
150
100
°C/km
Range
Valley
1 km
Sillangkitang, Indonesia
Main Fault Zone
200°C
250°C
300°C
325°C
1 km
Rhyolite Dome
Proven Reservoir
Aprox. SW Extent of Faulting Associated with Main Structure
Decreasing Secondary Permeability, Hydrothermal Alteration & Cementation
Mori, Japan
100°C
150°C
200°C
250°C
300°C
1000m
800m
500m
1055m
1 km
Caldera Edge
Contour of Caldera Wall, 500 m Intervals
Well Intersects of Culdera Wall
Groundwater Aquifer
Caldera Wall
Production Areas
Intrusions & Dome
Hatchobaru-Otake, Japan
Hatchobaru Field
Otake Field
100°C
200°C
250°C
210°C
150°C
270°C
Cl - SO4 reservoir
HCO3 - SO4 reservoir
Cl +/- HCO3 reservoir
Silicified zone
Alunite & kaolinite alteration
Fractured zone filled with anhydrite & calcite
Reservoir Zones
1 km
Ngatamariki, New Zealand
100°C
150°C
200°C
250°C
275°C
Aratiatia Fault Zone
1 km
Smectite Alteration (Cap)
Extent of Deep, Permeable Reservoir
Likely Transition to Lower Permeability
Patuha, Indonesia
Bend
100°C
150°C
200°C
220°C
240°C
120°C
1 km
Inferred condensate & acidic gas neutralisation
Steam zone
Approx. top/edge of permeability
Very dilute Na - SO4 - Cl waters (inferred top)
Margin of young volcanic belt
Rotokawa, New Zealand
100°C
140°C
180°C
220°C
260°C
300°C
320°C
330°C
240°C
280°C
1 km
Smectite Alteration (Cap)
Likely Transition to Lower Permeability
Cool Flow
Hot Flow
Upflow
Temperature Contour
Lake or River
Well
Natural Suface Discharge
Fault
Lithologic Contact
Intrusion
Basement

Metamorphic and intrusive rocks, which can collectivity be referred to as crystalline rocks, influence reservoir geometry. They have low primary porosity and permeability depends on secondary porosity. Therefore, the tectonic-geological history and the active stress state have great influence on the permeability distribution, so permeability can vary over a huge range (Figure 5, Achtziger-Zupančič et al., 2017). Depth of burial also influences the permeability of crystalline rock: Mean permeability at surface is 10^{-13} m^2 whereas the mean at 2 km depth is 10^{-17} m^2 (Achtziger-Zupančič et al., 2017), where the latter is below the limit for convection (~10^{-16} m^2: Hanano, 2004).

Deep crystalline rocks tend to result in focused or truncated reservoirs unless fault-fracture networks proliferate. For example, at depth, Coso consists of four weakly connected reservoirs hosted in fractured Mesozoic intrusive and metamorphic rocks (Adams et al., 2000). Permeability is high within these reservoirs, low in the surrounding rock, and faults play a significant role in the reservoir geometry (Davatzes and Hickman, 2010; Newman et al., 2008). At Sillangkitang, Indonesia, the reservoir extends west from the fault zone into rhyolitic tuff but not east into the basement (Figure 4: Hickman et al., 2004). At Ngatamariki, the geometry of the permeable reservoir is truncated by the intrusive complex and the overlying zone of intense high-temperature alteration (Figure 4: Chambefort et al., 2017; Clearwater et al., 2015).

Despite their overall low permeability, the margins of intrusions and basement unconformities may provide sweet spots for geothermal production because these zones can be foci of intense fracturing. Despite the generally low permeability of the hot and potentially productive basement at Ohaaki, New Zealand, drilling losses are only observed in the upper ~200 m of that unit (Wood et al., 2001). A similar pattern is seen at Hatchobaru-Otake, Japan, where the deep, fault-focused reservoirs spread in lateral extent at the contact between the basement and overlying volcano-sedimentary sequence (Figure 4: Fujino and Yamasaki, 1984). At Ngatamaiki, wells completed into the pluton found low permeability except where they encountered damage zones at the edge of the intrusions (Clearwater et al., 2015). Not all intrusions result in local permeability increase; For example, Wood et al. (2001) described a well at Ohaaki that intersected an ~10 m wide dike in the basement without any noticeable increase permeability. Permeability would depend on the persistence of open fractures in the face of alteration and their connection with the surrounding reservoir.

5. Concluding Remarks

We summarized our multi-scale review of the relationship between geologic context and geothermal permeability. The key points are listed below.

- Our review is consistent with previous studies demonstrating that geothermal systems are prolific in regions with active tectonic processes: In particular, extensional or transtensional tectonic settings. Although there is a spatial overlap with the distribution of recent volcanism, this may be coincident because amagmatic reservoirs exist and both are methods of fluxing heat from the crust.

- Developed geothermal systems are often associated with regional transfer zones (i.e., zones that accommodate stress between major structural alignments). In turn, the localization and geometry of those transfer zones are influenced by deep-rooted basement structure.
- Using case studies, we demonstrated that crystalline rocks play a major role in reservoir permeability, such that they influence both the overall geometry of the convection cell and the distribution of well productivity (sweet spots).
- The existing nonculture for describing the architecture of the permeable reservoir was found inadequate for capturing the global diversity. Therefore, we proposed a continuum that supports characterization of the relationship between geology and permeability, as well as reservoir-to-reservoir comparison.

Our review provides a robust conceptual framework for planned further research into the causal relationships between geologic context (structure, lithology and alteration) and permeability in high-temperature geothermal reservoirs.

ACKNOWLEDGEMENTS

The research is funded by a University of Auckland Doctoral Scholarship. The literature review benefited greatly from the ready access to grey literature provided by the IGA and GRC conference paper databases.

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